Reusable Biosensor Based on Differential Phase Detection at the Point of Darkness

Shilpa Samdani, Abhinav Kala, Rishabh Kaurav, Sruthi Kaladharan, and Venu Gopal Achanta*

A differential phase sensor based on a narrowband perfect absorber uses the phase singularity at the point of darkness (100% absorption). Herein, a structure with a top SiO₂ layer is proposed that is index matched with a glass flow cell that shows the point of darkness for both s- and p-polarizations. Detailed numerical results to optimize the structure, study the role of fluctuation in thickness and roughness of the analyte layer show that the proposed structure has a refractive index sensitivity of 147.3 RIU⁻¹. Experimental results of launches angle independent >99.9% absorption in the 45°–73° range are reported, with the highest reported till date quality factor in planar narrowband absorbers of ≈42, and high figure of merit of 556 for p-polarization. The structure also exhibits the generalized Brewster effect with a perfect absorption (>99.99%) for s-polarization at ≈74° angle. Experimental results are presented to demonstrate the sensor operation for two different biomolecules at the p-polarization resonance. The configuration presented is ideal for reusable and cost-effective biosensors.

1. Introduction

Sensors that detect the change in refractive index, thickness, concentration, or type of molecule are important for physical, chemical, biomedical, and various engineering applications. Plasmonic sensors use either the shift in resonance for a given launch angle or the resonant angle shift for a given wavelength in the Kretschmann geometry, differential phase measurements in Kretschmann, and interferometer configurations among others for high-sensitive detection.[1–5] Plasmonic metamaterial-based perfect absorbers have been demonstrated in structures having perfect impedance matching with free space and by making use of high loss guided modes.[6–9] Due to near unity absorption in the ultrathin absorbing layer, perfect absorber metamaterials gained prominence, and are demonstrated for light absorption, spatial and spectral modulation of light, thermal emission, and detection as well as refractive index sensing of gases and liquids.[10–20] Perfect absorber structures are either broadband or narrowband depending on their absorption bandwidth.[21,22] While broadband perfect absorbers are studied to improve solar energy harvesting, perfect narrowband absorbers are demonstrated for optical sensing, modulation, and thermal emission tailoring applications. Approaches based on metasurfaces, photonic crystals, and plasmonic nanostructures require high precision and expensive lithography which limits their large-scale implementation. Thus, research on structural coloration based on planar films is gaining prominence due to the simple and inexpensive design, and fabrication of the structures. Perfect absorption in planar multilayer structures has been demonstrated in metal-dielectric–metal (MDM), i.e., Fabry–Perot cavity configurations.[23,24] Alternatively, perfect absorption has also been demonstrated by depositing a lossy dielectric (Ge, a-Si) on metallic substrates with finite conductivity.[25,26] The strong–light matter interaction arising due to the nontrivial (non-0 and non-π) reflection phase shift and high absorption coefficient of the lossy dielectric causes near-perfect absorption in ultrathin lossy materials. It was shown that coupling of Fabry–Perot cavity resonance to the Brewster modes supported by the ultrathin semiconductor thin films (such as Si, Ge, GaAs, etc.) deposited on optically opaque metallic films resulted in the observed perfect absorption and an angle independent absorption of >80%.[27]

Narrow absorption bandwidth (full width at half maximum, FWHM of resonance) is an important parameter for sensing, and there is further scope to design structures with sharp resonances. The sensor performance is quantified by the figure of merit (FOM) given as the ratio of sensitivity to FWHM, where sensitivity is the ratio of change in wavelength/phase/intensity to the change in refractive index.[28] Thus, a narrow bandwidth is beneficial for higher FOM applications like color filters and sensors. By decreasing losses in the ultrathin film and adding a top thin layer of low loss metal that enhances the reflectance at the top interface, the bandwidth can be lowered.[28,29] Further
practical applications of narrow-band perfect absorbers require the absorbers to be angle insensitive. Angle invariant resonance response of planar absorbers incorporating ultrathin lossy dielectric layer in Fabry–Perot configurations\(^\text{[30–32]}\) and with lossless dielectric overlay over MDM cavities have been explored\(^\text{[31,34]}\). Though perfect absorbers with narrow-band response have been reported, so far, a structure showing simultaneous perfect narrowband absorption, angle insensitivity, and wavelength tunability in structural color due to planar multilayer structure has not been demonstrated. Such properties are essential for high-purity structural color filter and sensing applications\(^\text{[35]}\).

