Applications of Hybrid Metal-Dielectric Nanostructures: State of the Art

Ángela Barreda,* Francesco Vitale, Alexander E. Minovich, Carsten Ronning, and Isabelle Staude*

Enhancing the light-matter interactions is important for many different applications like sensing, surface enhanced spectroscopies, solar energy harvesting, and for quantum effects such as nonlinear frequency generation or spontaneous and stimulated emission. Hybrid metal-dielectric nanostructures have shown extraordinary performance in this respect, demonstrating their superiority with respect to bare metallic or high refractive index dielectric nanostructures. Such hybrid nanostructures can combine the best of two worlds: strong confinement of the electromagnetic energy by metallic structures and high scattering directivity and low losses of the dielectric ones. In this review, following a general overview of the properties of metal-dielectric nanostructures, some of their most relevant applications including directional scattering, sensing, surface enhanced Raman spectroscopy, absorption enhancement, fluorescence and quantum dot emission enhancement, nonlinear effects, as well as lasing, are summarized.

1. Introduction

The interaction of electromagnetic radiation with matter structured at nanometric scales has opened a new research field in the last decades, giving rise to important theoretical and practical developments. This branch of physics and engineering is well known as nanophotonics, and one of the most active topics among nanophotonics is plasmonics. Here, progress has provided interesting perspectives for different applications, such as biosensing, communications, microscopy, or solar cells.[1,2] However, in spite of the good performance of metallic nanostructured materials in the near-infrared (NIR) and visible (VIS) spectral ranges, for some applications their inherent ohmic losses make them less attractive. Most importantly, ohmic losses give rise to joule heating of the metallic structure and its environment, which is not always desired and reduces the efficiency of plasmonic devices.

Nanostructures made of high refractive index dielectric (HRID) materials, which exhibit negligible absorption in the VIS-NIR spectral regions, are a promising solution to this problem.[3] Some of their most important advantages are related to the fact that light can travel long distances inside the dielectric material without being absorbed, as well as their compatibility with well-known technologies. For example, they can be made from either classical pure semiconductors (Si, Ge),[4–10] semiconductor compounds (GaAs, AISb, GaP, ZnO, etc.),[3] or insulators (TiO2, LiNbO3). Furthermore, HRID nanostructures can exhibit both electric and magnetic multipolar resonances even for basic particle shapes.[4] Moreover, as a consequence of coherent effects between different electric and/or magnetic resonances, even single HRID nanoparticles (NPs) can exhibit strong directionality properties.

Hybrid nanostructures consisting of both metallic and dielectric parts were suggested with the goal to combine the advantages of both implementations: large confinement of the electromagnetic energy in the surroundings of the metal and high scattering directivity and low losses in the dielectric part.[11] Such hybrid structures consisting of metallic (HRID) NPs on HRID (metallic) substrates, metal-dielectric core-shell NPs, plasmonic-dielectric gratings, HRID photonic crystals coupled to plasmonic NPs, or dielectric waveguides or cavities decorated with plasmonic NPs have been recently introduced to improve the performances of bare metallic or HRID structures in different applications, such as photovoltaics, quantum-sources, photoluminescence emission, lasing, sensing, and surface-enhanced Raman scattering (SERS) to name just a few.[12–17] The requirement of combining at least two different materials for creating the hybrid nanostructures, and the necessity of precise location of a component with respect to the other, increases the complexity in the fabrication process. For that reason, many hybrid metal-dielectric works are based on numerical simulations. Although there are a lot of numerical tools for solving problems concerning the interaction of electromagnetic radiation with matter, the most commonly used are T-matrix,[18] finite-difference time-domain, and finite element method.
In 2019, the first review about hybrid metal-dielectric nanostructures was published by Lepeshov et al.\cite{Lepeshov2019} who emphasized on the importance of these nanostructures in different applications, focusing, particularly, on the influence of hybrid nanostructures on the spontaneous emission of quantum emitters along with their application to nonlinear optics.

In our review, we rather focus on the state of the art of hybrid metal-dielectric nanostructures as photonic components in certain applications. To avoid repetitions with ref. [11], we pay specific attention to the studies published after 2018. Furthermore, we make a systematic analysis of the contribution of different kind of geometries, which are used in each of the applications. In particular, we consider metal NP-dielectric NP, metal-dielectric core-shell NPs, dielectric/metallic NPs on a metallic/dielectric substrate, hybrid plasmonic-waveguide structures, metallic NPs on dielectric microparticles or photonic crystals, as well as metasurfaces. The work is organized as follows: in Sections 1.1, 1.2, and 1.3, we describe the main electromagnetic properties of metallic, HRID, and hybrid metal-dielectric nanostructures and their applications, respectively. In Section 2, we show how the optical properties determine the electromagnetic response of metallic and dielectric NPs. We also include an overview of the coupled oscillator model for hybrid nanostructures and the Kerker’s conditions. Section 3 shows a summary of the different hybrid metal-dielectric geometries analyzed. Several fabrication techniques for manufacturing hybrid metal-dielectric nanostructures are included in Section 4. In Section 5, we pay attention to the most popular applications of these hybrid geometries. In particular, in Section 5.1 we consider directionality improvement. In Section 5.2, we introduce their applications in sensing and SERS. In Section 5.3, we turn our attention to absorption enhancement, and we analyze the increase in the fluorescence enhancement and quantum dot (QD) emission in Section 5.4. In Section 5.5, we focus on nonlinear effects. Finally, in Section 5.6, we discuss hybrid nanowires for lasing.

1.1. Properties of Plasmonic Nanostructures

Plasmonics is a field of research devoted to the study of the interaction between electromagnetic radiation and materials or nanostructures, whose optical response is dominated by free carriers. Typically these are metals, but, for instance, plasmonics effects can also be observed in highly doped semiconductors. For simplicity, we will just refer to all these materials as metals in the following. Due to the presence of free carriers, metallic materials are characterized by high values of the electric conductivity. Plasmons are defined as quantized collective oscillations of the free electron gas density in a metal. In general, light propagates in a 3D space and is not easy to confine. However, when the incident radiation interacts with metallic materials, under certain conditions, it can be confined, traveling along their surface. Such “surface light” consists not only of an electromagnetic field, but also involves the oscillations of the free electron gas of the metal.

These surface waves, called “surface plasmons” (SPs), were first predicted in 1957 by Rufus Ritchie.\cite{Ritchie1957} Depending on how SPs are excited, two kinds of SPs can be distinguished: surface plasmons polaritons (SPPs) and localized surface plasmons (LSPs). The former are excited at a flat surface separating two media, one dielectric and the other metallic, when illuminated by electromagnetic radiation under certain conditions: the dielectric function has a negative real part \( \text{Re}(\varepsilon_m) < 0 \) and the losses are small \( \text{Im}(\varepsilon_m) \ll \text{Re}(\varepsilon_m) \).\cite{Maradudin1967} The former is a characteristic of metals, while the latter is a property of a good plasmonic metal: for example, for silver, this applies throughout most of the VIS region. In contrast, LSPs arise when an incident electromagnetic wave illuminates a metallic NP, which is typically smaller than the wavelength of the incident radiation. In Figure 1, the electric permittivity of different metals: Ag and Al is shown. The large absolute values of the real part of the electric permittivity for metals lead to strong electromagnetic confinement in plasmonics.

Another important property of metals is the skin depth, which is defined as the distance a wave must travel within the metal before its amplitude has decayed by a factor of \( 1/e \).\cite{Chu1965} It can be expressed as

\[
\delta = \sqrt{\frac{2}{\mu_0 \sigma \omega}}
\]

where \( \omega \) is the angular frequency of the incident radiation, \( \mu \) is the magnetic permeability, and \( \sigma \) is the electrical conductivity.

For certain frequencies of the incident radiation, plasma oscillations can exhibit resonances.\cite{Warburton1964} In these cases, a large amount of electromagnetic energy is transferred to the free electrons in the metal, which oscillate at maximum amplitude. This resonant behavior generates strong enhancements of the electric field (hot spots) in the proximity (near-field regime) of the metallic structure. Both enhancement and confinement effects find applications in many different areas,\cite{Lepeshov2019} like sensing (contamination, biomedicine),\cite{Gonzalez2010, Pernice2012, Zheng2013} material analysis—like SERS,\cite{Farmer2011, Wang2012, Zhang2013} Förster resonance energy transfer (FRET),\cite{Förster1947, Brown2004} surface enhanced fluorescence scattering (SEFS),\cite{Mohite2011, Zhang2014} nonlinear optics,\cite{Gupta2012, Khan2013, Khan2014} absorption spectroscopy,\cite{Metzner2012, Xu2013, Schulte2014} solar cells,\cite{Antonopoulos2012, Pan2013}, or optical

![Figure 1. Real (solid line) and imaginary (dashed line) part of the electric permittivity of different metals. Ag: red and Al: blue. Ag data from ref. [374]. Al data from ref. [375]. Note that the imaginary part (right y-axis is represented in logarithmic scale).](Image)
communications.\textsuperscript{[47,69–71]} To enhance the intensity of the electric field, aggregates of NPs, particularly dimers, two particles separated by a nanogap, or bow tie antennas have been suggested. The electric field in the gap between the particles is several times larger than near a single NP due to the coupling effects between both components of the structure.\textsuperscript{[20,72–74]}

In the particular case of subwavelength metallic particles, the coherent oscillations of the electron plasma depend on the material properties, particle size, and shape, and also on the wavelength of the incoming radiation and the refractive index of the surrounding medium. These oscillations result in particular surface charge distributions.\textsuperscript{[22,75,76]} While in the quasi-static approximation, that is, for NPs with sizes much smaller than the wavelength, the resonance wavelength depends only on the material properties, it becomes size-dependent for larger NPs. Specifically, as the particle size increases (decreases), plasmonic resonances are redshifted (blueshifted).\textsuperscript{[22]} This means that the tuning of the resonance wavelength can be obtained by changing the particle size. This same effect is observed if the optical constants of the surrounding medium are increased (decreased).\textsuperscript{[22]}

Another way of tuning the spectral position of the plasmon resonance is changing the material of which particles are made or modifying the geometry of the scatterer. In particular, core-shell NPs have been proposed for such an objective: \textsuperscript{[77,78]} for larger and elongated particles, higher multipoles become important, especially the quadrupole electric resonance.\textsuperscript{[22]}

An important parameter of any resonant excitation is the quality factor, $Q$, which, for the plasmonic case, describes how many optical periods of free SP oscillations occur before the field decays. Typical $Q$-values for LSP resonances are on the order of up to few tens.

1.2. Properties of Dielectric Nanostructures

The growing interesting in HRID nanostructures can be readily understood by examining their optical properties. On the one hand, the imaginary part of the refractive index of elemental semiconductors (Si, Ge), or semiconductor compounds (AlAs, AlSb, GaP, etc.), is very small for wavelengths beyond their fundamental electronic bandgaps and in the absence of other resonant excitations. This is the reason why nanostructures composed of these materials can present negligible absorption, making them an interesting alternative to the metallic ones in resonant nanophotonics. On the other hand, the real part of the refractive index takes large values, $n \approx 3$, allowing for the confinement of electromagnetic energy inside the nanostructure. Due to the high refractive index, the effective wavelength inside the dielectric material is reduced compared to free space by a value equal to its refractive index. In Figure 2, we show the real and imaginary parts of the electric permittivity of different dielectrics. In particular, the optical constants of Si and Ge are represented. The real part takes positive values for dielectrics, contrary to metals. On the other hand, the imaginary part of the electric permittivity is almost negligible in the NIR for many dielectrics (like Si), while it exhibits large values for metals, which explains the difference in the losses in both types of materials. In particular, for Si, we have represented the bandgap wavelength (black dashed line). For wavelengths larger than the bandgap, we can observe as the absorption is almost negligible. In the figure it is not included the bandgap wavelength for Ge as it is attained at larger wavelengths than those represented in the plot.

The high values of the refractive index at below-band gap wavelengths of the semiconductors originate from a continuum of interband transitions.\textsuperscript{[79]} The value of the refractive index of a semiconductor is related to the electronic band gap. When the energy gap increases, the electrostatic refractive index of a semiconductor decreases.\textsuperscript{[79]}

Due to the practical absence of free electrons in HRID NPs, instead of electronic plasma oscillations (observed for plasmonic NPs), certain distributions of displacement currents inside the NPs are responsible for the electric and magnetic resonances.\textsuperscript{[79]} In the following, in accord with common practice in the literature, we will refer to the resonances of HRID NPs as Mie resonances, while noting that the theory is strictly valid only for spherical particles and that plasmonic resonances can also be described by the Mie theory.

Dipolar electric and magnetic modes are associated with linear and circular displacement currents inside the NP, respectively. According to the induction law, an oscillating circular current induces an oscillating magnetic field, and vice versa.\textsuperscript{[80]} Notably, the hierarchy of magnetic and electric resonances for spherical HRID NPs is changed with respect to the plasmonic resonances of metallic spheres and the lowest-order resonance of the dielectric NPs corresponds to the dipolar magnetic mode. This can be observed when the wavelength of the incident radiation ($\lambda$) inside the particle is approximately equal to its diameter, that is, $\lambda/n_1 = 2R$ (where $n_1$ is the NP refractive index and R its radius).\textsuperscript{[81,82]} The exact resonance position depends on the NP size and shape, its refractive index and that of the surrounding medium. As the size and/or the refractive index of the NP or that of the surrounding medium increase, the resonance position is shifted to longer wavelengths.\textsuperscript{[83]} Eventually, for particles with sizes exceeding few wavelengths inside the material, whispering
gallery modes (WGMs) are formed, which can be described as closed circular light paths supported by total internal reflection from the periphery of the resonator.\textsuperscript{[84]}

As a consequence of coherent effects between the excited electric and/or magnetic modes, HRID NPs can be designed to control the direction of the scattered radiation,\textsuperscript{[95–99] see Section 2.4.}

To efficiently excite and spatially overlap dipolar or higher-order electric and magnetic resonances, different geometries were analyzed. In ref. [92], it was shown that by tailoring the aspect ratio of silicon nanodisks, it is possible to tune the dipolar electric and magnetic resonances with respect to each other, which allows to achieve a spectral overlap of both resonances. More complex geometries like all-dielectric core-shell NPs have been studied with the same objective.\textsuperscript{[93,94]} The most important advantage of such nanostructures is that the resonances can be tuned to simultaneously support electric and magnetic modes of different orders by changing the core size relative to that of the particle.\textsuperscript{[95]} In contrast, anisotropy can also be employed to tune the spectral position of electric and magnetic resonances.\textsuperscript{[96,97]}

In\textsuperscript{[98]} high directivity values of optical nanoantennas (based on the excitation of higher-order magnetic multipole moments) were achieved using a HRID antenna with a notch, which is excited by a dipole located within it.

Directionality properties exhibited by this kind of structures make them attractive for several applications.\textsuperscript{[99]} To name a few, HRID NPs have been suggested for improving the performance of photovoltaic devices,\textsuperscript{[100–103]} radiation sensing,\textsuperscript{[88,104–107]} radiation guiding at the nanoscale (nanoantennas),\textsuperscript{[108–111]} enhancing nonlinear phenomena such as second- and third-harmonic generation,\textsuperscript{[112–119]} waveguiding,\textsuperscript{[120]} and exciting Fano resonances,\textsuperscript{[99,121–129]} among others.

The possibility of exciting nonradiating anapole modes has also been demonstrated by means of HRID NPs.\textsuperscript{[130,131]} The excitation of this mode can be useful for invisibility purposes or for obtaining high Q factors due to the scattering suppression at resonance.\textsuperscript{[130]} Such null scattering effect can be explained in terms of the physical origin of the anapole, which can be understood as a composition of electric and toroidal moments. Because of the similarities between their far-field scattering patterns, radiation fields can interfere destructively in all directions.\textsuperscript{[130]}

HRID NPs have also been proposed as building blocks for metamaterials and metasurfaces.\textsuperscript{[92,132–149]} A large variety of functionalities ranging from various wavefront shaping effects such as beam shaping,\textsuperscript{[113]} focusing\textsuperscript{[150]} or holography,\textsuperscript{[151]} over-polarizing elements\textsuperscript{[152]} to electric and magnetic\textsuperscript{[153–155]} were demonstrated, to name just a few. For further details on the fields of dielectric metasurfaces, we refer to other recently published reviews such as refs. [156–159]. All the mentioned results so far are based on far-field scattering phenomena. However, HRID NP systems have also shown their applicability in near-fields effects like SERS,\textsuperscript{[160,161]} fluorescence enhancements,\textsuperscript{[162]} or thermal therapy,\textsuperscript{[163]} among others.

In ref. [164], it was demonstrated that by using silicon dimers, electric and magnetic hot spots can be observed in the gap (distance between the particles), which can find applications in enhanced spectroscopy techniques. The strong confinement of electromagnetic radiation is produced due to the interaction effects between the NPs. The low absorption of HRID NPs allows to design nanoantennas with both high surface enhanced fluorescence and surface enhanced Raman scattering, which generate, at the same time, a negligible temperature increase in the hot spots and the surrounding.\textsuperscript{[165]} Although the electromagnetic field enhancement is less intense in dielectric NPs compared to the metallic ones, the absence of radiative emission quenching, together with the high quantum efficiency, makes the aggregates of HRID NPs efficient units for enhancing the emission of quantum emitters. The possibility to excite magnetic hot spots is also interesting for the study of fluorescence enhancement of magnetic emitters.

Ultimately, nonlinear effects have been vastly explored also in all-dielectric nanostructures. Non-centrosymmetric III–V alloys, like aluminum gallium arsenide (AlGaAs) and gallium arsenide (GaAs), which possess high $\chi^2$, nonlinear Mie resonances, have been proposed as an alternative to centrosymmetric materials, like silicon, where second-order bulk nonlinear processes are inhibited.\textsuperscript{[166]} Depending on the considered semiconductor material, the described effects can be tuned within different spectral regions.

### 1.3. Properties of Metal-Dielectric Nanostructures

Based on the previous description of the electromagnetic properties of metals and dielectrics as well as their respective resonant nanostructures, it is possible to understand the advantages and disadvantages of both implementations and how they can be combined to access new state space in light-matter interactions at the nanoscale. The goal of this section is to discuss the main aspects in this respect in a general fashion. The discussion of particular implementations making use of these effects follows in Section 5.

#### 1.3.1. Light Funneling

As described in detail in Section 1.1, plasmonic nanoantennas provide the strongest possible light localization. However, due to their small size, they are restricted in the coupling efficiency regarding their excitation by diffraction limited far-field optical waves generated by macroscopic sources.\textsuperscript{[166]} For a quantitative estimate of how the size of a nanoantenna influences the far-field coupling, it is instructive to check the expression for the power emitted by a time harmonic line current element (size $\Delta l$, oscillation frequency $\omega$, peak amplitude of the current $I$)\textsuperscript{[167]}

\begin{equation}
\frac{P_{\text{rad}}}{\lambda} = 4 \pi^2 \left(\frac{2}{\pi}\right) Z_W \left(\frac{\Delta l}{\lambda}\right)^2 \left(\frac{\Delta l}{\Gamma}\right)
\end{equation}

where $Z_W = \sqrt{\frac{\mu_0}{\epsilon_0}} = 377\text{\Omega}$ is the wave impedance of free space.

In plasmonic nanostructures, the electrons respond to an electromagnetic field scattered by a metal particle, which generates a near-field. The combination of the fields scattered by the metal particle and the near-field generated by it results in the enhancement of the electromagnetic field at the resonance frequency. This enhancement is due to the resonance of the metal particle, which absorbs or reflects the electromagnetic field. The enhancement factor $\lambda/\lambda_{\text{eff}}$ is typically in the range of 2–5, which is much stronger than the enhancement factor for the electromagnetic field generated by a dielectric particle. Considering, for example, a half-wavelength antenna made of a gold wire of 5 nm radius and resonance wavelength of $\lambda = 800$ nm, the wire length turns out to be $\Delta l = \lambda_{\text{eff}}/2 \approx 80$ nm. With $\lambda/\lambda_{\text{eff}}=5$, the
term \((\Delta l/\lambda)^2=0.01\), that is, the emitted power is reduced by two orders of magnitude due to the size mismatch. Note that the power emitted by a quantum emitter composed of quanta of discrete energy \(E = h\nu = hc/\lambda\) can be expressed as \(P = E\gamma\) with a photon emission rate \(\gamma\), which relates to the excited state lifetime \(\tau\) by \(\gamma = 1/\tau\). Thus, the maximum number of emitted (and by reciprocity also of the absorbed) photons per unit time is limited.