Phase interrogation biosensing is based on detecting the change in phase with and without the analyte. This technique is shown to be more sensitive than tracking changes in amplitude or resonance wavelength\(^\text{[19]}\). Tracking the rapid phase flip at zero reflection for biosensing was first studied in surface plasmon resonance (SPR) sensors based on ellipsometry\(^\text{[12]}\), interferometry\(^\text{[36]}\), and other setups\(^\text{[37]}\).

In a simple layered structure, it has been shown that the sharp phase jumps associated with the point of darkness could be used for femtomolar (fm)-level sensitivity in biomolecule detection\(^\text{[20]}\). A very thin layer of low molecular weight, biotin, is put on top of the metal layer to attach Streptavidin molecules. In this technique, from the Fresnel reflection coefficients for the s- \((r_\text{s} = |r_\text{s}|ei\phi_\text{s})\) and p- \((r_\text{p} = |r_\text{p}|ei\phi_\text{p})\) polarized lights, the ellipsometric parameters, \(\Psi = \tan^{-1}\left(\frac{r_\text{p}}{r_\text{s}}\right)\) and the phase difference \(\Delta = \phi_\text{s} - \phi_\text{p}\) are estimated and \(\Delta\) is used as the sensing parameter near the wavelength corresponding to the point of darkness for p-polarization. The FOM of such a sensor is defined as the ratio of differential phase \(\delta\Delta\) and differential amplitude \(\delta\Psi\) measured with and without the analyte. Thus, FOM would be larger for structures showing larger phase change and smaller amplitude change in the presence of the analyte. When the change in reflectivity for s-polarized light is negligible at the p-resonance, then FOM \(\approx 1/\Psi_\text{min}\) where \(\Psi_\text{min}\) is the value of \(\Psi\) at the p-reflectivity minimum\(^\text{[12]}\).

In this work, we present design details as well as experimentally demonstrate a metal–dielectric–dielectric–metal–dielectric (MDDMD) structure having an ultrathin semiconducting absorbing layer (Si) with the highest reported quality factor \((Q)\) of \(\approx 42\) (FWHM \(\approx 19\) nm). We demonstrate the biosensing application of the designed multilayer stack by tracking the phase change at resonance. A FOM of 556 and refractive index sensitivity of 147.3\,RIU\(^{-1}\) are experimentally measured for two different biomolecules. Angle-insensitive super-absorption \((\Delta > 95\%)\) for both p- and s-polarizations in the 0\(^\circ\)–80\(^\circ\) range as well as the observation of generalized Brewster effect (GBE) at 74\(^\circ\) are presented. Perfect absorption is achieved for p-polarization in the 40\(^\circ\)–73\(^\circ\) incident angle range on account of the optimal design of the structure. A good match between experimental and simulation results has been observed.

2. Differential Phase Sensor Design and Response

3D Finite difference time domain (FDTD) simulations are carried out using commercial FDTD solver—FDTD Solutions by Lumerical Inc\(^\text{[38]}\). The details are presented in Section 6. The schematic of the optimized asymmetric Fabry–Perot cavity structure is shown in Figure 1a. The sensor is a multilayered stack.
over a silicon (Si) substrate. It has an optically thick, 135 nm bottom gold layer, and a semitransparent 35 nm top gold layer with 230 nm-thick silicon dioxide (SiO$_2$) and a 10 nm absorbing silicon (Si) layer in between. Another 200 nm-thick top SiO$_2$ layer is introduced to integrate a flow cell or microfluidic pattern to the sensor. The top SiO$_2$ layer has several advantages. It prevents the cavity surface from oxidation (in the case of metals like Ag) and against physical or chemical wear/ing. It acts as a transparent anti-reflection layer (compared with the air–metal interface). Higher optical admittance is achieved as seen from the simulated absorption spectrum of p-polarization with SiO$_2$ and Au as the top layers in the multilayer stack Figure S1, Supporting Information. The presence of SiO$_2$ layer increases the absorption by $\approx$10%, enabling perfect absorption for p-polarization and more than 95% absorption of s-polarization. The resonance is also much sharper than without the SiO$_2$ layer. A higher optical admittance was observed for the MDM cavity due to TiO$_2$ overlay earlier.$^{[33]}$ One may also integrate a microfluidic geometry by patterning the top layer by laser writing.