For a Mie resonant dielectric NP, the lowest-order resonance, which corresponds to the dipole dipole resonance, appears approximately at a wavelength of \(\lambda = 2na\), where \(n\) and \(a\) are the refractive index and the particle radius, respectively. While the magnetic dipole resonance features a circular displacement current and, therefore, cannot be described as a line current element, this expression can still serve to estimate a lower bound for the size of a line current element. One can argue that the electric dipole resonance, which roughly implements a line displacement element, occurs at higher frequency for spherical dielectric particles and therefore requires an even larger particle size to establish a resonance at the same operation wavelength. Following this argument, we can estimate \(\Delta l = 2a = \lambda/n\) and thus \((\Delta l)^2 = (\lambda/2a)^2\). For silicon particles, for example, this amounts to \((\Delta l)^2 = (\lambda/2a)^2 \approx 0.1\); thus, almost an order of magnitude larger than for the plasmonic example. For materials with lower refractive indices, the size mismatch is reduced even further. We can conclude that since the ratio of the size of the antenna and the operation wavelength enters the coupling efficiency/cross-section formula quadratically, using a resonant dielectric NP as a collector element of a hybrid antenna can significantly help funneling the light to the plasmonic antenna without adding further significant absorption losses.

1.3.2. Electromagnetic Field Enhancement

As discussed in the previous section, hybrid plasmonic/dielectric approaches help addressing plasmonic nanoantennas more efficiently. Thereby, they can also lead to greater field enhancements. Although for certain hybrid nanostructures, for example, dimers composed of a metallic and a HRID NP, the enhancement of electromagnetic energy in between the particles may be smaller than for metallic NP dimers,[168] in the last years other different kind of hybrid structures have been proposed to increase the electromagnetic field enhancement. In particular, particle on mirror geometries (dielectric NPs separated of a metallic substrate by a nanometer-sized dielectric spacer) have demonstrated to provide strong confinement of electromagnetic radiation overlapping that attained for purely plasmonic systems.[14,169–174] In addition, the enhancement of plasmonic nanostructures can be increased by placing them in the nearby of a dielectric structure.[175] The physics underlying these geometries will be described in Section 3. In Table 1, we show a comparison of the electric field enhancement of hybrid nanostructures. Field enhancement, in turn, is the key performance parameter for boosting various other processes and effects, for example:

**Purcell Effect:** The radiative decay rate of an emitter system depends on its environment. In the literature, it is frequently stated that the Purcell factor \(F_P\), which relates the radiative decay rate of a coupled emitter-cavity system to that of an emitter situated in free space, is given by the ratio of the cavity quality factor \(Q\) and its mode volume \(V\).\(^\text{[176]}\) However, it was shown that for emitters coupled to plasmonic nanoantennas, this simplified equation does not yield accurate results.\(^\text{[177]}\) Instead, one should consider the more fundamental expression stating that the radiative decay rate of an emitter scales with the partial local density of the final photonic states, which in turn is directly related to the electric field via the imaginary part of the Green’s dyadic of the system (see, e.g.,\(^\text{[167]}\) for a formal discussion). As such, as discussed, for instance, in ref. [11], the Purcell factor depends only on the electromagnetic properties of the surrounding medium. By modeling hybrid systems combining a cavity and a dipolar antenna as coupled harmonic oscillators, it was shown that such hybrid systems can achieve higher Purcell factors than the cavity or antenna alone.\(^\text{[178]}\) This effect is reviewed in more detail below in Section 2.2.

| System | Electric field enhancement \(|E_j|/|E_0|\) | Work type | Ref. |
|--------|--------------------------------|------------|------|
| Si NP + QD monolayer nanogap + Au substrate | >50 | Experimental | [14] |
| Au nanosphere + Au-sloped Si3N4 strip on SiO2 substrate | \(\approx 30 \pm 1.5\) w/o nanosphere | Theoretical | [17] |
| SiO2 microsphere + Au NP | \(\approx 45\) (9 × bare Au NP) | Theoretical | [72] |
| Si NP + SiO2 nanogap + Ag film | \(\approx 60\) (12 × bare Si NP) | Theoretical | [169] |
| Si nanodisk + Al2O3 spacer + Au substrate | \(>40\) | Experimental | [179] |
| Ag-coated polystyrene nanospheres + Ag-passivated TiO2 film on Si/Ge substrate | \(6 \times\) w/o Ag coating and w/o TiO2 film | Theoretical | [256] |
| Si NP + Au substrate | \(\approx 80\) | Theoretical | [171] |
| Au nanostrip dimer lined in a Si nanodisk with air slot | \(\geq 2.5\) (1.8 × NP on SiO2 substrate) (1.4 × NP in air) | Theoretical | [172] |
| Si NP + Al2O3 nanogap + Au film on Si substrate | \(37\) (20 × dimer w/o Si nanodisk) (4 × Au nanostrip w/o dimer) | Theoretical | [258] |
| LiNbO3 nanodisk-based metasurface on Au substrate | \(\approx 17\) | Theoretical | [174] |
| Au nanorod dimer + spacer (n = 1.46) + disk-ring structure | \(\approx 400\) (15 × individual plasmonic antenna) | Theoretical | [175] |

(Table 1. Summary of electric field enhancement \(|E_j|/|E_0|\) for different geometries of hybrid metal-dielectric systems.)
Nonlinear Optical Processes: In nonlinear optics, the polarization of a lossless, dispersionless medium with instantaneous reaction can be expressed as a power series in the electric field \[ \chi^{(n)} \] as

\[ P(t) = \chi^{(1)} E(t) + \chi^{(2)} E(t)^2 + \chi^{(3)} E(t)^3 + \ldots, \tag{3} \]

where \( \chi^{(n)} \) is the \( n \)-th order susceptibility of the nonlinear medium. Consequently, second-order nonlinear processes, such as second harmonic or sum-frequency generation, scale with the square of the electric field, whereas third-order nonlinear processes, such as third harmonic generation or the Kerr effect, scale with its cube. Thus, by enhancing the fields inside the nonlinear medium, these effects can be strongly boosted. This topic is more deeply analyzed in Section 5.5.

Absorption Enhancement: While in many cases researchers strive to decrease the losses in a nanophotonic system to a minimum, a strong and tailorable absorption is needed in many applications including sensing, spectroscopy, solar energy harvesting, and detectors. The more the fields can be concentrated in a nano-scale volume containing the active material (or analyte), the higher the absorption that can be achieved. The refractive index is a complex number \( n + i \cdot k \), since the real \( n \) and imaginary \( k \) parts are related to the ratio of the wave velocity in vacuum and the velocity in the medium, and to the extinction coefficient, respectively. The last magnitude is connected to the absorption coefficient. In particular, the absorption coefficient \( \alpha \) is related to the imaginary part of the refractive index \( k \) by means of the following expression\[180\]

\[ \alpha = \frac{2k\omega}{c} \tag{4} \]

where \( \omega \) is the frequency of the incident radiation and \( c \) the speed of light in vacuum.

Raman Scattering: Surface enhanced Raman scattering (SERS) is a surface-sensitive technique which enhances the Raman signal of molecules adsorbed on rough metals, metal NPs, or other metal nanostructures. The increase in the Raman signal is produced due to the enhancement of the electric field at the metal surface as a consequence of the excitation of LSPs\[181\]. The SERS effect can be very pronounced for strong field enhancements, as the Raman signal scales with the fourth power of the electric field, \( |E|^4 \)[182]. This factor can be understood by taking into account the fact that the field enhancement contributes to the amplification of the Raman signal twice. On the one hand, it increases the incident radiation, which excites the Raman modes in the molecule. On the other hand, the actual Raman signal itself is also enhanced by the surface. For each of these steps, the Raman signal is increased by \( |E|^2 \). To obtain such fourth power enhancement, the Raman shift must be small compared to the pump frequency\[187\].

Directional Emission Enhancement: Combining the effects of improved light funneling and strong Purcell enhancement is particularly attractive for boosting directional emission while preserving a high radiation efficiency. As it will be reviewed in detail in Section 5.4, combining a plasmonic feed element concentrating the light into a strongly subwavelength volume with HRID director elements constitutes the prototypical architecture for this purpose.

1.3.3. Tailoring Absorption

Apart from enlarging the state space for the field enhancement at the nanoscale that can be achieved by a metal-dielectric nanostructure, the combination of one nearly lossless and one absorbing materials also allows for a careful tailoring of the amount of light that is absorbed in the structure under certain illumination conditions. To make this point more clear, we can first compare the two extreme cases: a purely dielectric, lossless structure, on the one hand, cannot be engineered to show strong or even perfect absorption. A lossy metallic structure, on the other hand, will always suffer from absorption losses. However, by combining both materials and by tailoring where in the structure the near-fields can be concentrated, the full state space from almost lossless to fully absorbing can be accessed. The nanostructures can even be engineered to show very different levels of absorption under different illumination conditions, for example, upon illumination from two different sides, corresponding to the phenomenon of asymmetric reflectance\[183\].

1.3.4. Tailoring Anisotropy

From the field of hyperbolic metamaterials\[184\], it is well known that layered nanostructures consisting of alternating thin layers of a metal and a dielectric offer a route to implement highly anisotropic effective material parameters, including the important case of negative and positive electric permittivities along different axes. While, by itself, this is an off-resonant effect and out of the scope of this review, the same recipe can be used to create resonant NPs composed of highly anisotropic effective materials\[96,97,185\]. In such hierarchical nanostructures, the possibility of tailoring not only size and shape of the NP, but also its permittivity tensor, provides a powerful means for engineering the optical response beyond what is possible with NPs made from pure natural materials. A possible implementation of such particles, which will be discussed in detail in Section 5.1, is represented by sphere-shaped “nano-onions” consisting of alternating concentric layers of a metal and a dielectric.

1.3.5. Local Functionalization of Waveguides for Integrated Optics

In the previous chapters we have described in detail that HRID nanostructures can support multipolar Mie-type resonances. However, much more commonly, known HRID nano- or microstructures are also used as linear waveguides in integrated photonics, where they can transmit light from one side of a photonic chip to another with almost no losses and implement various functions such as interferometers, splitters, and bends. Plasmonic NPs can be used to functionalize such on-chip waveguides locally, adding functionalities such as light routing\[186,187\] all-optical switching\[188,189\], or enhancing the emission from a nanoscale source directly into a guided mode\[190\]. The primary advantage of such an approach is the small footprint of the plasmonic antennas, which may enable highly compact on-chip...
devices and/or a high integration density. Likewise, dielectric on-chip waveguides can be bent to form high-Q WGM resonators, which can also be hybridized locally by plasmonic nanoantennas, forming coupled antenna-cavity systems for high Purcell enhancements as described under the corresponding point above in this section.

1.4. Metallic and Dielectric Materials in Hybrid Nanostructures

One of the most relevant advantages of hybrid metal-HRID nanostructures is that it is possible to benefit of the small losses of the HRID materials. However, HRID materials are only lossless in certain spectral regions (i.e., wavelengths longer than that corresponding to the bandgap). This suggests that depending on the application that we are interested in, it is necessary to draw on to different HRID materials. The selection of the metallic material is mainly related to its compatibility with the pursued goal. For example, for sensing purposes, Au is more commonly used than Ag due to its lower oxidative character. In Table 2, it is shown a summary of the most commonly used metallic and dielectric materials in hybrid nanosystems, depending on the application.

2. Theoretical Considerations Regarding Hybrid Metal-Dielectric Nanoparticles

In 1908, Gustav Mie developed the theory for solving the problem of electromagnetic scattering by an isolated spherical particle of arbitrary radius \( R \) and refractive index \( n \), embedded in a homogeneous and isotropic medium illuminated by a plane wave. This theory plays an important role in the analysis of interaction of electromagnetic radiation with matter, as it provides an analytical solution, allowing to have a better understanding of the underlying physics. It is important to remark that analytical solution can only be found for a few geometries: spheres, coated spheres, and infinite long cylinders. For further insight into Mie’s theory see ref. [191].

2.1. Absorption, Scattering, and Extinction Cross-Sections

The scattering, extinction, and absorption cross-sections can be written as a function of the Mie coefficients (Equation (5)–(7))

\[
C_{sca} = \frac{2\pi}{k^2} \sum_{n=1}^{\infty} (2n+1)(|a_n|^2 + |b_n|^2)
\]

\[
C_{ext} = \frac{2\pi}{k^2} \sum_{n=1}^{\infty} (2n+1)\text{Re}(a_n + b_n)
\]

\[
C_{abs} = C_{ext} - C_{sca}
\]

where \( a_n \) and \( b_n \) are the Mie coefficients for the scattered field. They indicate the strength of the multipolar contributions of order \( n \), electric or magnetic, respectively. In particular, \( a_1 \) and \( b_1 \) correspond to the dipolar electric and magnetic modes, respectively, and \( a_2 \) and \( b_2 \) correspond to the quadrupolar modes, respectively. \( k \) is the wavevector of the incident radiation.

The efficiencies for scattering, extinction and absorption (Equations (8)–(10)) are obtained dividing the respective cross-sections by the particle cross-sectional area projected onto a plane perpendicular to the incident beam, \( G \). For the spherical case, \( G = \pi R^2 \).
2.2. Influence of the Optical Material Properties

In this section, we explain how the material optical constants influence the kind of resonances that are observed in the electromagnetic spectrum. With this aim, we analyze the absorption and scattering efficiencies, as well as, the different contributions of the Mie coefficients ($a_n$ and $b_n$) to the extinction efficiency spectra for metallic and dielectric spherical NPs. In particular, in Sections 2.1.1 and 2.1.2, we depict the results for silver and silicon NPs, respectively. In Section 2.1.3, we examine the case of metallo-dielectric core-shell NPs.

2.2.1. Silver Nanoparticles

In visible spectral region, the refractive index of silver is a complex number. This means that this material presents absorption, that is, Joule losses. In Figure 1, the electric permittivity of Ag is shown. As it can be observed, the real and imaginary parts take negative and positive values, respectively.

In Figure 3, the absorption and scattering efficiency spectra of a silver spherical NP are plotted for several radii. For the smallest NP sizes, the absorption efficiency is larger than the scattering. In addition, for the dipolar limit (particle is small compared to the wavelength of the incident radiation) the resonance is observed at $\lambda = 355$ nm, corresponding to $Re(\varepsilon) = -2$. As the particle size increases, scattering prevails over absorption. To understand the origin of the different resonances observed in the spectra, we have studied the contribution of the first Mie coefficients $a_n$ and $b_n$ to the extinction efficiency (see Figure 4).

For the smallest analyzed radii ($R = 10–30$ nm), the resonances present a dipolar electric ($a_1$) character and do not depend on size as the size can be described in the quasi-static approximation. As the NP size increases, resonances are redshifted and higher multipolar order modes are excited. In particular, for $R = 70$ nm, we observe a new resonance at the left of the dipolar electric one, which can be identified as a quadrupolar electric resonance ($a_2$). For $R = 90$ nm, the octupolar resonance is also excited ($a_3$). It is observed that increasing the particle radius, the strength of the higher multipolar orders is enhanced, whereas the opposite applies for the dipolar mode. In addition, all the resonances are broadened and redshifted, due to dynamic depolarization and radiation damping, respectively. The explanation of these two effects was provided by Meier and Wokaun in 1983.[192] According to this work, the polarization $P$ over the volume of a sphere can be calculated from

$$\varepsilon = 1 \left( E_0 + E_{dep} \right)$$

where $E_0$ is the incident electric field and $E_{dep}$ is a depolarization field as it is given by

$$E_{dep} = \left( -\frac{4\pi}{3} + k^2 \frac{4\pi}{3} a^2 + \frac{2}{3} k^2 \frac{4\pi}{3} a^3 \frac{3}{3} \right) P$$

$\alpha$ and $k$ correspond to the particle radius and wave vector of the incident radiation, respectively.

Figure 3. a) Absorption and b) scattering spectra of a spherical silver NP. The NP radius increases from $R = 10$ nm to $R = 150$ nm with steps of 1 nm. The dotted white and blue lines represent a guide line of the dipolar electric and quadrupolar electric resonances, respectively.
Substituting Equation (12) into Equation (11), the following expression for $P$ is obtained

$$P = \frac{3\pi}{4\varepsilon_0 C_0} \left( \frac{\varepsilon - 1}{\varepsilon + 1} \right) q^2 \frac{E_0}{(\varepsilon - 1)\frac{\varepsilon}{C_1}}$$

(13)

where $q = k\alpha$.

In Equation (13), the term $-(\varepsilon - 1)\frac{\varepsilon}{C_1}$ corresponds to the radiation-damping correction to the electro-static solution. It refers to the damping of the dipole due to the radiative losses and results in the broadening of the resonances. The term $-(\varepsilon - 1)q^2$ is known as the dynamic depolarization and is responsible for the redshift of the resonances with the increase of the particle size.

Another way to identify the origin of the different resonances observed in the spectrum is to plot the electric or magnetic near-field maps. In Figure 5, it is represented the electric field amplitude of a silver NP of radius $R = 25$ nm at the dipolar electric resonance ($\lambda = 365$ nm).

2.2.2. Silicon Nanoparticles

Contrary to the metallic materials, for the dielectric ones, the imaginary part of the refractive index may be negligible. That is the reason why these materials do not present ohmic losses in certain spectral regions. As an example of dielectric material, we focus on silicon. In Figure 2, we have represented the real and imaginary parts of the Si electric permittivity. It is observed that in the VIS, Si is absorptive. However, in the NIR, absorption is almost null. In addition, from the inspection of the real part of the electric permittivity, we can see that it takes large values. This makes sure that the electromagnetic radiation can be confined inside the NPs, generating displacement currents, which are responsible for the electric and magnetic resonances. In Figure 6, the absorption and scattering efficiency spectra are represented for a spherical silicon NP as a function of its radius. In Figure 7, the different contributions of the first Mie coefficients to the extinction efficiency are shown.

One of the most remarkable differences with respect to the plasmonic NPs is that we observe magnetic resonances. This can be observed from the inspection of the near-field maps.

**Figure 5.** Normalized electric field amplitude for a silver NP of radius $R = 25$ nm at the dipolar electric resonance $\lambda = 365$ nm.

**Figure 6.** a) Absorption and b) scattering efficiency spectra of a spherical silicon NP. The NP radius increases from $R = 90$ nm to $R = 150$ nm with steps of 1 nm. The dotted red, white, and black lines represent a guide line of the dipolar magnetic, dipolar electric, and quadrupolar magnetic resonances, respectively.

**Figure 7.** Contributions of the Mie coefficients $a_1$, $b_1$, and higher multipolar orders ($a_2$ and $b_2$) to the extinction efficiency for a silicon spherical NP of radius ranging from $R = 90$ nm to $R = 150$ nm with steps of 1 nm.
represented in Figure 8. In Figure 8a and b, it is plotted the electric field amplitude for a Si NP of radius $R = 230$ nm at the wavelengths where the dipolar electric ($\lambda = 1283$ nm) and magnetic ($\lambda = 1667$ nm) resonances are excited, respectively. In fact, for a fixed NP size, the dipolar magnetic resonance occurs at the largest wavelength of the incident radiation compared to other resonances.[79] Similar to the case of metallic NPs, for the dielectric ones, as the NP size increases, higher multipolar orders can be excited. For $R = 90$ nm, only the dipolar electric ($a_1$) and magnetic ($b_1$) resonances are contributing to the extinction spectra. However, for $R = 150$ nm, the quadrupolar electric ($a_2$) and magnetic ($b_2$) resonances are also excited. Moreover, resonances are redshifted and broadened with the increase of the radius. From the absorption efficiency spectra, it can be concluded that in the NIR, where the imaginary part of the electric permittivity is negligible, absorption is null and the extinction is determined by the scattering of the NP.

2.2.3. Metallo-Dielectric Core-Shell NPs

Metallo-dielectric core-shell NPs were proposed as novel scattering units, as they can support plasmonics and Mie-type resonances. The case of a spherical shape, that is, the simplest metal-dielectric system, can still be analytically described by the Mie theory, but it already shows some of the advantages of hybrid nanostructures. The plasmonic resonances are due to the metallic core, whereas the Mie resonances correspond to the dielectric shell. This allows to tune the spectral position of the resonances by changing the core size with respect to that of the particle. In Figure 9, the extinction efficiency spectrum is plotted for a silver core-silicon shell NP of radius $R = 200$ nm as a function of the core size, $R_{\text{core}}$. The contribution of the first Mie coefficients to the extinction efficiency are also represented. In Figure 9a, it is observed that the dipolar magnetic resonance appears at larger wavelengths compared to the dipolar electric one. This is the same behavior as for pure silicon NPs. However, for $R_{\text{core}} = 70$ nm, we find the opposite situation. The dipolar electric resonance is achieved at longer wavelengths than the magnetic one. As the core size increases, the dipolar electric/magnetic resonances are red/blueshifted. In addition, losses can also be tuned by changing the core size. This behavior can be observed in Figure 10a, where the absorption efficiency is plotted for several core radii of a core (silver) shell (silicon) NP of size $R = 200$ nm. In Figure 10b, we show the evolution of the resonances in the scattering efficiency spectra as a function of the core radius, for the same core-shell NPs as in Figure 10a.
2.3. Coupled Oscillator Model for Hybrid Nanostructures

Hybrid systems consisting of a plasmonic NP, or a dimer, coupled to a photonic crystal, have been proposed as efficient nanostructures to enhance the Purcell factor to values not attainable with either bare photonic or bare plasmonic cavities. These hybrid plasmonic–photonic cavities can take advantage of the high Q factor values of the photonic crystal and the strong confinement (small mode volume \( V \)) of electromagnetic radiation in the surroundings of the metallic NP, or in the gap between the NPs constituting a dimer. Due to the hybridization of the plasmonic and photonic modes, the Q factor and mode volume \( V \) values can be tuned. This also allows to obtain Purcell factor values suitably chosen for the required application.

It was shown in 2016 by Doelman et al. \[^{[178]}\] that the electromagnetic behavior of hybrid plasmonic–photonic systems can be predicted by an analytical model based on coupled harmonic oscillators. According to this theoretical description, the antenna and cavity are considered as coupled harmonic oscillators driven by a dipole source (emitter). This simple model, which only requires as inputs the properties of the bare antenna (scattering cross-sections and LDOS for the bare plasmonic NP, i.e., in absence of the cavity) and cavity (mode volume, Q factor), provides precise quantitative results of the Purcell factor enhancement for a large kind of hybrid plasmonic-photonic resonators (photonic crystal cavities, showing TE confined modes, coupled to plasmonic antennas exhibiting a dipolar behavior).

The model works under the assumption that the antenna and the cavity are weakly coupled, as it is possible to describe the antenna response by means of its dipole moment.

According to this model, the LDOS can be expressed as

\[
\text{LDOS} = 1 + \frac{6\pi\varepsilon_0 c^3}{\omega^2 n} \text{Im}[\alpha_H G_{bg}^2 + 2G_{bg}\alpha_H\chi_H + \chi_H] \tag{14}
\]

where \( n \) corresponds to the refractive index of the surrounding medium, \( c \) is the speed of light in vacuum, \( \omega \) is the optical frequency and \( \varepsilon_0 \) is the vacuum electric permittivity.

LDOS is the result of the interference of three different terms. Each of these incorporate the response functions of the antenna and the cavity, given by the multiple scattering interactions between them. \( \alpha_H = \alpha/(1 - \alpha\chi) \) is the antenna polarizability, perturbed by the presence of the antenna itself, and \( \chi_H = \chi/(1 - \alpha\chi) \) is the cavity response function modified by the presence of the antenna. These hybrid quantities depend on the bare antenna polarizability \( \alpha \) and the bare cavity response function \( \chi \). \( G_{bg} \) is the Green’s function in the surrounding background medium.

The strongest Purcell enhancements are found for systems in which the cavities are significantly red-detuned from the antenna, as in these cases multiple scattering paths that radiation can take in the system interfere constructively. In a specific example, the Purcell factor of the hybrid system exceeds that of the antenna at resonance by more than a factor of 3 and that of the cavity by more than a factor of 8. However, these systems cannot only break the fundamental limit on single antenna enhancement but also allow to tune the bandwidth of enhancement to any value between that of the cavity and that of the antenna.

2.3.1. Directivity of a Nanoantenna

In the past decades, NPs and their arrangements have been proposed as efficient nanoantennas, that is, efficient links between propagating light waves and localized optical near-fields. At their resonance frequencies, strong enhancements of electromagnetic radiation can be concentrated in the NP surroundings or inside the NPs for metallic and HRID NPs, respectively. When an emitter is coupled to the nanoantenna modes, the enhanced local field can be converted to propagating radiation, whose directional properties are mainly given by the antenna structure. By reciprocity, an incident far-field will be converted to localized electromagnetic energy by the antenna modes.

An important measure to characterize the ability of the nanoantenna to direct the emitted light in a particular direction is its directivity, defined as the ratio of the radiation intensity in a certain direction to the radiation intensity averaged over all directions. \[^{[193]}\]

\[
D(\theta, \phi) = \frac{4\pi U(\theta, \phi)}{\int_{\theta=0}^{\pi} \int_{\phi=-\pi}^{\phi=\pi} U \sin(\theta) \, d\theta \, d\phi} \tag{15}
\]
where \( U(\theta, \phi) \) is the radiation intensity in a certain direction given by the spherical coordinate angles \( (\theta, \phi) \).

Government of the angular distribution of the scattered radiation can be achieved by a careful tailoring of the excited modes in the NPs and it is important for many different applications. To name a few of them, the collection efficiency of the light emitted by quantum emitters may be improved by enhancing the directivity of the scattered radiation.

### 2.4. Kerker Conditions

In 1983, Kerker et al. described some unusual electromagnetic scattering effects for magnetic spheres much smaller than the wavelength of the incident radiation. They demonstrated that under certain conditions of the electric permittivity and magnetic permeability (known as Kerker conditions), the particle response to an electromagnetic incident radiation will consist of equal amplitude-crossed electric- and magnetic-induced dipoles. When \( \varepsilon = \mu \), both dipoles (electric and magnetic) oscillate in phase\(^{[194]} \) (the first electric and magnetic Mie coefficients \( a_1, b_1 \) verify \( a_1 = b_1 \)) and the scattered intensity in the backward direction \( (\theta = 180^\circ) \) is zero, being all the incident radiation scattered in the forward region.\(^{[195]} \) It is known as the zero-backward condition or first Kerker condition. The opposite behavior, null scattered intensity in the forward direction \( (\theta = 0^\circ) \) (zero-forward condition) should be observed when \( \varepsilon \) and \( \mu \) verify

\[
\varepsilon = \frac{4 - \mu}{2\mu + 1}
\]  \( (16) \)

In this case, \( (a_1 = -b_1) \) and electric and magnetic dipoles oscillate out-of-phase.\(^{[195]} \)

### 3. A Survey of Typical Hybrid Metal-Dielectric Nanostructure Geometries

A survey of the published literature on metal-dielectric photonic nanostructures reveals that most studies converge towards a relatively small set of prototypical sample geometries or variations thereof. Thus, in this section we provide an overview of the most common hybrid sample geometries for reference in Section 5, which deals with the applications of hybrid nanostructures. Schematic images of these geometries are summarized in Figure 11. In the following, for each of these prototypical nanostructures, we briefly outline how a single hybrid structure can provide an advantage over its bare metallic and dielectric constituents in the enhancement of light-matter interactions.
3.1. Metal + Dielectric NPs

Nanostructures consisting of two or more resonant NPs made from different types of materials can be interesting with respect to two different arguments (Figure 11a): Control of the scattered radiation in the far-field. On the one hand, the dielectric NPs exhibit Mie resonances of electric and magnetic character. On the other hand, the metallic NPs show plasmonic resonances. Furthermore, due to the coupling effects between the metallic-HRID NPs, it is possible to excite hybrid plasmonic-Mie modes. All of these resonances can be tailored by the NP geometry. The larger number of modes and degrees of freedom to tailor the resonance properties compared to bare plasmonic or dielectric NPs makes metal + dielectric nanostructures important scattering units to control the direction of the emitted radiation in the far field via interference effects from the light scattered by different modes (see Section 2.4). Near- and far-field properties.

The combination of a metallic NP with a dielectric one allows to benefit simultaneously of each of the advantages from the bare components. Through the metallic NP, strong enhancements of the electromagnetic energy can be observed in the NP surroundings. In addition, by means of the dielectric NP, it is possible to govern the direction of the enhanced scattered radiation. This is particularly important for amplifying the emission from nanoscale sources, which typically requires a strong confinement of the electromagnetic energy to enhance the decay rate of spontaneous emission in combination with a high collection efficiency.

3.2. Metallo-Dielectric Core-Shell NPs

The advantages and applications of these nanostructures, where plasmonic and dielectric NPs are integrated into each other, are similar to those of hybrid metal + dielectric NPs (Figure 11b,c). However, this structure type is accessible by fabrication schemes, which have the potential for larger throughputs (see Section 4); furthermore a better structural stability is also expected. However, these advantages come at the cost of reduced degrees of freedom, which for concentric core-shell NPs (see Figure 11b) and a given material combination boil down to changing the size of the core with respect to the particle size. Eccentric core-shell NPs (see Figure 11c), that is, core-shell NPs, where the core has been shifted with respect to the center of the NP, provide an additional degree of freedom and can consequently provide superior capabilities. Multilayer core-shell NPs constituted by isotropic materials are another interesting option, as they are able to exhibit effective radial anisotropy, which can be used to overlap electric and magnetic resonances. They can also provide larger enhancements of the electromagnetic near-fields than simple core-shell NPs.

3.3. Dielectric/Metallic NPs on Metallic/Dielectric Substrates

For this geometry, we distinguish two different configurations (Figure 11d,e): HRID NPs on a metallic substrate (see Figure 11d) and metal NPs on a dielectric substrate (see Figure 11e). In both cases, the NP is typically separated from the respective substrate by a spacer layer. The thickness of the spacer layer has a crucial influence of the mode structure of the hybrid system. Spacers thick enough to accommodate half a wavelength at the relevant operation frequency in the spacer material can act as Fabry–Pérot cavities, which couple to the modes supported by the NPs. Thin spacers down to single molecular layers allow for near-field coupling similar to the interaction between the two particles of a dimer nanoantenna with a small feed gap. Both material configurations have the advantage of relatively easy fabrication, which is comparable in complexity to the fabrication of bare HRID or plasmonic nanostructures, respectively, such that an appropriately layered or coated substrate has to be employed.

3.3.1. HRID NPs on a Metallic Substrate

This hybrid nanostructure makes use of the following principles. Strong Near-Field Enhancement and Large Field Confinement: If the HRID NP is separated from the metallic substrate by a thin low-refractive-index dielectric spacer, resonant near-field enhancement can be produced in the spacer layer below the particle due to the interaction of the HRID NP with its mirror image in the metallic substrate. The resulting response is comparable to that of a HRID dimer. Also, the HRID NP can convert the incident light to evanescent waves that excite the SPs at the substrate interface, enhancing, by this way, the electric field in the spacer layer near the particle. In both cases, to make use of the strong enhancement of electromagnetic energy in the spacer layer, the latter can be directly formed by the material with which one aims to enhance the interaction with light, such as an analyte or an emitting species. For thicker spacers, hybrid modes consisting of the Fabry–Pérot modes of the spacer and the Mie-modes of the HRID NPs can be formed.

Low Ohmic Losses: Large ohmic losses of metallic NPs give rise to Joule heating of the own NP and its environment. In some cases, this can be harmful for the sample to analyze. To avoid this issue, HRID NPs on metallic substrates are an alternative. These hybrid nanostructures can work at higher temperature than plasmonic NPs, since the closed metallic layer has a high heat conductivity and can efficiently distribute the energy over a large area instead of trapping it at the position of the NP. The HRID NPs themselves also possess high temperature stability.

3.3.2. Metallic NPs on a HRID substrate

The metallic NP is usually separated from the HRID substrate by a relatively thick low-permittivity dielectric layer, thereby forming a Fabry–Pérot cavity. Due to the coupling between the plasmonic and cavity modes, hybrid resonances are generated and strong enhancement can be observed in the spacer layer below the NPs.

3.4. On-Chip Waveguides Decorated With Plasmonic Nanostructures

This configuration can be used in on-chip integrated optics and relies on the coupling between waveguide modes and plasmonic modes (Figure 11f). Depending on the design of the plasmonic structures, they can locally add functionalities, including mode conversion, light routing, or all-optical switching to the
waveguide architecture, while exhibiting a very small footprint. Furthermore, similar to the case of plasmonic NPs on HRID substrate, for field enhancement purposes, it is possible to include a thin dielectric spacer separating the metallic nanostructures from the dielectric waveguide.

3.5. Plasmonic NPs + High Q Cavities

The idea of these systems is to combine the strong enhancements of the electromagnetic near-field and small mode volume provided by plasmonics NPs with high Q factor values achieved by dielectric cavities such as microresonators or photonic crystal point defect cavities (Figure 11g,h). As described in Section 2.2 for the example of Purcell enhancement, the performance of such configurations can exceed that of the individual components significantly.

3.6. Hybrid Metasurfaces

Planar arrangements of hybrid-metal-dielectric scatterers can exploit the respective advantages of the chosen scattering elements, while adding further degrees of freedom (lattice constant, lattice type, order vs. disorder, spatial variability, ...) and resonance types (bound states in the continuum, surface lattice resonances, ...) based on the in-plane arrangement (Figure 11i). Furthermore, metasurfaces feature a flat, areal nature, and while having nanoscale thickness, they can reach macroscopic dimensions in the plane. The areal nature and enhanced complexity of metasurfaces compared to individual scatterers can unlock a flurry of additional functionalities and applications, as briefly discussed above (see, e.g., Section 1.2 and described in detail in several recent review articles[197-199]).

3.7. Hybrid Semiconductor Nanowire-Based Plasmonic Structures

The possibility of exploiting SPs instead of photons for the amplification of spontaneous emission has paved the way to the development of a new class of nanolasers, also known under the acronym of SPASERs (surface plasmon amplification by stimulated emission of radiation) (Figure 11j). In particular, the realization of semiconductor nanowire-insulator-metal (SIM) structures (Figure 11i) has allowed to overcome the diffraction limit, which photonic nanolasers are subject to, enabling subwavelength confinement of the hybrid modes at the insulator/metal interface with typical mode areas more than 100 smaller compared to the photonic case. Although the overall Q factor of such structures is mostly hampered by the ohmic losses from the metal, which results in larger lasing threshold compared to photonic devices, the further optimization of such platforms has provided the opportunity to mitigate the losses. For instance, the possibility of structuring the metal layer to provide additional feedback (Figure 11k,l) has enabled the amplification of new hybrid modes by the modified cavity: pseudowedge plasmon polaritons in grating-like structures and channel plasmon polaritons in V-groove structures. Such hybrid modes are characterized by even smaller mode volumes compared to those supported by the bare SIM planar structures, resulting in a further lowering of the lasing threshold and acceleration of the lasing dynamics at the same time.

4. Fabrication Techniques

Hybrid metal-dielectric nanostructures are composed of nanoscale components made of at least two different materials, one metallic and one dielectric (including HRID). Note, one further needs a proper substrate or matrix material, which is required to ensure the stability of the structure. In any case, the need to combine various materials in one nanostructure naturally increases the fabrication complexity compared to structures where the functional components are all made from the same material. Additionally, in many cases, the different components have to be precisely positioned with respect to each other to achieve specific coupling conditions between them, such as hot-spot formation or directional scattering. Furthermore, additional hybridization with a third or even further materials is often required to achieve functionalities such as emission, gain, or tunability. Altogether, the required hybrid nanoarchitectures can reach high levels of complexity, which is also the main reason why many studies in the area of hybrid metal-dielectric nanophotonics are limited to theoretical analyses. It is also worth mentioning that not for all the theoretically studied hybrid architectures discussed in this review, a clear nanofabrication scheme exists already (see, e.g., Figure 11c). In the following, we will summarize the most common methods that have been demonstrated for the fabrication of some of the prototypical hybrid architectures introduced in Figure 11.

The most common approach for the deterministic definition of arbitrary 2D nanoscale distributions on metallic or dielectric material in a plane is electron-beam lithography (EBL). Thereby, a thin film of positive (negative) resist is exposed to a focused electron beam. The exposed resist regions undergo a chemical modification, allowing to wash away the exposed (unexposed) regions in a subsequent development step. By using a computer to control the path prescribed by the electron beam on the resist, nearly arbitrary 2D patterns can be defined with very high resolution, reaching feature sizes of few tens of nanometers or even less for specialized resists. To transfer the pattern into the desired metallic or dielectric material in a subsequent step, either dry etching[202] or evaporation followed by a lift-off procedure[200] are typically employed. In many cases and depending on the target materials, intermediate steps, such as hard-mask fabrication, have to be performed to improve the quality of the outcome.[201] Single step electron beam lithography on layered substrates is a straightforward way to realize both dielectric NPs or their arrangements on a layered substrate such as a mirror coated by a dielectric spacer layer (see Figure 11d) and plasmonic NPs on a layered dielectric substrate (see Figure 11e). For the creation of hybrid structures, where designed nanoscale dielectric and metallic building blocks or structures have to be carefully positioned with respect to each other, two subsequent steps of EBL-based fabrication can be combined with a precision-alignment step, reaching accuracies of few tens of nanometers and below. This method can be used to define both lateral and vertical arrangements of metallic and dielectric NPs (see Figure 11a and ref. [202] as an example).
The same method can be used for hybridizing waveguides, microcavities, and photonic crystals with plasmonic elements (see Figure 11f,g,h and refs. [187,203,204]) as well as for the fabrication of hybrid metasurfaces (see Figure 11i and ref. [146] for an example). While multistep electron beam lithography provides the largest design flexibility, for specific hybrid geometries simpler schemes that involve only a single step of EBL, for example, in combination with the deposition of several layers of different materials may be sufficient. Also, in some cases it is possible to replace EBL by direct patterning with a focused ion beam (FIB). However, while offering tremendous design freedom making them ideal for proof-of-principle demonstrations, EBL and FIB are rather expensive techniques and cannot be used to pattern large areas on the order of square meters or above. Also, there are certain particle shapes that are not accessible by EBL. The latter, for instance, applies for the theoretically important case of spheres or spherical core-shell geometries. Thus, the study of alternative methods for the fabrication of hybrid metal-dielectric nanostructures offering better scalability than EBL-based techniques and accessing different particle shapes is an active field of research.

Particles that are in good approximation spherical can be obtained by wet-chemical colloidal synthesis, chemical vapor deposition or laser-induced techniques. The obtained particles can be combined with metal-dielectric systems in several principal configurations: separate dielectric and metallic NPs can be brought in close proximity to each other to form hybrid dimers or clusters (Figure 11a). Also, they can be readily placed on layered substrates, allowing to realize, for example, dielectric NPs on a mirror (Figure 11d) or plasmonic NPs on a layered dielectric substrate (see Figure 11e). Alternatively, they can be integrated into each other to form metal-dielectric core-shell NPs. Colloidal synthesis was used to produce various versions of core-shell particles combining a low-index dielectric with a metal. For example, Ag core SiO₂ shell, SiO₂ core Ag shell, and Au core silica shell have been realized. The fabrication of core-shell NPs combining a plasmonic metal with a HRID material has proven to be more challenging for wet-chemical methods. Here, laser ablation techniques are a promising alternative, and both silicon core Au shell as well as Au core silicon shell architectures could be demonstrated, although in the former case dewetting poses a problem. Eccentric core-shell NPs such as nanocups and nanoeggs, can, for example, be fabricated by random deposition of spherical dielectric NPs on a substrate followed by angled metal evaporation or by immobilizing concentric core-shell particles on a substrate in combination with an anisotropic electrolyte plating technique, respectively.

Semiconductor nanowires are typically grown by various deposition techniques enabled by the so-called vapor–liquid–solid mechanism. The nanowires are subsequently transferred to the desired substrate by mechanical methods. For the creation of hybrid metal-dielectric architectures the target substrate typically features a layered structure (see Figure 11j), which can be obtained by various thin-film deposition techniques such as evaporation or sputtering. Pre-structuring of the target substrate can be performed via FIB or EBL-based techniques (see Figure 11k and l). Micromanipulation techniques can be used to precisely position the semiconductor nanowires with respect to the underlying pattern.

5. Applications

In this section, we describe some of the most relevant applications of hybrid metal-HRID nanostructures. We focus on directionality, sensing and SERS, absorption enhancement, emission enhancement, nonlinear effects, and lasing.