The ellipsometric parameters, $\Psi$ and $\delta$, for the multilayer stack calculated from the simulated reflectance results, are shown in Figure 1b, at 50.3$^\circ$ angle of incidence. The perfect absorption is seen as a dip in $\Psi$ at 802 nm for p-polarized light and as a peak at 748 nm for s-polarized light. The singularity in the phase ($\delta$) observed at these resonances is used as the sensing parameter. The localization of field in different layers is seen in the cross-sectional view of the electric field intensity profile at the p- and s-resonance wavelengths as shown in Figure 1c,d, respectively. Maximum electric field trapping occurs within the middle SiO$_2$ layer for optimum thicknesses of the top Au and SiO$_2$ layers. The penetration of the field into the Au layer and the presence of absorbing ultrathin Si layer lead to the nontrivial reflection phase shift at the dielectric–metal interface that enables the interfering waves to be out-of-phase.$^{[30]}$ The layered structure is prepared by radio frequency (RF) magnetron sputtering on silicon substrate (details in Section 6). The samples were studied by variable angle spectroscopic ellipsometer (Woollam M-2000 XI). The measured reflectance spectra are shown in Figure 2a, and the ellipsometric parameters for the multilayer stack in Figure 2b. The $\Delta\delta$ is $\approx$272.39$^\circ$ and $\Psi_{\text{min}}$ is $\approx$0.1$^\circ$ ($\approx$1.8 mrad) corresponding to a FOM of 556.

Figure 3 shows the reflectance spectra for the p-polarization in the presence and absence of the Si layer. The presence of Si red shifts the resonance and reduces the reflectance minima to 1.4% from 1.4% due to absorption. Consequently, the $\Psi_{\text{min}}$ value reduces by fivefold when the Si layer is included. Negligible

![Figure 2](image-url)  
**Figure 2.** a) The measured reflection spectra for p- (in black) and s- (in red) polarized light incidence are shown for 48$^\circ$ incidence angle. The two resonances corresponding to the point of darkness matched well with the calculations. b) The measured ellipsometric parameters, $\Psi$ (in black) and $\delta$ (in blue) of the multilayer MDDMD stack are shown.

![Figure 3](image-url)  
**Figure 3.** a) Calculated reflectivity spectra and b) corresponding ellipsometric phase for p-polarized incident light with and without the Si absorbing layer in the structure. The presence of Si layer is essential to attain the point of darkness and phase singularity.
propagation phase shift in ultrathin Si layer and nontrivial reflection phase shift from the Si-bottom Au interface gives rise to the singular phase at the resonance.

As the bottom Au layer is optically opaque, the absorbance ($A$) is, $A = 1 - R$, where $R$ is reflectance. Different layers in the multilayer stack are optimized to minimize the reflectance. As one would expect, the thickness of the top Au layer introduces a trade-off between the resonance bandwidth ($Q$-factor of the cavity) and the light throughput into the structure.[31,39] The semi-transparent, 35 nm thick, top Au-layer is optically transparent while also efficient in trapping light within the cavity.