5.1. Controlling Scattering Directionality

In the Rayleigh regime characterized by the pure electric dipole response, the scattering patterns have the typical dipole characteristic, that is, a doughnut shape with the minimum pointing along the dipole axis. In particular, this means that backscattering is significant and that the directivity of the scattering pattern is very low. In many applications, these characteristics are not desired, but instead one wants to suppress backscattering and/or create a highly directional pattern. This is for example the case for photovoltaic devices, where the radiation that is incident from the far field should be scattered as efficiently as possible into the photosensitive substrate while avoiding any reflections. Another example are wavefront-shaping metasurfaces, where the suppression of backward-scattering allows to reach near-unity transmission efficiencies. Other applications such as light switching or routing demand even more complex scattering patterns. In this context, it may be useful to induce a modification of the scattering pattern by changing the incident field wavelength, polarization, or intensity. This effect is particularly relevant in optical nanocircuitry. Based on the scattering directionality conditions described in Section 2.4, hybrid metal-dielectric nanophotonic systems offer numerous opportunities for shaping the directional properties of their scattering response. In this paragraph, we will mainly concentrate on directional far-field effects, while directional effects observed for the emission from localized sources will be discussed in Section 5.4. Furthermore, hybrid nanoantennas have been used to build superscatterers of the incident radiation or sensors. Janus dimers consisting of dielectric and metallic spherical NPs of different size have been reported as an interesting nanostructure to achieve directional scattering radiation patterns. This effect is due to the interference between the electric and magnetic resonances excited in the metallic and dielectric NPs, respectively.

Metal-HRID core-shell NPs have been proposed in the last years because they support electric and magnetic resonances that can be tuned by geometry. Changes in the size of the core with respect to the total particle size lead to electric and magnetic resonances shifts. Hence, changing the relative size of the core can be used to control the direction of the scattered radiation.

In ref. [95], the authors theoretically showed the influence of increasing core sizes of a core-shell Ag-Si NP on the scattering directionality conditions (SDCs). It was found that the SDCs can be either enhanced by exciting higher multipolar orders, or disabled. In particular, it was demonstrated that the zero-backward
condition is boosted by the overlap between of electric and magnetic modes of the same order and magnitude.\[232\]

Enhanced forward scattering can be achieved by adding suitable gain into the shell of an isolated metallo-dielectric core-shell NP, see Figure 12a. In addition, this structure is also useful to get anomalous weak scattering. Zero-forward scattering cannot be achieved for lossy and lossless particles. However, it can be obtained for the right gain choice of the dielectric shell.\[233\] This means that by adding gain in the dielectric shell, the electric and magnetic responses may be completely counteracted at the forward direction. This effect cannot be attained by passive structures. In Figure 12a, the scattering pattern at the zero-forward condition is shown theoretically for a metallic core-gain doped dielectric shell NP. The null scattering in forward direction is due to the cancellation of the first four terms of the Mie expansion coefficients, provided that higher orders are negligible. In particular, to obtain complete destructive interference, the real

and imaginary parts of the Mie term $3(a_1 + b_1) + 5(a_2 + b_2)$ must be simultaneously equal to zero.

In contrast to spherical NPs, where the scattering is suppressed only in the backward direction, silver nanowire cores surrounded by a HRID material of refractive index 3.5 (see Figure 12b) were theoretically proposed to observe two vanishing scattering angles in the superscattering regime (it is important to clarify that in the superscattering regime, the scattering cross section far exceeds the single-channel limit\[234\]). This is due to the dipolar electric and magnetic interference.\[235\] The magnitude of the electric dipole resonance is twice that of the magnetic one. This is due to the fact that the magnetic dipole corresponds to one scattering channel, whereas the electric dipole corresponds to two degenerate scattering channels. The relevance of the multilayer structure in the nanowire geometry can be understood through inspection of Figure 12b, which compares the scattering efficiency spectra for a uniform dielectric nanowire

Figure 12. a) Left: Scheme of a core-shell NP. The yellow area of radius $r_1$ corresponds to the gold core. The blue area is the dielectric shell of thickness $t$. The green points represent the doped gain medium. Middle: Spectrum of the real and imaginary parts of the Mie term $3(a_1 + b_1) + 5(a_2 + b_2) = 0$ for the described core-shell NP. At the wavelength where that condition is fulfilled (green star), complete destructive interference is produced and zero-forward scattering is observed. Right: Scattering pattern at the zero-forward condition for both scattering components TE (blue line) and TM (red line). The black arrow represents the direction of the incident radiation. Reproduced with permission.\[233\] Copyright 2017, De Gruyter. b) Left: Geometry of a metallo-dielectric core-shell nanowire. The core (radius $r_1$) is made of silver, and the shell has a refractive index of $n = 3.5$. Top middle: Scattering efficiency spectrum for a uniform dielectric nanowire with $r_1 = 0$, $r_2 = 145$ nm and $n = 3.5$. Top right: Scattering diagram for the uniform dielectric nanowire. The red and blue curves correspond to the scattering diagrams at the wavelengths marked in the scattering efficiency spectrum by the $E$ and $M$ points, respectively. Bottom middle: Scattering efficiency spectrum for a silver core-dielectric ($n = 3.5$) shell nanowire with $r_1 = 70$, $r_2 = 145$ nm. Bottom right: Scattering diagram for the core-shell nanowire at the wavelength corresponding to the $S$ point in the scattering efficiency spectrum. At $\theta = 120^\circ$ and $\theta = 240^\circ$ the two vanishing scattering angles are observed. Reproduced with permission.\[235\] Copyright 2013, The Optical Society of America.
and a silver core-dielectric shell nanowire. For the former, the electric and magnetic dipolar resonances are attained at different wavelengths. However, for the latter, both resonances are observed at the same frequency, enhancing the scattering in the forward direction. Furthermore, due to this resonance overlap, the scattering vanishes at two different angles.

In ref. [185], by means of a metallo-dielectric core-shell nanorod, made of a gold core and a hollow silicon shell (see Figure 13a), a dual-frequency Kerker condition for zero-backward scattering was theoretically demonstrated. This effect is due to the shift of the dipolar electric resonance, which leads to a matching of the scattering strength of the dipolar electric and magnetic resonances at two different frequencies. With the aim of observing broadband zero-backward scattering, a metallo-dielectric core-shell NP made of a silver core and a dielectric shell of refractive index 2 was proposed. This effect is achieved due to the excitation of dipolar and quadrupolar electric and magnetic resonances.[236]

More complex designs of core-shell NPs have been proposed to gain further control in the directional properties of the scattered radiation. In particular, eccentric metallic core-shell NPs were analyzed as new plasmonic units, providing both novel opportunities for spectral tuning and for directionality effects.[213] Examples are nanoeggs (the core is shifted with respect to the NP center within the shell)[237] and nanocups (the core displacement is greater than the thickness of the shell layer, that is, the core pierces the shell).[237] Nanocups can be described as 3D optical frequency analogues of split ring resonators. Also, the possibility of manufacturing them in a controlled manner makes these nanounits very attractive for many application purposes where good tunable plasmonic performances are necessary.[213,214,237,238] In ref. [237], the near- and far-field, optical properties of core-shell NPs with reduced symmetry were analyzed. In particular, the electromagnetic behavior of nanoeggs and nanocups was studied and compared to that of nanoshells (concentric core-shell NPs). Three different configurations of particles consisting of a silica core and a thin gold shell were considered. The different spectral response of these geometries (in the quasi-static limit) can be understood by means of a plasmon hybridization model.[214,238,239] The electromagnetic behavior of eccentric NPs depends on their geometry, orientation with respect to the impinging radiation, and variations in the dielectric environment.[240] In,[213] the ability of Au nanocups to redirect the scattered light in a direction dependent on the cup orientation was demonstrated.

Eccentric metallo-dielectric core-shell NPs consisting of a metallic core and a HRID shell were introduced as hybrid nanostructures to rotate the SDCs.[108] By means of these NPs, it was observed that the incident radiation can be scattered into some specific directions while simultaneously suppressing either backward or forward scattering and that the rotation of the scattering diagram depends on the core displacement. In addition, it was demonstrated that there is an optimal core displacement at which the ratio between the scattered intensities in the forward and

---

**Figure 13.** a) Left: Illustration of a metallo-dielectric core-shell nanorod. The core is made of gold and is embedded in a shell composed of a silicon cylinder. Between the Au and Si cylinders there is an air gap. Right: Forward-to-backward scattering ratio for a (Au-Si) hybrid nanorod of $H = 220$ nm, $R = 120$ nm, $r_2 = 50$ nm, and $r_1 = 48$ nm. The inset shows the 3D scattering diagrams at the frequencies where the zero-backward condition is observed. Reproduced with permission.[185] Copyright 2019, American Institute of Physics. b) Left: Multilayer spherical cavity composed of alternating isotropic layers. The permittivity of the layers corresponds to $\epsilon_1$ and $\epsilon_2$. Middle. Scattering and absorption spectra for a multilayered cavity consisting of 14 layers with alternating silver and dielectric layers. The width of the metallic and dielectric layers corresponds to 4 and 36 nm, respectively. $f$ is the filling factor of the layer of permittivity $\epsilon_1$ in terms of overall layer width. Right: Scattering patterns at the resonance wavelength ($\lambda = 1533$ nm). Reproduced with permission.[97] Copyright 2015, Nature Publishing Group.
backward regions for the first (second) Kerker condition is the largest (lowest). By taking advantage of these directionality properties, the possibility of using aggregates of eccentric core-shell NPs for guiding the incident radiation was explored. In this respect, a Yagi-Uda type light guiding scheme was also studied.

Multilayer core-shell (onion-like) nanostructures have also been introduced for controlling the scattering properties of the NPs. A dielectric core, surrounded by alternating plasmonic and dielectric layers can exhibit comb-like scattering characteristics originating from Fano-type interference between Mie modes with the same multipole moment inside each plasmonic shell layer. It was also demonstrated that multilayer cavities composed of isotropic materials are able to exhibit effective radial anisotropy responsible for the overlapping of electric and magnetic resonances, which can lead to unidirectional superscattering, as summarized in Figure 13b.

Apart from core-shell nanostructures, hybrid dimers, consisting of a metallic and a HRID NP may enhance the SDCs. By choosing the appropriate size of the NPs and gap distance, directional scattering effects can be observed at the resonance peak of the dimer extinction spectrum. A theoretical enhancement of forward scattering intensity by a factor of 2.7 compared to that of the single dielectric NP was achieved with a hybrid configuration formed by a Ag metal NP and a lossless TiO₂ NP, see Figure 14a.

By increasing the number of scatterers, the scattering directionality properties can be further enhanced. However, due to the rise in the complexity of the nanostructure, it is necessary to utilize more complex optimization methods. In the authors used a Bayesian optimization approach to boost the SDCs of three gold disks separated by two dielectric layers.

Other novel hybrid metal-dielectric configurations were introduced to tune the interference of electric and magnetic resonances. Different techniques are used to get this capability, including integration with liquid crystals or phase-change materials or by exploiting the thermo-optical effect of materials. For example, through the independent control of the thermo-optical properties of metallic and dielectric materials, it is possible to turn on and off the zero-backward condition in a reversible way, as

Figure 14. a) Left. Scheme of the dipole–dipole interaction model for a dimer consisting of an Ag NP and a TiO₂ NP illuminated by a plane wave propagating along the z-direction and linearly polarized in the y-axis. Right. Forward/backward ratio for a dimer consisting of a silver NP of diameter \( D_{\text{Ag}} = 55 \) nm and a TiO₂ NP of diameter \( D_{\text{TiO}_2} = 145 \) nm. The distance between them is 10 nm. The gray area represents the region with a forward/backward ratio >20 dB. The inset shows a comparison of the scattering diagrams in YZ- and XZ-planes between the Ag-TiO₂ heterodimer (solid line) and the bare TiO₂ NP (dashed line), at the wavelengths where the First Kerker condition is fulfilled for each one of the geometries. Reproduced with permission. Copyright 2020, The Royal Society of Chemistry. b) Left. Geometry of a metasurface consisting of silicon cylinders with rectangular gold bars stacked above them, separated by a thin film of SiO₂. Top middle. Scattering cross-section before heating. \( Q \) corresponds to the total scattering and ED, MD, EQ, and MQ refer to the contributions of the electric dipole, magnetic dipole, electric quadrupole and magnetic quadrupole to the total scattering, respectively. Top right. Scattering cross-section after heating. Due to the heating the refractive index of silicon is changed. Bottom middle. Far-field scattering pattern before heating. Bottom right. Far-field scattering pattern after heating. Reproduced with permission. Copyright 2013, The Optical Society of America.
theoretically shown for a hybrid metal-dielectric metasurface\(^2\)\(^4\)\(^6\) (Figure 14b). During the heating, the electric-magnetic coupling is modified due to changes in the refractive index of silicon. This leads to significant differences in the magnitude of the excited resonances, which allow to attain new interference effects between electric and magnetic modes, varying, in this way, the scattering patterns. In particular, suppression of backward scattering was reported due to the interference of quadrupolar electric and magnetic resonances of comparable magnitude.

5.2. Sensing and SERS

The capability of detecting changes in the physical, chemical, or biological properties of a medium is known as sensing. A common type of optical sensor is based on the spectral shifts detected in the response of the optical system due to changes in the refractive index. Depending on the increase/decrease of the effective refractive index, the optical response of the system is red-/blueshifted. This scheme is, exemplarily, relevant for applications, where concentrations (e.g., of a particular solvent in a liquid) are to be measured, or where the optical properties of media are to be determined. However, especially in biosensing, often one is not interested in refractive index changes of a bulk medium, but rather wants to detect the local presence of small amounts of a specific molecular species. This is also possible in such a scheme, since if an object with a refractive index slightly different than that of the surrounding medium is included in the medium, the effective refractive index of the medium is modified, which again leads to a spectral shift of the optical response features. With the progress in nanotechnology, NPs have demonstrated their utility as sensors. As the position of the plasmonic and Mie resonances depends on the refractive index of the surrounding medium, small changes in the refractive index of the latter are transduced into spectral shifts in the optical response. To improve the sensing efficiency in local sensing schemes, the object to be detected should be located at the position of strongest electromagnetic energy enhancement. This evidences the important role of the electromagnetic confinement in sensing applications. Note that the effective refractive index “seen” by a NP depends strongly on its positioning, as the contributions from the different refractive indices of medium and object to the total optical response have to be weighted by the intensity distribution in the sensitive volume.

The sensitivity of a device (S) is usually expressed in nm-RIU\(^{-1}\) (Refractive Index Units). This magnitude accounts for the spectral shift of the resonances as a consequence of changes in the (effective) refractive index. However, from an experimental point of view, the width of the resonances is also important. For broad resonances, small spectral shifts cannot be experimentally detected. For that reason, resonances with a high Q factor are often beneficial. Thus, the figure of merit (FOM), defined as the ratio of the sensitivity to the full width at half maximum, is often used instead of the sensitivity to quantify the performance of a particular sensor system.

According to the aforementioned description, two requirements are necessary for developing efficient sensors: large electromagnetic confinement and high Q-values. The first condition can be achieved by using metallic NPs; however, they show a broadband response. The second prerequisite can be attained through HRID NPs; nevertheless, the electromagnetic confinement is more modest than for metallic NPs. Hybrids, combining metallic and dielectric nanostructures—like microwavities—may provide improved sensing capabilities with respect to bare metallic or dielectric nanostructures, due to the large enhancement of the electromagnetic energy in the surroundings of the NP and the high Q factor of the microwavities. In addition, the electromagnetic energy enhancement can be boosted by means of hybrid metal-dielectric structures due to the hybridization of plasmonic and Mie modes, as explained below.

A drawback of refractive index sensing is that the observed resonance shifts depend only on the refractive index changes in the system, but are not able to distinguish different materials or molecular species inducing the same effective refractive index change. A technique providing fingerprint information of molecules that are present at the surface of a rough metal surface or metallic nanostructure—and even allows for analyzing the composition of a mixture on the nanoscale—is surface-enhanced Raman spectroscopy. As described in Section 1.3, SERS can profit particularly well from the strong field enhancement provided by engineered nanostructures.

The combination of hybrid metal-dielectric NPs has opened new avenues for sensing purposes and surface-enhanced spectroscopies. Different nanostructures have been analyzed regarding their capability to detect changes in the refractive index of the surrounding medium or for boosting the SERS signal. Tailoring the near-field enhancement is crucial for sensing applications. With this objective, aggregates of NPs (oligomers) have been considered. In,\(^2\)\(^4\)\(^7\) the near-field properties of oligomers of hybrid metal-dielectric (gold-silicon) NPs were modified by reshaping the nanostructure geometry by means of a femtosecond laser. Due to the reshaping of the gold components of the oligomers, there is a shift of the dipolar magnetic resonances, which enables to engineer the near-field enhancement. This effect was observed with a near-field optical microscope.\(^2\)\(^4\)\(^7\)

Metallo-dielectric core-shell nanostructures play an important role in the development of more efficient sensing devices. In ref. [95], the sensitivity of the linear polarization degree at right angle scattering configuration \((P_\parallel(90°))\), at the wavelength where the SDCs are fulfilled \((P_\parallel(90°) = 0)\), to the refractive index of the surrounding medium \(n_{\text{med}}\) was theoretically investigated, showing that metallo-dielectric core-shell HRID NPs combined with \(P_\parallel(90°)\) detection are a promising tool for sensing applications. The sensitivity reaches values of 250 nm-RIU\(^{-1}\) at the largest core sizes. The spectral location of \(P_\parallel(90°) = 0\) is significantly more sensitive to \(n_{\text{med}}\) for metallo-dielectric core-shell HRID NPs than for pure HRID NPs. This is a direct consequence of the reinforcement of the dipolar electric mode due to the metal core.

Multilayer core-shell nanostructures were theoretically demonstrated to further enhance the electromagnetic confinement in the NP surroundings with respect to simpler core-shell NPs. Designs which combine different plasmonic materials sandwiching a dielectric layer, provide strong near-field enhancements. This behavior is due to the distinct coupling produced between the core-shell interfaces. Taking advantage of the high energy concentration in the NP surrounding, hot spots could be observed by means of dimers of multilayer core-shell NPs.\(^1\)\(^9\)\(^6\)
One of the most important advantages of dimers over multilayer core-shell NPs is the possibility to excite additional higher order resonance modes, desirable for the design of multiresonant systems for multiplexed sensing. Metasurfaces composed of hybrid metal-dielectric NPs were also considered for sensing applications. In ref. [248], a metasurface consisting of Al disks, separated from Si cylinders by a SiO₂ spacer was experimentally analyzed (see Figure 15 top) and a sensitivity of 208 nm·RIU⁻¹ was obtained. However, the largest enhancement of electromagnetic energy is concentrated inside the dielectric spacer, which prevents the contact of the analyte with the region of highest electromagnetic intensity. To increase the contact between the electric field and the background medium, an undercut was created in the SiO₂ spacer, thereby reaching a sensitivity of 245 nm·RIU⁻¹. The undercut decreases the refractive index of the spacer region, modifying the near-field distribution. By this way, the electric field is pushed towards the background medium, as obvious from comparison of Figure 15 middle left (nanoantennas with an undercut in the SiO₂ spacer) and middle right (nanoantennas without an undercut in the SiO₂ spacer). Figure 15 bottom shows the transmission spectrum corresponding to the hybrid metasurface with a 50 nm undercut in the SiO₂ for different values of the surrounding medium refractive index.

As explained at the beginning of this section, hybrid nanostructures composed of a metallic NP and an optical microcavity (see Figure 16) can provide high values of the FOM. Specifically, these configurations have experimentally demonstrated to boost the FOM by up to 36 times, compared to the case of a metallic NP on a semi-infinite substrate, that is, without the cavity.[249] This effect is due to the combination of the electromagnetic field enhancement in the surroundings of the NP, as it can be observed from the near-field map represented in Figure 16 top right, and the narrow Fabry–Pérot mode excited inside the

---

**Figure 15.** Top left. Scheme of a metasurface consisting of hybrid nanoantennas made of an Al disk and a Si cylinder separated by a SiO₂ spacer. Top right. SEM image of the hybrid nanoantenna metasurface. Middle left. Electric field enhancement in the YZ-plane for a metasurface of hybrid nanoantennas with an undercut in the SiO₂ spacer. Middle right. Electric field enhancement in the YZ-plane for a metasurface of hybrid nanoantennas without an undercut in the SiO₂ spacer. Bottom. Transmission spectrum corresponding to the hybrid nanoantenna with a 50 nm undercut in the SiO₂ for different values of the surrounding medium refractive index. Reproduced with permission.[248] Copyright 2020, American Chemical Society.
high index cavity. Figure 16 bottom displays the FOM as a function of the wavelength for different Fabry–Pérot mode orders, where the inset shows the width of the Fabry–Pérot resonances as a function of the wavelength.