We studied the angle-resolved absorption spectra of the multilayer stack. Simulations show that more than 95% of the p-polarized light is absorbed for all angles in the range of 0°–70° and more than 99% absorption is obtained for incident angles in the range of 40°–70° (Figure 4a,c). This is confirmed by spectroscopic ellipsometry measurements which showed more than 99% absorption for angles in the range of 45°–75° (Figure 4b,d) (measurement angle range limited by the instrument). The $Q$-factor of the structure is ≈42 at a resonance wavelength of 812 nm at 48° incidence angle for p-polarization. Though bandwidth of the resonance does not vary significantly with the angle of incidence, the blue-shift of the resonance with angle (seen from Figure 4) decreases the $Q$-factor for increasing angles of incidence. Figure S2, Supporting Information, shows the FDTD simulation results of the reflection spectrum for p- and s-polarization over a broad range of incidence angles.

To understand the angle independent nature, one may note that in the MDM cavities, the constant differential phase shift within the cavity at all incidence angles accounts for the angle insensitivity. By studying the reflection phase shift at each interface in the MDM cavity, it was found that the angle insensitivity arises because of the compensation of the reflection phase shift from the metal–dielectric layers and propagation phase shift within the cavity spacer layer.[39] In the MDM cavities integrated with dielectric overlay/spacer layer—Ag/TiO$_2$/Ag, the TiO$_2$ acts as a phase compensator countering the phase shift arising within the cavity. This was shown to account for the angle-insensitive absorption with a high $Q$-factor of ≈33.[13] Even in the case of an ultrathin semiconductor layer deposited on a highly reflecting metal layer—Ge/Ag, Gires-Tournois etalon, the phase shift at each interface remains constant for a wide range of incident angles on account of the large refractive index contrast between air and Ge.[27] In addition, a near-unity absorption of ≈98% is observed in this bilayer due to the negligible phase shift within the ultrathin layer and the nontrivial reflection phase shift from the metal–dielectric interface that results in destructive interference. It is also important to note that the high absorption in the dielectric is essential to observe near-unity absorption in such structures.[25,27]

The simulated and measured absorbance for p- and s-polarizations as well as second-order s- resonance are shown in Figure 5a. We experimentally observed the GBE effect at 74° angle of incidence, as the second-order s- or transverse electric (TE) mode shows perfect absorption, with ≈99.99% of incident light absorbed. This can be attributed to the presence of the transparent dielectric layer (SiO$_2$) on an absorbing substrate (in our case a multilayer stack).[49] The peak in the ellipsometric $\psi$ plot further confirms the observation of generalized Brewster effect. Zero-reflection of the s-polarization is manifested as a peak in the $\psi$ spectrum, approaching the value of 90°. As shown in Figure 5b, $\psi$ reaches a maximum of ≈89°. It is observed that the singular phase is obtained at the generalized Brewster angle and the phase change is ≈152° (Figure 5b). The observation of the singular phase also confirms the perfect absorption of s-polarized incident light.[12] Due to the ultrathin Si layer in

![Figure 4](https://先进光子学研究/2000147 (4 of 9) © 2021 The Authors. Advanced Photonics Research published by Wiley-VCH GmbH)
the cavity, the interfering waves acquire an abrupt nontrivial phase change upon reflection (from the reflecting interface below the Si layer) and destructively interfere. This so obtained singular phase has applications in high precision metrology and sensing. Singular phase accompanying the GBE has been demonstrated in the TiO2 (60 nm)/Ni(100 nm) system and used for hydrogen gas sensing with graphene deposited on top. While the resonance position of the mode exhibiting GBE can be tuned by changing the thickness of the top spacer layer, from simulations, we observe that the resonance can be tuned by changing the middle spacer layer thickness as well. Similar to our structure, the effect of spectral tunability of the resonance mode with the spacer thickness has been observed in Ag/SiO2/Ag asymmetric Fabry–Perot cavity.