Hybrid metasurfaces operated near the perfect-absorption regime were investigated with the same aim. Perfect absorption attainable with metal nanostructures together with the narrow bandwidth of the resonances supported by dielectric metasurfaces make this combination particularly promising in the context of refractive index sensing. In ref. [250], it was evidenced that a Si nanodisk array on top of a gold mirror can reach absorption values of 99.8% at a wavelength of 932 nm in air. In addition, a redshift of the wavelength is observed as the refractive index increases. A sensitivity of 325 nm·RIU⁻¹/C₀ was numerically reported for this configuration. Another perfect absorber metasurface for sensing applications was theoretically proposed in ref. [251]. The structure consists of a dielectric patch array made of SiO₂ on an aluminum metal substrate and reaches a sensitivity of 840 nm·RIU⁻¹. In ref. [252], a metasurface formed by an array of silicon crosses on a gold substrate showed three perfect absorption peaks. The triple-band perfect absorption is produced due to the excitation of the guided modes originated by the standing waves and the losses of silicon and the gold substrate in the VIS spectral range. Sensitivity values for this triple-band perfect light absorber are 1185, 726, and 940 nm·RIU⁻¹.

Hybrid plasmonic-waveguide structures have also demonstrated their extraordinary performances for sensing in integrated architectures. In such a hybrid configuration, it is possible to distinguish two different kinds of modes: SP modes and guided modes. By means of the coupling of the plasmonic mode to the waveguide mode, it is possible to increase the sensitivity and FOM of the system, compared to the pure photonic waveguide, while preserving the sharpness of the guided photonic mode. In the past years, hybrid plasmonic-waveguides, consisting of a thin metal layer separated from a high index material by a low index spacer, have been a focus of research. It was demonstrated that the hybrid mode is more strongly confined than the pure plasmonic mode, making this geometry attractive for detecting small changes in the environment refractive index. In ref. [253], race-track μ-ring resonators were suggested for sensing applications using different configurations of hybrid plasmonic-waveguides as a basis. Values of 230 nm·RIU⁻¹ were numerically reported.

These novel hybrid plasmonic-waveguide geometries can be fabricated by combining top-down—like laser interference lithography (LIL)—and bottom-up—like colloidal synthesis and
template-assisted self-assembly (TASA)—approaches, enabling the assembly of NPs in one or two dimensions. In ref. [254], gold NP lines (fabricated by LIL and TASA) were applied to a titanium dioxide (TiO$_2$) layer waveguide. The hybrid modes (produced by the coupling of plasmonic radiant modes of the gold NPs and the photonic modes of the TiO$_2$ waveguide) showed higher sensitivity to changes in the refractive index surrounding medium and higher FOM compared to the isolated NPs or waveguides components. Sensitivity and FOM values of 739 nm·RIU$^{-1}$ and 1.74 RIU$^{-1}$, respectively, were numerically obtained. However, both values were not reached in corresponding experimental studies. The obtained values were 209 nm·RIU$^{-1}$ and 0.56 RIU$^{-1}$, respectively.

Configurations of hybrid dielectric NPs on metallic substrates acting as mirrors can provide strong near-field enhancement and large field confinement. The optical response depends on the NP size, shape and also on the optical properties of the NP, the substrate, and the gap distance between them. In ref. [169], the influence of the NP size, metal substrate and gap size was analyzed in a system composed of a silicon NP on a metallic substrate, as shown in Figure 17a.

The authors claimed that the near-field enhancement originates from the interaction of the magnetic resonance of the silicon NP with its mirror image and the SP in the metal film. In particular, strongly enhanced Raman spectroscopy was demonstrated for a silicon NP on a silver substrate with a thin spacer layer between them. The spacer was made of SiO$_2$. This hybrid system showed extraordinary field enhancement (about 400-fold) and large field confinement ($\lambda/40$ in one dimension). Other NPs on mirror geometries were reported with the aim of improving the performance of these structures for SERS. In ref. [170], a HRID disk was located on top of a metallic mirror. This configuration was experimentally demonstrated to combine the large field enhancement and extreme localization of the metallic structure with the low absorption of the dielectric NP. The nature of the modes supported by the NP on a mirror geometry was analyzed by cathodoluminescence spectroscopy. The effect of the incident angle in the coupling between the modes supported by HRID NPs and those of a metallic substrate was recently explored. Strong near-field enhancement in the NIR spectral region was observed using a Si NP on a gold film system under oblique illumination.[255] In particular, values of $\approx$1200 were reported for the normalized enhancement of the electric field in the gap between Si NPs and the metallic (gold) thin film. To enhance the near-field intensities, the possibility of coating the dielectric spheres with a metallic layer was experimentally introduced. In ref. [256], the electromagnetic energy confinement of an array of polystyrene spheres on an Ag substrate was reinforced by adding a thin Ag coating onto the spheres and a thin TiO$_2$ passivation layer on the Ag substrate. This configuration provided a 6-fold near-field enhancement of the same structure without the two coatings. The design was prepared by self-assembly at an air–liquid interface. Furthermore, hybrid nanostructures formed by HRID NPs on metallic substrates can operate at higher temperatures than the plasmonic structures, since the closed metallic films enable a better heat transport and they are more temperature stable than the delicate nanostructures. Thus, in addition to molecular sensing, these hybrid systems enable real-time tracing of molecular events with Raman spectroscopy and nanoscale Raman thermometry. For example, it was experimentally shown that a Si NP on a gold film can be a useful hybrid metal-dielectric cavity to operate up to 1200 K with a Raman scattering enhancement of up to 10$^4$ fold, see Figure 17b.[171]

Another way to obtain strong enhancements of the near-field in small volumes for sensing or SERS purposes is to couple plasmonic and dielectric nanoantennas. HRID nanostructures can provide strong enhancement of the electric field around the entire structure volume. In ref. [175], it was demonstrated that a HRID cavity can enhance the local electric field of a plasmonic nanoantenna located in its proximity. In particular, a hybrid system consisting of a gold nanorod dimer on top of a HRID cylinder and surrounded by a HRID ring was theoretically considered. The electric field enhancement at the gap center of the Au nanorod dimer in the hybrid system is 382 times (for a gap size of 5 nm). This corresponds to a 15-fold enhancement with respect to the dimer without the HRID nanostructure.

More complex geometries are also promising for improving the SERS enhancement. As one example, a micro-SERS sensor made of a metallic Au nanoslot on a dielectric Si$_x$N$_y$ strip was presented.[17] The SERS enhancement is due to the plasmonic field of the SPP excited in the slot by the evanescent field of the Si$_x$N$_y$ strip photonic mode. However, this sensor only provides a 10$^2$–10$^3$ enhancement around the slot corners. To improve the SERS ability of such a structure, a new method was theoretically proposed, which makes use of metallic NPs located in the metallic

![Figure 17](https://www.advancedsciencenews.com)
slot of the micro-sensor. This makes it possible to couple the SPP of the slot with the LSP of the NP, boosting the SERS detection capability. With the objective of optimizing the sensing performances, the influence of the size, shape, position, and number of NPs on the enhancement was studied. Average enhancement factors of $10^6$ in the probe volume were reported.

To increase the near-field enhancement, the excitation of anapole modes was also proposed. At the anapole resonance, the scattering shows a minimum due to the destructive interference between the cartesian electric and toroidal dipole, and most of the energy is concentrated inside the scattering object. To decrease the scattering and increase the near-field enhancement, a hybrid nanostructure that allows strong coupling between dark plasmon and anapole modes was numerically investigated. This effect was analyzed with a side-by-side gold nanostrand dimer placed on the long sides of the air slot in a silicon nanodisk. The dark mode of the gold dimer is excited due to the strong coupling with the anapole mode of the silicon disk. The dark mode coupling in the metal-dielectric nanostructure provides an almost nonradiating air cavity with improved field enhancement in a broadband spectral region. In the strong coupling regime, the hybrid anapole-plasmon mode can show intensity enhancements 20 times larger than those of the uncoupled cases.

Hybrid metasurfaces are also interesting for SERS: for instance, in ref. [259], 2D silicon regular bars, covered by a nano-thin silver film, were experimentally shown to provide enhanced electromagnetic energy confinement on the surface of the resonators, due to the multiple metal-dielectric resonances. An enhancement of over $10^5$ of the Raman scattering intensity was reported. Even higher SERS enhancements were obtained with Si nanowires coupled to metallic NPs. In ref. [260], silver NPs were deposited on silicon nanowires providing an experimental enhancement factor of the Raman scattering of $2.3 \times 10^5$. In ref. [261], a substrate for Raman signal enhancement was experimentally introduced by arrays composed of silicon nanowires decorated with silver NPs. As a convenient overview, we have summarized the earlier reviewed configurations of hybrid nanostructures for sensing and SERS in Table 3 together with their performances.

### 5.3. Absorption Enhancement

While absorption of electromagnetic radiation is often considered detrimental for the performances of optical systems, efficient absorption is actually absolutely necessary for many different applications such as photodetectors, photovoltaic devices, photothermal therapy or photocatalysis. While purely plasmonic particles provide favorable absorptive properties and can be used in many cases, in this section, we especially focus on the advantages of hybrid metal-dielectric nanostructures over pure metallic nanostructures.

One prominent example for an application where absorption enhancement plays a crucial role are solar cells, which have become a powerful alternative energy source and are indispensable for solving the problem of climate change. Conventional solar cells are made of silicon wafers having a typical thickness of 200–300 μm. To reduce the production costs, thin-film solar cells with a thickness of only about 1–2 μm were proposed. The main disadvantage of such thin films is the low absorbance of the radiation due to the small thickness of the indirect semiconductor silicon. Random deposition of metallic NPs of different sizes ranging from several nanometers to several tens of μm are proposed.

| System | Electric field enhancement in hot spot | Sensing scheme | Sensitivity [nm RIU⁻¹] | FOM [RIU⁻¹] | Ref. |
|---|---|---|---|---|---|
| Metallo-dielectric (Ag-Si) core-shell NPs | Refractive index | 250 | [95] |
| Multilayer NP. Silver NP covered by a dielectric ($\epsilon = 3.9$) and a Au shell | 30 | Local SERS | [196] |
| Multilayer NP dimer. Silver NP covered by a dielectric ($\epsilon = 3.9$) and a Au shell. Gap: 2 nm | 84 | Local SERS | [196] |
| Hybrid metal-dielectric metasurface. Al disk + SiO₂ spacer + Si cylinder | 6 | Refractive index | 245 | [248] |
| Au NP + HRID microcavity on low-index substrate | Refractive index | 3.6x sensitivity of bare NP | 36x FOM of NP on substrate | [249] |
| 2D Si nanodisk array + Au mirror + SiO₂ substrate | Refractive index | 325 | 11 | [250] |
| SiO₂ patch array + Al plane + dielectric substrate | Refractive index | 840 | 84 | [251] |
| Au NPs chains + TiO₂ waveguide | 5–15 | Refractive index | 739 (sim.) 209 (exp.) | 1.74 (sim.) 0.56 (exp.) | [254] |
| Si nanosphere + SiO₂ spacer + Ag substrate | 400 | Local | [169] |
| Si NP + thin Au film + glass substrate | 1250 | Local | [255] |
| Gold nanorod dimer + spacer (n = 1.46) + concentric disk-ring nanocavity (n = 3.3) | 382¹ | Local | [175] |

²No cavity; ¹$15 \times$ the individual plasmonic antenna.
nanometers has been used to maximize light absorption.\textsuperscript{[262,263]} However, due to the large ohmic losses of such metallic NPs, part of the incident radiation is converted into heat. In other words, although these photons are absorbed, they are absorbed directly in the metal instead of in the semiconductor and thus do not generate electron–hole pairs and, as a consequence, do not contribute to the electric current. This fact limits the utility of metallic NPs in solar cells. To overcome this issue, the possibility of using HRID NPs for improving the efficiency of solar cells was proposed.\textsuperscript{[100–102]} Their low losses, good directionality properties, and the possibility to directly fabricate them from semiconductors make them useful for this kind of applications.\textsuperscript{[4]}

Hybrid metal-dielectric nanostructures offer interesting additional opportunities in this respect and they have been, indeed, predicted to provide efficiencies close to or even surpassing the 1-sun Shockley–Queisser limit.\textsuperscript{[264]} This limit, defined as the maximum power conversion efficiency of a solar cell, mainly depends on the semiconductor band gap for a single junction solar cell. It peaks at 33.6% (solar cell with a band gap of 1.34 eV) under terrestrial conditions. For the case of silicon (band gap of 1.1 eV), this limit is lower, taking values of 32%. To obtain efficiencies exceeding the Shockley-Queisser limit, a large absorption cross-section is not sufficient, as this enhances both the generation and the recombination of electron–hole pairs, cancelling out the overall effect. Instead, anisotropy in the absorbed pattern is required,\textsuperscript{[264]} making it necessary, for example, to reduce the absorption at oblique angles. A viable way to enhance absorption directivity in a solar cell is to combine an absorbing nanostructure with a nonabsorbing one that enhances directivity.\textsuperscript{[264]}

In ref. [265], asymmetric absorption enhancement was reported by means of a hybrid structure consisting of Mie-resonant silicon nanopillars and gold nanodisks. The absorption was shown to be different depending on the direction of illumination. When the nanostructures were illuminated from the silicon side, the absorption was enhanced. However, the absorption was suppressed when the system was illuminated from the metal side, because most of the energy was reflected. An absorption enhancement by a factor of two was numerically calculated for illumination from the silicon side with respect to illumination from the gold side. Experimentally, only a factor of 1.3 was obtained. The increase in the absorption can be understood by examining the near-field enhancement at the interface between gold and silicon due to the excitation of the Mie resonances. In the cited work, the electric field enhancement at the wavelengths of the Mie resonances (dipolar electric and magnetic resonances) and of the plasmonic resonance was analyzed for both illumination directions. The near-field enhancement mediated by the dipolar electric and magnetic Mie modes was found to be larger for illumination from the silicon side. The absorption mediated by the plasmonic resonance, in contrast, was similar for both illumination directions. In this case, silicon acts as a transparent medium with little influence on the plasmonic absorption. Similar asymmetric enhancements were reported when, instead of silicon, other HRID materials such as TiO\textsubscript{2} or Ge were used.

HRID nanowire arrays were also proposed as promising geometries to improve the performance of solar cells due to their extraordinary light-trapping characteristics and high mobility for carriers. By attaching metallic NPs to HRID nanowires, it is possible to further enhance the light scattering. In fact, in ref. [266], an organic solar cell was hybridized with Si nanowire arrays with attached Ag NPs to increase the optical absorption in the organic layer. This effect was put into evidence by measuring the short-circuit current and external quantum efficiency. A 58% enhancement of the short circuit current was attained for the Ag NP-decorated cell compared to the reference cell (without Ag NPs). In particular, it increased from $I_{sc} = 10.5\text{mA} \cdot \text{cm}^{-2}$ to $I_{sc} = 16.6\text{mA} \cdot \text{cm}^{-2}$. The current gain boosted the conversion efficiency from $\eta = 2.47\%$ to $\eta = 3.23\%$. The enhancement can be understood as an interplay of light trapping effect of Si nanowires and SP resonance scattering of Ag NPs.

In refs. [266,267], the electrical and optical properties of hybrid silicon solar cells incorporating Si pyramids or nanowires, decorated with Ag NPs of radius $R = 10\text{nm}$, were investigated (see Figure 18 top left). In this work, the authors introduced the increased percentage of light absorption ($M_{abs}$), defined as

$$M_{abs} = \frac{M_2 - M_1}{M_1} \cdot 100\% \quad (17)$$

where $M_1$ and $M_2$ are the absorption integrated in the whole range of wavelengths $\lambda = 300 – 700\text{nm}$ for the pyramidal or nanowire structure and the pyramidal or nanowire structure combined with Ag NPs, respectively.

The maximum value for $M_{abs}$ for a Si nanopyramid of height $L = 120\text{nm}$ was $157.05\%$, see Figure 18 top right. For the hybrid structures (including the Ag NPs) the absorption is higher than for the nanostructures without the metallic NPs, independently of the height of the pyramid. The enhanced absorption is attributed to the increase of the electric field intensity. This analysis was also performed for Si nanowire arrays decorated with Ag NPs, as shown in Figure 18 middle left. The diameter and period of the nanowire array corresponded to 17 and 21 nm, respectively. The average absorption for silicon nanowire solar cells with height $L = 80\text{nm}$ in the spectral range $\lambda = 300 – 700\text{nm}$ was $19.09\%$. When the silicon nanowires were coated with Ag NPs, the average absorption was $31.51\%$, see Figure 18 middle right. The enhancement is due to the increased light-trapping caused by the inclusion of Ag NPs. The current density was also enhanced for the hybrid structures. In fact, the current density of the solar cell with the bare pyramid was $157.05\%$, see Figure 18 top right. For the hybrid structures (including the Ag NPs) the absorption is higher than for the nanostructures without the metallic NPs, independently of the height of the pyramid. The enhanced absorption is attributed to the increase of the electric field intensity. This analysis was also performed for Si nanowire arrays decorated with Ag NPs, as shown in Figure 18 middle left. The diameter and period of the nanowire array corresponded to 17 and 21 nm, respectively. The average absorption for silicon nanowire solar cells with height $L = 80\text{nm}$ in the spectral range $\lambda = 300 – 700\text{nm}$ was $19.09\%$. When the silicon nanowires were coated with Ag NPs, the average absorption was $31.51\%$, see Figure 18 middle right. The enhancement is due to the increased light-trapping caused by the inclusion of Ag NPs. The current density was also enhanced for the hybrid structures. In fact, the current density of the solar cell with the bare pyramid was $27.1\text{mA cm}^{-2}$. For the nanowire, it reached a value of $23.72\text{mA cm}^{-2}$. For the combined structure (pyramid+Ag and nanowire+Ag), the current density corresponded to $29.78$ and $26.28\text{mA cm}^{-2}$, respectively, see Figure 18 bottom.

Combinations of metallic coatings with 1D semiconductor gratings and nanoantennas have been proposed as perfect absorbers.\textsuperscript{[268,269]} Semiconducting components absorb the electromagnetic energy, generating a large number of electron–hole pairs. Moreover, metallic coatings provide field localization and enhancement in the interior of the semiconducting components as a consequence of the plasmonic resonances. These structures are useful in photovoltaic devices, for example, as solar cell coatings.

Absorption enhancement is also required for photocatalytic applications. Recently, the incorporation of semiconductor layers such as ZnO or TiO\textsubscript{2} has been suggested in photoelectrodes
designs for boosting the solar-to-hydrogen efficiency. Hybrid nanostructures combining metal NPs with these semiconductor layers show increased absorption in the VIS light region. This effect is produced by two different mechanisms. On the one hand, plasmonic NPs lead to the direct injection of charge carriers to the dielectric layers. On the other hand, radiative transfer of energy through the near-field coupling and resonant photon scattering lead to enhanced absorption. In ref. [270], a gold pyramidal film covered by a TiO₂ layer, decorated with Au NPs was experimentally demonstrated to improve the light absorption in a broadband spectral range. TiO₂ was obliquely deposited, giving rise to asymmetric pyramidal shapes, as shown in Figure 19 top. The enhanced absorption for asymmetric nanostructures compared to symmetric ones is due to spatially inhomogeneous resonances and the differences between the physical and optical sizes of a local resonance system. The described design provided absorption values larger than 90% in the entire UV-VIS range (see Figure 19 bottom left). This corresponds to an enhancement factor of 1.5–2 compared to the Au-TiO₂ system without the metallic NPs. This enhancement is due to interference-induced antireflection at the Au-TiO₂ interface and the enhancement of the electric field in the surroundings of the metallic NPs caused by the excitation of localized surface plasmon resonances (LSPRs). When operating the structure as a TiO₂ solar cell after inserting a Ti layer between Au and TiO₂, the photocurrent density was enhanced 3.4 times compared to a flat TiO₂ layer, taking values of 0.16 mA cm⁻² (see Figure 19 bottom right). Apart from absorption enhancement, this result is also

Figure 18. Top left: Scheme of the Si pyramid and Ag NPs on a solar cell. Top right: Percentage of the absorption increase for different heights of pyramid arrays (L = 40, 80, and 120 nm) due to the inclusion of the metallic (silver) NPs decorating the HRID (silicon) pyramids. Middle left: Geometry of the Si nanowire and Ag NPs on a solar cell. Middle right: Absorption spectra for different heights of nanowire arrays (L = 40, 80, 120, 160, and 200 nm), coated with Ag NPs. Bottom: J – V curves of different structures of the heterojunction solar cell under illumination: bare pyramid, pyramid coated with Ag NPs, bare nanowire, nanowire coated with Ag NPs. For the bare nanowire, the results for different etching times are shown. Reproduced with permission.[267] Copyright 2017, American Chemical Society.
influenced by the specific electronic transport properties of the structure. \[270\]

2D hybrid systems consisting of three layers of gold film, TiO\textsubscript{2} film and gold NPs were numerically proposed and experimentally demonstrated for enhanced UV and VIS light absorption and photocatalytic applications. \[271\] The Au film is responsible for the light absorption in the UV spectral region with the TiO\textsubscript{2} acting as an impedance matching layer. Au NPs
increase the absorption in the VIS spectral region due to the excitation of LSPRs. In addition, the Au film is also important to boost the electromagnetic enhancement at the TiO₂ film, which is in contact with the Au NPs.

Broadband absorption enhancement was also proposed for core-shell heterostructures. The effect was experimentally examined in a hybrid system consisting of a dielectric (SiO₂) core, coated by a metal (Au) NPs interlayer and a tunable semiconductor (TiO₂) shell.²⁷² Such a nanostructure was proposed for catalytic applications. The Au NPs exhibited enhanced absorption, generating and injecting hot carriers into the TiO₂ shell. The broadband absorption enhancement in the metallic NPs was achieved by modifying their dielectric environment. The semiconductor shell could act as a reflecting layer, amplifying the photons absorbed by the Au NPs.

In ref. [273], it was numerically demonstrated that dielectric core NPs coated with catalytic Pt NPs (see Figure 20 left) can be efficiently designed for enhancing the VIS light absorption in the Pt NPs. The absorption enhancement is originated by the Mie resonances excited in the dielectric NP. The results reported in this study are useful for VIS light photocatalysis and solar energy conversion. For a system consisting of 66 Pt NPs of diameter 5 nm decorating the surface of a spherical TiO₂ dielectric NP of radius 150 nm, immersed in a water environment, a wavelength-dependent averaged absorption enhancement factor of 6 was reported (see Figure 20 right). The averaged absorption enhancement was obtained by normalizing the absorption cross section to the product of the number of Pt particles by the absorption cross section for the isolated single Pt NP. The enhanced absorption is due to the increase of the local electric field $|E|$. By means of near-field maps, it was observed that the largest $|E|$ values are accumulated at the back side of the TiO₂ core. In addition, through these maps, it is possible to determine the electromagnetic modes that are responsible for the enhancement. This can be corroborated by means of the multipolar decomposition. In the absorption spectra four different peaks were identified corresponding to the dipolar, quadrupolar, octupolar and higher order magnetic resonances. It was observed that the electric field enhancement increases with the multipolar order. The maximum absorption enhancement factor for individual Pt NPs corresponds to 20, 40, 70, and 80 at the dipolar, quadrupolar, octupolar, and higher-order magnetic resonances, respectively. The peak average absorption enhancement factor intensity takes values between 7 and 10. The enhancement of the maximum local heating power density is two orders of magnitude larger than the intensity found for an isolated Pt NP at the same wavelength.

Another application for absorption enhancement are photodetectors. In ref. [274], the enhancement of the absorption of a graphene monolayer was demonstrated by means of a dielectric-metal core-shell nanoresonator. The graphene layer was coated at the outside of the nanoresonator. The absorption increased due to the excitation of the hybridized bonding plasmon resonance supported by the core-shell NP. By changing the size of the core or the thickness of the shell, the enhancement could be optimized at different wavelengths. For a silver shell of thickness 5 nm and a dielectric core of radius 12 nm and refractive index 1.59 (polystyrene), the graphene absorption efficiency $Q$ obtained by dividing the absorption cross-section by the particle cross-sectional area projected onto a plane perpendicular to the incident beam, as explained in Section 2.1) took on a value of 8.8 at the resonance wavelength ($\lambda = 455$ nm). This corresponds to a 50-fold enhancement with respect to a graphene-wrapped silver nanosphere. The electric field intensity enhanced an enhancement of 450 times the intensity of the incident field ($\lambda = 455$ nm) due to the excitation of the hybridized dipolar bonding plasmon resonance. Through a numerical analysis, the size of the core and the thickness of the shell were optimized to achieve the maximum absorption enhancement in the graphene coating, keeping the refractive index of the core to 1.59. Enhancements of 2–3 orders of magnitude for the hybrid system compared to a graphene-wrapped silver nanosphere were reported. This optimization process was also carried out for cores made of HRID materials. The obtained enhancements were similar to those previously reported.

Metal-dielectric metasurfaces were analyzed to improve the photoresponse of Ge/Si QD IR photodetectors.²⁷⁵ The metasurface consisted of an array of Si nanopillars protruding through subwavelength holes in a perforated gold film on the detector top. It was demonstrated that the photoresponse can be improved with hybrid metal-dielectric nanostructures compared to bare dielectric or metallic gratings. In particular, the responsivity of

---

**Figure 20.** Left: Geometry composed of a dielectric spherical TiO₂ core ($R = 150$ nm) coated by 66 Pt spherical NPs ($r = 2.5$ nm). Right: Averaged absorption enhancement factor (AEF) for the Pt NPs on different sphere supports. Blue line: TiO₂ support. Green line: ZnO support. Red line: SiO₂ support. The AEF is obtained by normalizing the scattering cross section to the product of the number of Pt particles by the absorption cross-section for the isolated single Pt NP. Reproduced with permission.²⁷³ Copyright 2021, Wiley.
the hybrid detector (at \( \lambda = 4.4\) m) was enhanced by a factor of 15 compared to the that obtained for a bare Ge/Si QD IR photodetector. More modest enhancement was reported for plasmonic 2D subwavelength hole arrays. In fact, for this case, the maximum enhancement was about 4. No enhancement was observed for Si pillar without the 2D subwavelength hole array.

Another intriguing effect was considered in the context of hybrid nanostructures is represented by radiative cooling. In ref. [72], the authors theoretically demonstrated that a hybrid optical-thermal antenna, which supports high Q factor photonic–plasmonic modes in the VIS range, provides a two orders of magnitude enhancement of localized electric fields and respective power absorption, whereas the temperature can be decreased by hundreds of degrees with respect to the pure metallic nanoantenna under a continuous radiance of \( 10^4 \) W m\(^{-2}\).

The mechanism that provides the temperature reduction is based on the enhanced radiative cooling, which is mediated by thermally excited localized surface phonon–polariton modes. Such surface phonon–polariton modes are supported by polar dielectrics, such as SiO\(_2\), in the IR spectral range. Dielectric antennas can be designed to show resonant phonon–polariton enhanced IR absorption cross section. Considering Kirchhoff’s law, this suggests that enhanced resonant thermal emission efficiency can be attained, since thermal emission is boosted by photon localization effects. The system considered in [72] consisted of a Au nanosphere, which was attached to a SiO\(_2\) microsphere. The absorption enhancement was produced by the hybridization of the WGMs in the dielectric microsphere with the LSPs in the metallic spherical NP. The local field intensity enhancement on the surface of a 150 nm diameter Au NP, attached to a SiO\(_2\) microsphere of diameter 3 micrometer, reached values of \( 2 \cdot 10^3 \) \( |E|^2/|E_0|^2 \), where \( |E|^2 \) is the intensity enhancement in the presence of the antenna and \( |E_0|^2 \) is the intensity of the incident radiation, and is plotted in Figure 21 left. This intensity enhancement was accompanied by an enhancement in the absorption. The power absorbed by the hybrid nanostructure was two orders of magnitude larger than that absorbed by a bare Au NP, under the same illumination conditions. In Figure 21 right, it is evident that the hybrid antenna can dissipate more power via thermal emission than bare Au NPs as well as Au NPs on top of SiO\(_2\) flat surfaces. The dissipated power for the hybrid structure was increased by two orders of magnitude with respect to Au NPs.

We have also summarized the different performances of the reviewed configurations of hybrid nanostructures for absorption enhancement in Table 4.

5.4. Increasing Purcell Factor and Collection Efficiency

The Purcell effect is defined as the modification of the spontaneous emission rate of a (quantum) emitter caused by its environment. It was originally introduced by Edward Mills Purcell to describe the acceleration of spontaneous decay at radio frequencies.\(^{276}\) Importantly, the lifetime of an excited state is not an intrinsic property of the emitter, but depends on the electromagnetic environment through the local density of photonic states (LDOS). As such, controlling and enhancing the LDOS allows to boost various light–matter interactions, including spontaneous emission, with important implications for many different applications in classical and quantum optics. In particular, an ideal source for many quantum technology applications would emit single or entangled photons on demand, requiring a high quantum yield and fast radiative decay.\(^{277–281}\)

For obtaining large values of the Purcell factor or, equivalently, of the local density of photonic states (LDOS), the photonic systems should ideally be able to strongly concentrate the light both spatially and spectrally. Traditionally, this means that one would ask for a photonic system with a small mode volume and a high Q factor. Note, however, that for lossy/open systems, the mode

Figure 21. Left: Intensity enhancement spectrum on the surface of a Au NP of diameter 150 nm, attached to a SiO\(_2\) microsphere of different diameters (shown as labels). The intensity enhancement for an isolated Au NP is represented by the gray line. Right: Power dissipated by hybrid antennas via thermal radiation as a function of the antenna temperature. The solid lines represent the power dissipated by the hybrid structure for different sizes of the dielectric microsphere. The dotted lines show the power dissipated by a NP on the top of a planar silica surface. For comparison, it is also plotted (in gray) the power dissipated by an isolated Au NP. Reproduced with permission.\(^{72}\) Copyright 2016, The Royal Society of Chemistry.
volume becomes difficult to evaluate, which can affect the Purcell factor by more than an order of magnitude. This issue can be overcome by expressing the electromagnetic field by a superposition of quasi-normal modes. Also note that the Purcell effect is only defined in the so-called weak coupling regime, where despite a possible strong interaction between the emitter and the environment, the emitter is basically incoherent and the coupled system is dominated by its damping rates. As the interaction becomes very strong and the coherent interaction of the emitter with the cavity field becomes dominant, the system enters the strong-coupling regime, where mixed states, which are partly light and partly matter, are produced.

The most common types of systems employed to increase the Purcell factor are cavities. However, one of the main limitations for achieving high Purcell factors in cavities are their large mode volumes. This suggests that extremely large \( Q \) factors (\( Q > 10^4 \)) are necessary to obtain high Purcell factors, leading to narrow linewidths of the cavity resonance and, thus, a small emission bandwidth. As an alternative to optical cavities, NPs exhibit broadband response. However, they show low \( Q \) values (\( Q \approx 3 \) – 30). As shown in ref. [178] and already described in Section 2.3, hybrid nanostructures combining nanoantennas and cavities can provide larger emission enhancements as well as control over the bandwidth where the enhancement is observed.

In the same work, the authors also applied their theoretical insights to a specific example, namely a hybrid system consisting of a whispering-gallery mode cavity and a gold antenna. The system was shown to achieve stronger emission enhancement than the bare cavity or antenna, when the cavity was red-detuned from the antenna. An experimental demonstration of a similar hybrid system was investigated in ref. [203]. The structure consisted of an AI antenna coupled to a SiN microdisk, as shown in Figure 22a. A QD was placed in the plasmonic hot spot. The hybrid system presented highly tunable quality factor (\( Q > 10^4 \)) and mode volume (\( V \)) values in between those observed for the cavity and the antenna. By means of the hybrid configuration a decrease of a factor \( \approx 6 \) in the emission lifetime of a single QD was demonstrated compared to that of a QD on a flat glass substrate. In ref. [286], a bow-tie antenna was integrated on a dielectric photonic crystal nanobeam cavity, as shown in Figure 22b left. The authors numerically explored what mode volumes and \( Q \) factors can be achieved in this kind of structures and discussed possible applications in classical and quantum optics. Again, it was demonstrated that the Purcell factor can be increased with respect to the bare plasmonic and cavity constituents. Figure 22b furthermore shows how the hybrid systems take intermediate values of \( Q \) and \( V \) with respect to the bare nanobeam (highest \( Q \) factor and highest \( V \)) and the bare nanoantennas (lowest \( Q \) factor and lowest \( V \)) as the gap distance of bow-tie antenna is varied.

In ref. [287], a hybrid plasmonic photonic cavity consisting of an L3 photonic crystal cavity and a bow-tie nanoantenna was theoretically proposed. The ratio \( Q/V \) was boosted 25 times compared to that of a bare L3 photonic crystal cavity and 60-fold greater than that corresponding to a plasmonic bow-tie antenna. As a consequence, strong coupling between light and a single emitter was achieved. This has important applications in quantum optics, quantum information and nonlinear optics.

The possibility of using hybrid nanostructures for the optical trapping of NPs was proposed in ref. [288]. The structure consisted of a photonic crystal cavity coupled to a plasmonic bow-tie nanoantenna. The optical intensity in the bow-tie nanoantenna gap was 40 times larger than the case when the bow-tie antenna was not located above the photonic crystal cavity. Such a device can create optical traps with an intensity gradient over a distance much smaller than the diffraction limit, being ideal for optical trapping of particles that are too small to be trapped by conventional optical tweezers.

### Table 4. Summary of the performances of different configurations of hybrid nanostructures for absorption enhancement.

| System | Photo-current enhancement [mA cm\(^{-2}\)] | Optical-to-electric conversion efficiency | Absorption enhancement factor | Electric field enhancement in hot spot | Ref. |
|--------|------------------------------------------|------------------------------------------|-------------------------------|----------------------------------------|-----|
| Au NP + SiO\(_2\) microsphere | 10.5 (Si nanowire) 16.6 | 2.47% (Si nanowire) 3.23% | 100× Au NP | 45 | [272] |
| Si nanowire decorated with Ag NPs | 23.72 (Si nanowire) 26.28 | 7.70% (Si nanowire) 8.80% | 31.51% (Si nanowire + Au NPs) | [267] |
| Si pyramid coated with Ag NPs | 27.1 (Si pyramid) 29.78 | 9.40% (Si pyramid) 10.6% | 21.96% (Si pyramid) 33.31% | [267] |
| Au pyramidal film + TiO\(_2\) layer + Au NPs | 0.16 | | 90% | [270] |
| Au film + TiO\(_2\) film + Au NPs (0.026) | 2.3× TiO\(_2\) film + Au NPs | 4.0× TiO\(_2\) + Au film (60%) | 5 | [271] |
| 66 Pt NPs attached to TiO\(_2\) NP immersed in water | 6×\(^{a}\) | | 50–200 | [273] |
| Core \((n = 1.59)\)-shell (silver) NP coated with a graphene monolayer | 59×\(^{b}\) | | 21 | [274] |

\(^{a}\) Compared to the number of NPs times the absorption cross section of a single Pt NP; \(^{b}\) Compared to a graphene-wrapped Ag nanosphere.
Hybrid configurations consisting of metallic bow-tie nanoantennas with diamond tips containing nitrogen vacancy centers were recently introduced to enhance the emission of quantum emitters.\cite{289,290}

Apart from photon emission enhancement, an enhancement of the collection efficiency is desirable. Ideally, photons should be emitted into a single well-defined mode, which can be a waveguide mode or a free-space mode with directional properties allowing for efficient collection with suitable optics. In ref. \cite{190}, a hybrid photonic–plasmonic cavity composed of a Au nanorod dimer and a photonic crystal nanobeam cavity was theoretically demonstrated to fulfill both requirements. It was calculated that the spontaneous emission rate of a single emitter could be boosted by 50-60-times and that the collection efficiency into a dielectric waveguide reached 67%.

Hybrids composed of metal-HRID NPs can be also useful to simultaneously increase the emission enhancement and control the scattering pattern of the emitted radiation. In a simple picture, the strong confinement of electromagnetic radiation in the surroundings of metallic NPs boosts the spontaneous emission of a quantum emitter, while the HRID NPs govern the directionality properties of the emitted light without introducing notable additional losses. In a numerical study reported in ref. \cite{291}, a gold nanorod dimer was used to increase the decay rate of an emitter. The directionality of the emitted radiation was controlled by a silicon cylinder. The gold dimer was separated of the silicon director by a SiO$_2$ spacer. Through this design, high radiative decay rate enhancement and a high directivity of 8.5 were reported. Furthermore, the radiation efficiency exceeded 70% over a broadband spectral range.

A dimer consisting of a spherical metallic NP (silver) and a spherical HRID (electric permittivity, $\varepsilon = 25$) NP was numerically studied to explore its capabilities in fluorescence enhancement. A 40% fluorescence excitation rate, higher than that of a pure HRID dimer, and a 30% quantum yield, larger than that of a pure metallic dimer, were achieved. In addition, due to the different size of the NPs composing the dimer, directional effects were also observed. Radiation was mainly scattered toward the dielectric side.\cite{292}

In ref. \cite{293}, a hybrid mushroom-shaped nanoantenna was designed to achieve high excitation rates, quantum yields, and fluorescence enhancements. The nanostructure consisted of a plasmonic metal stripe and a dielectric cap. A fluorescence enhancement factor 2-fold higher than that for a pure metal antenna could be theoretically achieved. The dimensions were chosen so that the metallic stripe provides a large resonant excitation enhancement, while the dielectric cap resonates at the emission wavelength of the emitter. Thus, the cap enhances the radiative decay rate while maintaining a high quantum yield. In addition, most of the radiation (about 70%) was directed towards the dielectric cap.

Also, a hybrid nanoantenna consisting of an inner metal nanodisk and an outer dielectric ring was theoretically presented to increase the fluorescence enhancement,\cite{294} as displayed in

Figure 22. a) Left: Scheme of a hybrid system consisting of an Al nanoantenna located on a SiN microdisk cavity. Right: Decay rate of a single QD. Reproduced with permission.\cite{203} Copyright 2020, American Chemical Society. b) Left: Illustration of a hybrid system composed of a gold dimer and a SiN nanobeam cavity. Right: Comparison of the $Q$ factor and $V$ values between hybrids systems and the bare components, i.e, bare cavity and bare antennas. Different gap distances between the NPs constituting the nanoantennas were considered: 25 nm (red), 5 nm (green) and 1 nm (blue). Reproduced with permission.\cite{286} Copyright 2019, De Gruyter.
Due to the coupling between the SPs of the metal nanodisk with the magnetic dipole resonance of the dielectric ring, the excitation rate in the gap could be enhanced by more than one order of magnitude, compared to that of pure metal or pure dielectric structures. In Figure 23a right, the fluorescence excitation rate $\gamma_{\text{ext}}/\gamma_0$ spectra for a single emitter placed at different positions of the hybrid nanoantenna gap are shown. For all of the considered emitter positions, a robust enhancement of the excitation rate was observed. The emission of randomly oriented emitters was enhanced by two orders of magnitude with respect to that of the metal or dielectric constituents. In addition, directional properties were observed. 74% of the radiation was emitted upward.

In ref. [295], a gold nanosphere on top of a truncated silicon cone (see Figure 23b) was theoretically proposed as a hybrid nanoantenna to enhance the emission of a single-photon emitter located in the gap between both nanostructures. Ultrahigh Purcell factors ($\approx 10^{3.5}$ for horizontal and $\approx 10^{6.5}$ for vertical dipole orientation) were reported. Furthermore, it was observed that when the dipole is horizontally oriented with respect to the symmetry axis of the hybrid nanoantenna, it radiates unidirectionally. This allows to improve the collection efficiency of the signal. The authors also analyzed the change in the electric field enhancement as a function of the gap distance. The results suggest that the Purcell factor depends strongly on the considered gap size, with smaller gaps providing stronger enhancements.

In ref. [296], a circular bulls-eye shaped metal-dielectric nanoantenna, containing a single nanocrystal QD in its center, was proposed experimentally as a single photon source. This nanostructure showed high collection efficiency and single photon purity. In particular, high directional emission of single photons into a narrow angular cone was attained due to the coupling of the single photons emitted by the QD to the nanoantenna optical modes.