3. Biosensor Performance

From simulations, FOM for the sensor is estimated to be $109$ for $\Psi_{\text{min}}$ value of 0.0092 radians (Figure 1b), whereas experimentally we obtained a FOM of 556 for $\Psi_{\text{min}}$ of 0.0018 radians (Figure 2b). To get a better estimate from simulations, a finer than 0.2° launch angle step needs to be considered. For sensing application, a higher-order cavity mode with stronger field confinement near the boundaries (and therefore in the Si layer) will lead to more absorption and the absorber layer will have a more prominent role in the sensing application. One such example is provided in the Section S1 and Figure S3 and S4, supporting information. Next, the effect of the biomolecules on the ellipsometric parameters was studied by adding a dielectric (analyte) layer over the top SiO2 layer. Figure 6a,b shows the simulation results for the incidence angle of 48°. For analyte thickness variation between 10 and 60 nm, no shift in the resonance wavelength was observed but the $\Psi_{\text{min}}$ monotonically increased from $1.69^\circ$ to $4.75^\circ$ with the increasing thickness (inset of Figure 6a). In contrast, the ellipsometric phase $\delta$ at the resonance increased by more than $22^\circ$ as the film thickness was increased (inset of Figure 6b).

To simulate the effect of nonuniform biomolecule film thickness, two different simulation studies were done. First, the roughness of the top layer was varied for the fixed average thickness to compare different molecular concentrations of the solution. And second, for the fixed thickness and roughness of the film, the surface profile was varied by changing the seed of the random number generator used to create the rough surface in the FDTD Solutions by Lumerical Inc. (details in Section 6). This would help see how much variation in the measurements one might expect to see at different locations on a particular sample. A 100 nm-thick dielectric layer with a refractive index of 1.33 (close to that of the biomolecules used in the experiment)
was placed on top of the stack and its root mean square (RMS) roughness was varied from 10 to 60 nm. The location of $\Psi_{\text{min}}$ did not change for any of the films (Figure 7a), but $\Psi_{\text{min}}$ itself varied from 4.7° to 3.8° as the roughness was increased (inset Figure 7a). In contrast, the phase $\delta$ at the resonance wavelength 806 nm showed a monotonic increase of around 14° with the roughness (Figure 7b and its inset).

For surface profile variation, the dielectric layer with a fixed average thickness of 100 nm and an average roughness of 30 nm was used. The location of resonance did not shift for any of the four different simulated surface profiles and the maximum variation in the $\Psi_{\text{min}}$ was $\approx 0.1°$ (Figure 7c). The $\delta$ at the resonance had fluctuations of less than 2.5° for the studied roughness profiles (Figure 7d). These studies show that the error in phase detection even with a significant roughness could be reduced in an experiment, with a large incident spot size.

To numerically estimate the sensitivity to the change in refractive index (RI), the refractive index of a 100 nm layer over the sensor was varied in the third decimal place, close to the value of 1.33. In Figure 8, the refractive index dependence of the ellipsometric phase $\delta$ is shown. A straight line is fitted to the data and its slope provides the estimate for RI sensitivity at 1.33 to be, $S = 147.3°$ RIU$^{-1}$.

4. Biosensing Experimental Results

Figure 9 shows the differential phase versus concentration for two different biomolecules, Bovine serum albumin (BSA) and Ficoll 70. Serum albumin is the most abundant protein in mammalian blood and helps in circulation via transport of both endo- and exogenous compounds.$^{[43]}$ BSA having a secondary structure very similar to the human serum albumin helps maintain the osmotic pressure balance and buffered pH.$^{[44]}$ In contrast, Ficoll PM70 and PM400 are high molecular weight sucrose-polymers used extensively in isopycnic and rate-zonal separations like density gradient centrifugation of tumor cells.
Phase singularity at the point of darkness in perfect absorber structure is an ideal candidate for a biosensor with high resolution. We proposed and demonstrated a reusable sensor consisting of an asymmetric Fabry–Perot cavity multilayer structure. The stability and resolution of the sensor are established with numerical studies. Sensitivity and FOM are calculated to be 147.3° RIU−1 and 109, respectively. From the differential phase measurements, the FOM is found to be 556. For the p-polarization resonance, we observed perfect absorption (≈99.9%), high Q-factor ≈42, and angle-insensitive absorption exceeding 95%. Generalized Brewster angle effect (99.99% absorption of s-polarization) with sharp singular phase is demonstrated. A good agreement between the experimental and simulation results is obtained for the multilayer metal-dielectric stack. Experimental demonstration with two different biomolecules of BSA and Ficoll 70 confirmed the high sensitivity of the sensor at the resonance corresponding to the p-polarization.