Hybrid configurations consisting of metallic dimers surrounded by dielectric nanostructures were also explored. In ref. [297], a dielectric TiO$_2$ microsphere was proposed to collect the light emitted by a QD centered in the gap of a pair of coupled silver nanospheres. In ref. [292], a gold bow-tie antenna was combined with a Yagi-Uda antenna composed of three silicon nanorods. The bow-tie is responsible for enhancing the Purcell factor, whereas the Si nanorods can govern the directionality of the emitted radiation. This structure was experimentally realized and showed the expected unidirectional in-plane directivity and beam redirection capability in the VIS spectral range. In ref. [298], a numerical analysis was conducted by means of
the transfer-matrix method to reveal the optimal core and shell radii to achieve maximum fluorescent enhancement values at the surface of metallo-dielectric core-shell NPs. Different materials of the core (Au and Ag) and the shell (SiO₂, Al₂O₃, ZnO) were considered.

Similar to the case of dimer architectures, the ultra-small mode volume and strong confinement of electric field in a thin spacer layer between a HRID NP and a metallic substrate make these hybrid structures promising for enhancing the luminescence of quantum emitters located in the nanogap. In ref. [14], a Si NP on a flat gold substrate was proposed to boost the emission of a monolayer of colloidal QDs, which also forms a nanogap resonator. It was experimentally demonstrated that this design enhances the photoluminescence of QDs by a factor of 786. A similar configuration as the previously described was used in ref. [173] to enhance the emission of a self-assembled CdSe/ ZnS QD monolayer of thickness 10 nm on a thin Al₂O₃ separation layer. In Figure 24a, the decay rate was 42-fold compared to QDs on glass. From Figure 24a right, it is possible to determine the enhancement of the photoluminescence signal from QDs in the nanogap resonator of the hybrid system, compared that from QDs on glass (17-fold enhancement), QDs on a gold film with 5 nm Al₂O₃ spacer layer (37-fold enhancement), and QDs on a bare gold film (188-fold enhancement). Moreover, a quantum efficiency of over 80% was reported. The results were obtained numerically and experimentally.

It is worth noting that the photoluminescence intensity enhancement factor is given by the excitation rate ($\gamma_{\text{exc}}$), the photon quantum efficiency ($Q_{\text{eff}}$), and the collection ($\eta$) efficiency through

$$E_F = \frac{\gamma_{\text{exc}}(r)}{\gamma_{\text{exc}}(0)} \cdot \frac{Q_{\text{eff}}(r)}{Q_{\text{eff}}(0)} \cdot \frac{\eta(r)}{\eta(0)}$$

In a similar fashion, HRID nanowires, separated from a metallic substrate by a thin dielectric spacer layer, can be efficient nanophotonic structures for enhancing the emission of QDs, Figure 24b. Due to the coupling of the resonance modes with the mirror, strong confinement of the electromagnetic fields are observed in the dielectric spacer layer. The PL enhancement factor, defined as the ratio of the PL of a QD monolayer in the Si nanowire-Au structure to that of the QD monolayer on a Au film (without a nanowire), takes values from 3.7 to 9.5 in the spectral range $\lambda = [600 \text{ nm} - 850 \text{ nm}]$.

We have summarized the performance of different reviewed configurations of hybrid nanostructures for emission enhancement in Table 5.
5.5. Enhancement of Nonlinear Effects in Hybrid Structures

As introduced in the preceding sections, the combination of metallic and dielectric materials can cause strong electric field concentration in small volumes, which are called hot spots. Furthermore, combining these dissimilar materials can assist to introduce a symmetry break near their interface. These properties can be successfully utilized for the enhancement of nonlinear optical effects. While second-order nonlinear effects such as second-harmonic generation (SHG), sum-frequency generation and optical rectification\cite{179} can be observed in semiconductors or crystalline dielectrics with non-inversion-symmetric crystal structure, they are not present in amorphous materials or in crystalline media with inversion-symmetric lattice structure. However, even in these materials, the inversion symmetry condition is broken at the surface and second-order nonlinear effects can be quite strong as, for example, at metal interfaces. Third-order nonlinear effects such as third-harmonic generation (THG), Kerr effect, four-wave mixing and two-photon absorption\cite{179} can be observed even in inversion-symmetric materials and in the absence of any interfaces. Nonlinear frequency generation processes have recently demonstrated their utility in many different applications. In particular,

| System | Quantum efficiency | Electric field enhancement in hot spot | Directivity | Purcell factor | Enhancement factor Exc./Em. | Collection efficiency β-factor | Ref. |
|--------|-------------------|---------------------------------------|-------------|---------------|-----------------------------|-----------------------------|------|
| Si₃N₄ microdisk cavity + Al nanorod antenna | 29× | 5290 > 21× bare L3 photonic crystal | 60× Au bow-tie antennas | 8× Au nanorod dimer | | | [203] |
| Si L3 photonic crystal nanocavity + Au bow-tie antenna | 10 | 25× bare L3 photonic crystal | 60× Au bow-tie antennas | | | | [287] |
| Au nanorod dimer + Si photonic crystal nanobeam | 97% | 5290 > 21× bare nanobeam cavity | 8× Au nanorod dimer | | | | [190] |
| Au nanorod dimer + spacer (n = 1.45) + Si disk | 70% | | | | | | [291] |
| Ag NP + Dielectric (ε = 25) NP | 60% +30% metallic dimer -8% dielectric dimer | ≈15 -20% metallic dimer +60% dielectric dimer | 20% more radiation towards dielectric than metallic NP | | Excitation rate 100 +40% dielectric dimer Emission enhancement 87 +30% dielectric dimer | | [292] |
| Hybrid mushroom nanoantenna Ag stipe + Si cap | 80% | 130 20× Ag cylinder 70% radiation emitted to Si cap | Average fluorescence enhancement factor 80 10x pure metal or dielectric | | Excitation rate enhancement 150 Radiative decay rate 90 | | [293] |
| Inner Au nanodisk + outer Si ring cavity | 40% | >3000 radiation propagates upwards | Fluorescence enhancement factor 80 10x pure metal or dielectric | | Excitation rate 400 10x pure metal or dielectric Radiative decay rate 300 10x pure metal or dielectric | | [294] |
| Au nanosphere + Si truncate cone + glass substrate | 20 | 10¹⁰ | | | | | [295] |
| Two Ag NPs + TiO₂ microsphere embedded in a n = 1.3 medium | 70% | 95 | Angular aperture 15° | 2000 | Excitation rate enhancement 16000 Emission rate enhancement 11 000 | | [297] |
| Au bow-tie antenna + 3 Si directors | 49.2 | 1800 | | | | | [202] |
| Si NP + Al₂O₃ spacer layer + Au film + Si substrate | >80% | >6 | >120 | | Decay rate enhancement >100 | | 75% [173] |
they are used in laser systems to enlarge the range of accessible frequencies and have been proposed for nonlinear imaging[299] and even for biological uses, like in visualization of biological molecules[300,301] and inner cell processes.[302,303] Hybrid metal-dielectric nanostructures have been introduced as efficient geometries to enhance SHG and THG.

For example, several early works reported SHG in different hybrid systems, including gold dipole antennas oriented orthogonal to a dielectric ZnS dipole antennas and hybridized with ZnS NPs,[304] metal-dielectric Janus dimers constituted by Au and BaTiO3 nanospheres,[305] and centrosymmetric meta-atoms supporting the excitation of the higher-order multipolar modes.[306] Similar combinations of metal-dielectric nanostructures were also described to enhance the THG, such as metallic dipole nanoantennas coupled to ITO NPs,[307] ITO NPs placed in the gap of plasmonic dimers,[116] and silicon disks located at the center of gold rings.[118]

In more recent works it was demonstrated that the SHG output in hybrid systems can also be enhanced by anapole modes. In ref. [308], this was attained in a hybrid structure consisting of a Au ring and an AlGaAs nanodisk (Figure 25a,b). The ring assists the coupling to the nonradiative anapole mode of the AlGaAs nanodisk and at the same time helps to outcouple SH emission. The conversion efficiency reached $5 \times 10^{-6}$ for this approach. Second harmonic generation in a lithium niobate nanodisk array located on a Au substrate was reported in ref. [174]. The presence of the metallic substrate leads to a significant enhancement of the local field in the lithium niobate nanostructure and therefore of the nonlinear response. The enhancement occurs due to the excitation of plasmon assisted dipole resonances. In this configuration, the intensity enhancement is inversely proportional to the material refractive index. For the SH signal at 400 nm a conversion efficiency of about $5 \times 10^{-4}$ was achieved. Similarly, SHG enhancement was shown in a CdSe nanowire coupled with Au film to form a hybrid plasmonic waveguide[309] (Figure 25c). A conversion efficiency of $4 \times 10^{-5}$ was reported. In a theoretical work[110] it was suggested that an AlGaAs disk resonator surrounded by gold nanorods can support quasi-bound states in the continuum[311] modes near the disk magnetic dipole (MD) resonance and thereby exhibit high field enhancement. Nearly 2000-fold enhancement of SH emission was predicted in this geometry when compared to a MD resonance in a single nanodisk without the metal framing. Field confinement near plasmonic structures can also be combined with nanodimers exhibiting multiple Mie resonances to achieve pronounced enhancement of SHG. In ref. [312], SHG was studied in heterodimers composed of gold and barium titanate (BaTiO3 or BTO) NPs (Figure 25d,e). When the LSP
mode of the gold nanoparticle was overlapping with dipole and higher-order Mie resonant modes in the BTO nanoparticle, the excitation of hybridized modes in the visible band was achieved. SHG signal enhancement due to these hybridized mode was enhanced by 2 orders of magnitude compared to a single BTO nanoparticle.

More recent works also highlight THG enhancement in hybrid metal-dielectric nanostructures. For example, in ref. [311] a plasmonic/dielectric metasurface supporting a hybridized mode between the metal plasmonic mode and Si waveguide mode was studied (Figure 25f,g). It was demonstrated that by balancing high Q factors and in-coupling efficiency, strong near fields and THG enhancement can be achieved. An enhancement factor of $10^4$ was reported when compared to the reference Au thin film.

In Table 6, we summarize the SHG and THG conversion efficiencies as well as the field enhancement factors provided in the works reviewed in this section.

Apart from nonlinear frequency generation, nonlinear effects can also be used for the purpose of all-optical dynamic tuning of the optical response of hybrid metal-dielectric nanostructures. For example, metal-dielectric metasurfaces allowing for dynamic beam steering,\[^{314}\] tunable topological insulators,\[^{315}\] and metamaterials reconfigurable by a fs laser pulse\[^{247}\] were reported.

### 5.6. Hybrid Semiconductor Nanowire-Based Plasmonic Structures for Lasing Applications

Since the demonstration of the very first lasing action in an optically pumped ruby rod,\[^{316}\] LASERs (light amplification by stimulated emission radiation) have certainly marked a significant step in the history of scientific and technological progress. More recently, the strenuous demand for the ever-increasing miniaturization of components like system on a chip devices (SoC) and optical interconnects (OI), as predicted by the “More Moore” and “More-than-Moore” schemes,\[^{317}\] has imposed a footprint shrinkage of coherent light sources down to the micro-, first, and, later, to the nanoscale. In this context, a wide variety of photonic components such as microdisk lasers,\[^{318}\] vertical cavity surface emitting lasers,\[^{319}\] and photonic crystal lasers\[^{320}\] based on semiconductor materials has been developed, especially at the turn of the millennium. Among them, semiconductor nanowires have stood out as promising nanolasers, owing to the relatively facile and low-cost top-down\[^{321,322}\] or bottom-up\[^{323,324}\] synthesis methods, together with the remarkable optical properties which arise from their unique (quasi) unidimensional structure. In addition to proving that the necessary material gain for attaining lasing action, semiconductor nanowires can effectively confine and guide the electromagnetic radiation along a micro-sized (generally from 5 up to 500 μm) optical cavity, which acts as a Fabry–Pérot resonator, thanks to the high reflectivity of the end facets and the large index contrast with the surrounding.\[^{325,326}\]

Typical gain material used for making nanowire lasers are II–VI and III–V semiconductor compounds—capable of covering the whole spectrum from the UV to the IR—like ZnS,\[^{327}\] ZnSe,\[^{328}\] CdS,\[^{329}\] InP,\[^{330}\] and GaS\[^{331}\] just to name a few, but also metal halide perovskites.\[^{332–334}\] Nonetheless, despite the remarkable optical performances and stability combined with their versatile applicability, nanowire-based photonic lasers are inevitably subject to the diffraction limit, which constrains their size—and, thus, their on-chip footprint—to approximately half of their emission wavelength. Such size of a few hundreds of nm is still an order of magnitude larger than the feature footprint of modern transistors: this mismatch can cause integration issues and strong energy dissipation, thus, hindering the applicability of such nanolasers.\[^{335}\]

Therefore, to confine the electromagnetic radiation down to the subwavelength regime, the concept of a SPASER, as theoretically formulated in ref. [336], has marked a major breakthrough toward such aim. To avoid confusion, the terms spaser and plasmonic nanolaser will be, henceforth, used interchangeably. Spasers can be described by means of a semi-classical theory, in which the gain medium is treated quantum-mechanically and the SPs are treated classically. One of the major results of this theory is the independence of the lasing condition on the gain medium size and geometry.\[^{320}\] Therefore, the absence of any size constraints on the spasing condition, can make plasmonic lasers truly nanoscopic. Moreover, the spasing frequency is also independent of the pumping rate and differs from both the gain medium and SP frequencies, similarly to the cavity-pull (or frequency walk-off) effect occurring in common lasers. This enables a wide tunability range, by simply changing the gain medium resonance frequency, while keeping the properties of the metal, like geometry and composition, fixed.\[^{337}\] Lastly, compared to conventional photonic lasing, spasing is rather characterized by the apparent absence of a perceptible threshold, which is usually marked by a nearly linear dependence of the output power from the pump power in a typical logarithmic (also known as $L = I$) plot. This is due to the fact that the values of the spontaneous emission coupling factor $β$ ≈ 1 are strongly enhanced via the Purcell effect. Indeed, since the Purcell factor is inversely proportional to the mode volume $F \propto V_m^{-1}$, the characteristic subwavelength confinement of the spasing modes leads

| System | Electric field enhancement in hot spot | Conversion efficiency | Ref. |
|--------|---------------------------------------|----------------------|-----|
| SHG. AlGaAs nanodisk surrounded by Au ring | 9 | $5 \cdot 10^{-4}$ (SHG) | [308] |
| SHG. Lithium niobate nanodisks on Au substrate | $\approx 10$ | $5 \cdot 10^{-4}$ (SHG) | [314] |
| SHG. CdS nanowire coupled with Au film | $\approx 10$ | $4 \cdot 10^{-3}$ (SHG) | [309] |
| THG. Metallic dimers Au + dielectric ITO in the gap | $\approx 10$ | $7 \cdot 10^{-4}$ (THG) | [116] |
| THG. Si nonodisk surrounded by Au ring | 9 | $7 \cdot 10^{-1}$ (THG) | [118] |
to an enhancement of $F$, which also promotes the acceleration of the laser dynamics.\textsuperscript{[338]}

The experimental realization of plasmonic nanolasers, arrived at the earliest in 2009. Two groups independently demonstrated the capability of exploiting either the LSPs building up in a core-shell structure formed by a gold NP core (acting as a cavity) and a dye-doped silica shell (providing the material gain),\textsuperscript{[339]} or the SPPs propagating at the interface between a semiconductor nanowire and a metal layer and mostly confined within the interposed nano-sized dielectric spacer,\textsuperscript{[15]} as shown in Figure 26b,c, respectively. The latter structure, indeed, represents the benchmark for all of the so-called semiconductor–insulator–metal (SIM) hybrid plasmonic structures, based on the coupling of semiconductor nanowires with a metal layer, which is separated by an insulating spacer whose function is to mitigate the losses and enhance the hybrid mode confinement. Oulton and coworkers successfully demonstrated lasing action supported by a hybrid plasmonic mode with a subwavelength area as small as $\lambda^2/4$, capable of overcoming the typical cutoff for photonic modes related to the cavity size.\textsuperscript{[340]} Such lasing action was also characterized by an accelerated dynamics, due to an enhancement of the Purcell factor caused by the stronger mode confinement within the spacer region, whose magnitude was found to scale inversely with the spacer thickness.

However, lasing action was only demonstrated at cryogenic temperatures, and it was only in 2013 that the first room temperature hybrid SNW-based spaser was demonstrated.\textsuperscript{[341]} Sidiropoulos et al. proved that ZnO nanowires separated from an Ag substrate by a thin LiF gap layer of about 10 nm thickness could be efficiently driven to spasing, on the basis of typical experimental evidence when compared to the photonic counterparts (i.e., ZnO NWs lying on SiO$_2$/Si substrates), as shown in Figure 27a. Since the fundamental hybrid plasmonic mode experiences no cutoff, spasers with cavity diameter $d < 100$ nm can be, in principle, obtained, provided that the gain can still efficiently overcome the total losses (see Figure 27b). Moreover, due to the TM character of the SPPs, the polarization of the fundamental hybrid mode lies along the NW axis, conversely to the case of the dominant photonic transverse mode which possesses a TE character and, therefore, is polarized perpendicularly to it. The increased losses, due to the presence of the metal in the spaser structure, lead to an overall increase of the lasing threshold compared to the photonic nanolasers. Hence, higher pumping intensities cause a blueshift of the gain envelope with respect to the photonic case (see Figure 27c): this shift is usually associated with a partial filling of the semiconductor conduction band states due to the close vicinity of the metal, which is known as the Burstein–Moss effect.\textsuperscript{[342,343]} Furthermore, the subwavelength confinement enhanced by the Purcell factor, enables a sub-picosecond operation regime for plasmonic nanolasers with pulse widths as low as 800 fs, that is, more than 10 times faster than their photonic counterparts.\textsuperscript{[344]}

Other exemplary SIM hybrid systems, which have shown remarkable plasmonic lasing properties over the last decade, feature II–VI and III–V semiconductor compounds with direct band gaps. For example, an InGaN-GaN core-shell nanorod on a 5-nm SiO$_2$/Ag substrate,\textsuperscript{[345]} a GaN NW on a 8-nm SiO$_2$/Al substrate,\textsuperscript{[346]} and a ZnO NW on a 5nm SiO$_2$/Al substrate.\textsuperscript{[347]} However, more recently, lead halide perovskites\textsuperscript{[348,349]} have also
gained more attention, thanks to their low-cost fabrication and high optical gain, following the pioneering work of Yu and coworkers,[350] who successfully achieved low-threshold spasing in a hybrid structure consisting of a CH3NH3PbI3 NW placed on a 10-nm MgF2/Ag substrate.

In such SIM structures, in addition to the optical properties and crystalline quality of the gain medium, the dielectric spacer plays a crucial role. In addition to basic features as low transparency gain, effective thermal dissipation, and large mode lateral confinement, a highly flat and smooth dielectric surface is usually required for attaining spasing action. Root-mean-square (RMS) roughness values ranging from a few nm down to the sub-nanometer scale are usually desirable for achieving a significant low lasing threshold.[351,352] This has called for the use of epitaxial growth techniques like atomic layer deposition (ALD)[353] and molecular beam epitaxy (MBE)[354,355] for growing highly crystalline and ultra-smooth plasmonic substrates, to minimize the scattering losses occurring at the surface corrugations.[356]

A different approach for improving the performances in plasmonic hybrid nanolasers has followed after the idea of a semiconductor nanowire—graphene–insulator–metal (GIM) structure,[357] as shown in Figure 28a. Two hybrid structures were realized by transferring a CVD-grown graphene layer on top of an Al2O3/Ag and an Al2O3/Al templates. Notably, they observed a contrasting behavior of the lasing properties of the nanolasers placed onto the two templates, according to the change in the electron density at the metal surface due to the Fermi level differences, as sketched in Figure 28b.

For Al, which has a smaller work function than graphene, the upward band bending at the metal/insulator interface resulted into an increase of the electron density in the metal. Hence, a blueshift of the SP frequency could be observed along with an overall reduction of 50% of the lasing threshold compared to the case without graphene, with a simultaneous two-fold increase in the SPP propagation length. Conversely for Ag, owing to the downward band bending, a decreased carrier density led to a red-shift of the SP frequency in Al, resulting in a highly dispersive SPP mode dominated by internal losses and, thus, a larger threshold compared to the case of the graphene-free template.

The realization of such hybrid platforms has paved the way to the electrical modulation of a plasmonic nanolaser.[358,359] Upon application of an external current to the graphene layer, nonreciprocal SPP waves could be generated at the interface with the metal, thus, enabling the propagation in one given direction upon breaking of the Lorentz reciprocity. This resulted in a typical Doppler shift of the hybrid mode to higher frequencies with the NW aligned parallel to the current direction. Additionally, this also led to an increase of the lasing threshold of nearly 100%. Since the Doppler shift is given by the scalar product of the SPP wavevector and the electron drift velocity, the efficiency of the lasing modulation, thus, depends on the orientation of the nanowire with respect to the direction of the applied field. Indeed, larger shut-off currents were found to occur when increasing the NW angle from 0° up to 90°,[359] as shown in 28c. Lastly, a room-temperature modulation was also attained.[359]

Recently, transition metal dicalchogenides (TMDs) have also gained a gigantic attention due to their outstanding

![Figure 27](image_url)

**Figure 27.** a) Schematic of the geometry and the emission of a ZnO nanowire-based spaser, optically excited with two time-delayed pump pulses. The inset shows a picture of a lasing plasmonic nanowire on the LiF (10 nm)/Ag (100 nm) substrate. b) Calculations of the effective index as a function of the NW diameter at \( \lambda = 385 \) nm for various modes, with the absolute electric field profile for the two hybrid plasmonic modes HSP1 and HSP2. c) Comparison of the measured emission spectra near twice the threshold and corresponding lasing curves (in the inset) from a selected plasmonic nanowire with a diameter of around 150 nm and a thicker (≈ 250 nm) photonic nanowire on a quartz substrate. The emission is separated into components with polarization along the nanowire axis (solid curves) and with polarization perpendicular to the nanowire axis (dashed curves). Reproduced with permission.[378] Copyright 2014, Springer Nature.
optoelectronic properties, which have made them promising alternatives to graphene. Therefore, owing to their direct bandgap, high carrier mobilities and large optical absorption in the VIS, the coupling with semiconductor gain media has proven to foster the exploitation of synergic effects arising from each constituent of the hybrid structure. For instance, Kim et al. have explored the possibilities of coupling a single TiO$_2$ NW with different plasmonic templates hybridized with a MoS$_2$ monolayer (ML), to further minimize the quenching of the ML emission, arising from the direct contact with the metal, as well as to enhance the field localization at the interface between the NW and the TMD ML. Following the configuration developed in ref. 360, they embedded a TiO$_2$ NW in the nanogap inside an Ag film and overlaid a CVD-grown MoS$_2$ ML on top, as shown in Figure 29a. Thereby, they achieved, upon resonant optical excitation, a nearly 50-fold enhancement for the ML emission near the TiO$_2$ NW (ON-NW) compared to that collected far away from the gap (OFF-NW). This was attributed to a Purcell enhancement induced by the formation of a pair of LSPs at the orthographic edge of the Ag film and the gap between the TiO$_2$ NW and the metal film, as evidenced in Figure 29a. Based on these findings,
they additionally realized a hybrid structure—shown in Figure 29b in which a TiO$_2$ NW ($d \approx 100$ nm) was placed on top of a MoS$_2$ ML, deposited on a plasmonic substrate composed of a 10 nm SiO$_2$ spacer and a 100-nm Ag film, to combine the photonic scattering from the NW and the plasmonic localization within the spacer for enhancing the MoS$_2$ photoluminescence emission. As a result, they attained an enhancement factor $EF \approx 22$ for the ON-NW case (estimated with respect to the OFF-NW one), related to an increased absorption of the ML induced by field localization, and an enhanced photoluminescence emission arising from radiative decays promoted by the Purcell effect.$^{[362]}$

Semiconductor nanowires have also been coupled to patterned plasmonic substrates, to modify the SPP dispersion and the properties of the corresponding hybrid modes. One of the earliest attempts in this direction was made by Bermúdez-Ureña et al., who successfully coupled core–shell–cap GaAs/AlGaAs/GaAs NWs with V-groove (VG) plasmonic waveguides lithographically designed and fabricated on a Au substrate,$^{[363]}$ thus, enabling on-chip routing of coherent and sub-diffraction confined light at room temperature. Such NW-VG hybrid system, which is schematically shown in Figure 30a, has proven to support the so-called channel plasmon polariton (CPP) modes$^{[364,365]}$ characterizing the lasing emission of the device. As a result, they have proven that the VG provides a twofold coupling route for the SPPs, which are not out-coupled directly into free space at the NW end facets. When the NW is placed alongside the VG, the SPPs supported by the Au film/air interface can possibly out-scatter from the VG edges, while when the NW is centered inside the VG, the SPPs are capable of launching CPP modes which eventually out-scatter at the VG ends. As evidenced in Figure 30b such modes are also clearly distinguishable from the others, owing to a strong anisotropy in the transversal polarization contributions at the VG ends as shown in Figure 30a. Following the idea that the structuring of the metal layer in a typical SIM structure could lead to the exploitation of more exotic plasmon resonances, Chou and coworkers demonstrated the realization of a hybrid platform capable of supporting pseudowedge plasmon polaritons, building up at the intersections in between a ZnO NW cavity and a subwavelength Ag grating coated with a nanometric Al$_2$O$_3$ spacer,$^{[366]}$ as shown in 30c. They found that the lasing emission was stable in a temperature range from 77 up to 220 K (with a corresponding redshift of the hybrid mode with increasing temperature) and was driven by the formation of hybrid modes confined at the grating notches, exhibiting a characteristic polarization perpendicular to the grating axis, regardless the orientation of the overlaying NW. Moreover, theoretical calculations showed that the mode confinement supported by a pseudowedge SPP could be two orders of magnitude larger than that of the planar counterpart. As a consequence, this could also lead to an enhancement of the

---

**Figure 30.** a) Schematic of a hybrid nanowire/V-groove platform for an on-chip nanolaser source and corresponding EMCCD images the NW-VG device—shown in the SEM image—in the lasing regime. The collection is accomplished from the VG ends and NW end facets for a polarization parallel (magenta) and transversal (orange) to the VG axis. b) Normalized emission spectra for a NW placed onto a Au film (top) and for the same NW positioned inside the VG (bottom), below (blue-sky) and above (orange) the lasing threshold. In the right panel are the corresponding EMCCD images and illustrations for the NW excited above the lasing condition under transversal polarization collection (white arrow), showing interference fringes characteristic of lasing emission. Adapted with permission.$^{[363]}$ Copyright 2017, American Chemical Society. c) Schematic of a ZnO nanowire lying on a Ag grating covered with a 3-nm thick Al$_2$O$_3$ layer, where the stimulated emission is scattered from the boundaries of the pseudowedge SPP cavity, as shown in the FDTD-calculated mode profile for a NW placed at 50$\degree$ with respect to the grating notch. Adapted with permission.$^{[366]}$ Copyright 2018, American Chemical Society. d) Schematic diagram of the plasmonic nanolaser with one open-nanotrench defect emission under optical pumping: the cavity length $L$ is 130 nm and the defect depth $h_c$ is 100 nm. Adapted with permission.$^{[367]}$ Copyright 2018, American Chemical Society.
spontaneous emission factor and to an acceleration of the carrier dynamics supported by the Purcell effect. Along the lines of these findings, Cheng et al.\cite{368} theoretically demonstrated the suitability of such kind of patterned hybrid plasmonic structure also for sensing applications. They realized a nanotrench defect cavity, sketched in Figure 30d, into an Al grating with an orthogonally overlaid ZnO NW on top, which exhibited superior spasing performances compared to the planar counterpart. They first fabricated an extended defect-free DBR-like metal grating, whose geometrical parameters had been beforehand optimized by numerically solving the Bloch modes. By maximizing the band gap of TM-like guided modes and accordingly shifting the gap center toward the target resonance wavelength $\lambda_0 = 373$ nm, they were able to prove a 10-fold enhancement of the reflectivity ensured by the DBR, compared to that provided by the NW end facets on the planar structure, found to be $R \approx 8.1\%$. Furthermore, they engineered via numerical simulations the design of the defect cavity with a characteristic length $L = 118$ nm, capable of sustaining a hybrid plasmonic mode at $\lambda_0$, with a mode volume as small as $5.75 \cdot 10^{-4}$ $\lambda_0^{-3}$ and a threshold gain as low as $3.40 \cdot 10^4$ cm$^{-1}$. Experimentally, they demonstrated single-mode lasing at $77$ K from a hybrid plasmonic cavity featuring a 0.9-m-long ZnO NW overlaid on a grating with an elongated defect length $L = 130$ nm. Ultimately, they compared the sensing performances of both the unetched and etched defect cavities, by simulating the refractive index change of the hybrid mode induced by an analyte (in this case glucose). They found that for a geometrically optimized nanocavity in contact with the surrounding medium (glucose), a resonant mode could be effectively supported by both geometries. Nonetheless, the etched cavity exhibited improved performances in terms of resolution and sensitivity, with an overall increase of nearly 20% compared to the unetched counterpart.

In conclusion to this section, it is worth noting that, in addition to the development of the aforementioned hybrid platforms, further implementations can be realized when considering a different coupling scheme other than a planar SIM geometry. For instance, back in 2009, Guo and coworkers\cite{368} pioneered the exploitation of semiconductor-metal coupling in NW-based structures by fabricating hybrid nanophotonic components, including polarization splitters, Mach–Zehnder interferometers, and microring cavities, by making use of coupled Ag and ZnO nanowires. Photon–plasmon coupling efficiency up to 80% with a coupling length down to 200 nm was achieved between individual Ag and ZnO nanowires, with a Q-factor as large as 520 for the hybrid NW microcavity. Moving from these findings, Wu et al. realized a hybrid photonic-plasmonic nanolaser featuring spatially-separated plasmon cavity modes.\cite{369} Namely, an ultra-long, 400-nm-thick CdSe NW was placed on a MgF$_2$ substrate and brought, via nanomanipulation, in close proximity to a 100-nm-thick Ag NW, which, upon bending, formed an X-shaped hybrid cavity. By optically exciting part of

---

**Table 7. Summary of the lasing performances of planar and patterned SIM, S-M, and GIM hybrid platforms.**

| System [Ref.] | Pumping conditions | Emission wavelength | Lasing threshold |
|---------------|-------------------|-------------------|-----------------|
| Planar Structures: Semiconductor-Insulator-Metal (SIM), Semiconductor-Metal (S-M), Graphene-Insulator-Metal (GIM) | | | |
| CdS NW on (5 nm) MgF$_2$/Ag (SIM)\cite{373} | $\lambda_{exc} = 405$ nm, $f_{rep} = 80$ MHz, $\tau_p = 100$ fs | 489 nm (multimode) @ T < 10 K | 10–60 MW cm$^{-2}$ @ T < 10 K |
| ZnO NW on (10 nm) LiF/Ag (SIM)\cite{377} | $\lambda_{exc} = 355$ nm, $f_{rep} = 800$ kHz, $\tau_p = 150$ fs | 370–385 nm (multimode) @ RT | 0.33–1.53 GW cm$^{-2}$ @ RT |
| GaN NW on (5 nm) SiO$_2$/Ag (SIM)\cite{346} | $\lambda_{exc} = 355$ nm, $f_{rep} = 100$ kHz, $\tau_p = 10$ ns | 370 nm (single-mode) @ RT | 3.5 MW cm$^{-2}$ @ RT |
| ZnO NW on (5 nm) Al (SIM)\cite{347} | $\lambda_{exc} = 355$ nm, $f_{rep} = 1$ kHz, $\tau_p = 0.5$ ns | 372 nm @ 77 K, 378 nm @ RT (single-mode) | 16 MW cm$^{-2}$ @ 77 K, 105 MW cm$^{-2}$ @ RT |
| CH$_3$NH$_3$PbI$_3$ NW on (10 nm) MgF$_2$/Ag (SIM)\cite{350} | $\lambda_{exc} = 400$ nm, $f_{rep} = 1$ kHz, $\tau_p = 120$ fs | 768–797 nm (single-mode) @ RT | 13.5–56.3 J cm$^{-2}$ @ RT |
| ZnO NW on (5 nm) Al$_2$O$_3$/Al (SIM)\cite{333} | $\lambda_{exc} = 355$ nm, pulsed | 378-380 nm (multimode) @ RT | 6.27 MW cm$^{-2}$ @ RT |
| ZnO NW on (3.6 nm) WO$_3$/Al (SIM)\cite{333} | $\lambda_{exc} = 355$ nm, $f_{rep} = 1$ kHz, $\tau_p = 2$ ns | 379 nm (single-mode) @ RT | 0.79 MW cm$^{-2}$ @ RT |
| ZnO NW on graphene ML (2.5 nm) Al$_2$O$_3$/Al (GIM)\cite{357} | $\lambda_{exc} = 355$ nm, $f_{rep} = 1$ kHz, $\tau_p < 0.5$ ns | 372 nm (single-mode) @ RT | 18.5 MW cm$^{-2}$ @ 77 K, 112 MW cm$^{-2}$ @ RT |

**Patterned Structures: V-groove (VG), Grating-like (GL)**

| Core-shell–cap GaAs/AlGaAs/GaAs on Au (VG S-M)\cite{345} | $\lambda_{exc} = 730$ nm, $f_{rep} = 80$ MHz, $\tau_p = 200$ fs | 868 & 875 nm (multimode) @ RT | 7 GW cm$^{-2}$ @ RT |
| ZnO NW on (3 nm) Al$_2$O$_3$/Ag (GL SIM)\cite{366} | $\lambda_{exc} = 355$ nm, $f_{rep} = 1$ kHz, $\tau_p = 0.5$ ns | 372 nm @ 77 K, 376 nm @ 220 K (single-mode) | 50 MW cm$^{-2}$ @ 77 K, 700 MW cm$^{-2}$ @ 220 K |
| ZnO NW on Ag (GL S-M)\cite{367} | $\lambda_{exc} = 355$ nm, $f_{rep} = 1$ kHz, $\tau_p = 0.5$ ns | 373 nm @ RT (single-mode) | 90 MW cm$^{-2}$ @ RT |
the CdSe nanowire, the longitudinal photonic modes could propagate to the coupling point and excite the SPP waves in the silver nanowire. The spatial separation between plasmonic and photonic emission could be achieved at the output facets, thus, providing a highly confined excitation source and enabling ultrafast modulation of the plasmonic mode. Photonic-plasmonic coupling in the near field, could also be suitably engineered for tailoring the nonlinear optical response of an individual GaAs NW. When coupling the NW with an ordered array of Au dimer nanoantennas (NAs), the SH signal from the semiconductor could be enhanced by more than twice with an optimum NW-NA feed-gap distance optimization (down to d = 90 nm), owing to a large electric field enhancement arising from the coupling of the incoming photons with the SPs of the metallic nanoantennas. Ultimately, it is also worth mentioning that many advances have been accomplished, especially over the last few years, in the investigation and exploitation of plasmonic (or photonic) coupling in metallic or dielectric nanowires in combination with dielectric NPs, for transfer-energy mediated enhancement of fluorescence or modulation of the nonlinear optical properties.

In Table 7, a summary of the lasing performances of planar and patterned SIM, S-M, and GIM hybrid platforms can be found.

6. Conclusions

The interaction of electromagnetic radiation with metallic NPs has been a vastly investigated research topic in the last years. The strong near-field enhancement and large field confinement in the surroundings of metallic NPs make them attractive for many different applications, like SERS, sensing, absorption enhancement, or increasing the spontaneous decay rate of quantum emitters. However, their applicability is limited due to the inherent ohmic losses suffered by metallic nanostructures (Joule effect). On the contrary, HRID NPs present negligible losses in certain spectral regions (VIS and NIR). This fact makes dielectric nanostructures with high refractive index a good alternative to the metallic ones. In addition, to the low losses, HRID materials can provide magnetic effects but also gain. The interference between electric and magnetic modes confer these nanostructures interesting directionality properties. However, the electromagnetic energy enhancement is small compared to that attained with metallic nanostructures. Another disadvantage is that the energy is mainly confined inside the nanostructure, making difficult their use in sensing or surface enhanced Raman spectroscopy. The combination of metal and HRID nanostructures forming hybrids, can profit of the advantages of each one of the bare components. Strong near-field enhancement and large field confinement of metallic nanostructures as well as the directionality and gain properties of the dielectric ones. This makes metal-dielectric hybrids interesting electromagnetic systems in different applications. In this review, we focused on the state of the art of hybrid metal-dielectric nanostructures as photonic components in sensing, surface enhanced Raman spectroscopy, absorption enhancement, fluorescence enhancement, QD emission, nonlinear effects, and lasing. We mainly paid attention to the most recent works in this field to avoid repetitions with a previous review about hybrid nanophotonics published by Lepeshov et al. in 2019. We carried out a systematic analysis of the contribution of different kinds of geometries (metal NP-dielectric NP, metallo-dielectric core-shell NPs, metallic/dielectric NPs on a dielectric/metallic substrate, metallic NPs on dielectric microcavities or photonic crystals, hybrid plasmonic-waveguide structures, and metasurfaces) for each of the investigated applications. The superior performances of metal-dielectric nanostructures compared to bare metallic or dielectric ones have been evidenced for the described uses. Additionally, we highlighted some of the most recent advances in the field of hybrid semiconductor nanowire-based plasmonic structures, with a particular focus on those featuring a typical SIM platform and showed how the exploitation and further implementation of planar hybrid SIM structures can enable subwavelength confinement of the hybrid modes in selected active areas, large field enhancement in the plasmonic coupling regions and a consistent acceleration of the lasing dynamics.

Acknowledgements

One of the authors (A.B.) acknowledges financial support by the Alexander von Humboldt Foundation. The authors further acknowledge support by the collaborative research center (CRC 1375) “NOA—Nonlinear Optics down to Atomic scales” financed by the Deutsche Forschungsgemeinschaft (DFG), projects B2 and C5.

Conflict of Interest

The authors declare no conflict of interest.

Keywords
dielectric materials, hybrid metal-dielectrics, lasers, nanoparticles, plasmonics, semiconductors, spasers

Published online: January 17, 2022

Received: September 15, 2021
Revised: October 28, 2021

© 2021 The Authors. Advanced Photonics Research published by Wiley-VCH GmbH
Ángela I. Barreda Gómez received the physics degree in 2013, the M.Sc. degree in physics, instrumentation, and environment in 2014 and the Ph.D. degree in 2019 in the University of Cantabria, Spain. She worked as a postdoctoral researcher in a European Project in the group of Prof. Martinez at Polytechnic University of Valencia. Currently she is a postdoctoral Humboldt fellow researcher in the group of Prof. Staude in Friedrich Schiller University Jena. Her research interests focus on optics and photonics and computational nanooptics.

Francesco Vitale received the B.Sc. in materials science in 2016 and the M.Sc. in materials science and technology in 2019 from the University of Rome Tor Vergata (Italy), together with a M.Eng. title within a double-degree program in collaboration with the Technische Hochschule Wildau (Germany). Currently, he is a Ph.D. student within the group of Prof. Ronning at the Institute of Solid State Physics of Friedrich Schiller University Jena, and his research interests focus on the realization and optical investigation of semiconductor nanowire-based hybrid plasmonic nanolasers.
Alexander E. Minovich studied physics at the Belarusian State University. He received his Ph.D. degree in physics in 2010 from the Australian State University, Canberra. He worked as a research fellow at the Australian State University, as an International Newton Fellow in King's College London, UK, and as a senior research scientist in Eureka Aerospace, Inc., CA, USA. Currently he is a research fellow in the group of Prof. Staude in Friedrich Schiller University Jena, Germany. His research interests focus on optics and photonics and metasurface structures.

Carsten Ronning is chair professor at the Institute of Solid State Physics at the Friedrich Schiller University Jena, Germany. He studied physics at the Universities of Bremen and Konstanz, and completed his Ph.D. thesis on the growth of diamond-like materials in 1996. After holding a postdoctoral position at the North-Carolina State University (USA), he performed intense research at the University of Göttingen on thin films, semiconductor physics as well as on semiconductor nanowires with a strong background in ion–solid interactions. Today at the University of Jena, his research concentrates also on the optical properties of nano-scaled solids.

Isabelle Staude is professor at the Institute of Solid State Physics at the Friedrich Schiller University Jena, Germany. She studied physics at the University of Konstanz, Germany, received her Ph.D. degree from the Karlsruhe Institute of Technology, Germany, in 2011, and spent several years as a postdoc at the Australian National University, Canberra, Australia. She received an Emmy-Noether Grant from the German Research Foundation, the Hertha Sponer Prize 2017 from the German Physical Society and she is a member of the German Young Academy (Junge Akademie).