5. Conclusion

Phase singularity at the point of darkness in perfect absorber structure is an ideal candidate for a biosensor with high resolution. We proposed and demonstrated a reusable sensor consisting of an asymmetric Fabry–Perot cavity multilayer structure. The stability and resolution of the sensor are established with numerical studies. Sensitivity and FOM are calculated to be 147.3° RIU−1 and 109, respectively. From the differential phase measurements, the FOM is found to be 556. For the p-polarization resonance, we observed perfect absorption (≈99.9%), high Q-factor ≈42, and angle-insensitive absorption exceeding 95%. Generalized Brewster angle effect (99.99% absorption of s-polarization) with sharp singular phase is demonstrated. A good agreement between the experimental and simulation results is obtained for the multilayer metal-dielectric stack. Experimental demonstration with two different biomolecules of BSA and Ficoll 70 confirmed the high sensitivity of the sensor at the resonance corresponding to the p-polarization.

6. Experimental Section

Numerical Simulations: For FDTD simulations with angled illumination, a broadband plane wave source, broadband fixed angle source technique (BFAST) source was used. For a broadband plane wave injected at an oblique incidence, the wavelength-dependent injection angle was a problem. BFAST was adapted to take care of this problem. The simulation region was taken to be 20 nm × 20 nm × 1.5 μm in the X, Y, and Z directions and different boundary conditions were used based on the symmetry and source requirements, to reduce the computation time. To model reflectionless (complete absorption of electromagnetic fields) behavior in the direction along which the source was injected, perfectly matched layer (PML) boundaries were used along z-direction and periodic boundary conditions in the semi-infinite x- and y-directions so that BFAST source can be used. The fields reflected from the structure were recorded by the “Frequency domain field and power monitor.” It could return electric and magnetic fields and transmission spectral information. The computation grid was chosen such that there are at least 10 grid points in each layer (e.g., 1 nm grid in Si layer). Optical parameters by Johnson & Christy for Au and Palik for Si and SiO2 were used in the simulation. We optimized the design of the metal–dielectric stack and angle of incidence by studying the reflection and change in phase of E-field reflected from the structure.

Roughness Profile Generation: An in-built structure group of Lumerical FDTD named “rough surface” was used to simulate the surface roughness. The purpose of this structure group was to generate a rectangular object with finite thickness and refractive index but with the rough top surface with a particular RMS roughness value. First, a uniform random matrix in the k-space was generated which was then transformed into real space. This transformed matrix had the surface height (about a fixed value)
as a function of in-plane coordinates $x$ and $y$. To generate the k-space matrix, a seed for the random number generator was taken as input. Changing the seed changed the profile of the rough surface while keeping the same RMS roughness. We provided the images of the roughness profiles in Figure S9A–D. Supporting Information. In the experiment, we used an AFM to measure the surface roughness.

**Sample Fabrication and Ellipsometry:** After cleaning the substrate with soap water, acetone, and methanol, it was blow-dried with dry nitrogen gas. Then different layers were deposited by RF-magnetron sputtering in a multitarget chamber. With the base pressure of $1 \times 10^{-6}$ mbar and deposition pressure of $1 \times 10^{-3}$ mbar, Ar-plasma is used to deposit the films with 100 W RF-power for Si and 50 W DC power for Au layers. The deposition rate for Au, Si, and SiO$_2$ is 50, 4, and 3.4 nm min$^{-1}$, respectively. The structure consisting of 130 nm bottom Au, 10 nm Si, 230 nm SiO$_2$, and 30 nm top gold followed by 200 nm SiO$_2$, were sequentially deposited. The structures with SiO$_2$ layers deposited by plasma-enhanced chemical vapor deposition were also tested to have an identical response.

J. A. Woollam M-2000 Variable Angle Spectroscopic Ellipsometer with $1690$ nm wavelength range and better than 0.01° resolution was used for the measurement of the ellipsometry parameters $\Psi$ and $\delta$. First, the reflection spectrum at different incident angles was measured to find the angle at which the lowest value of zero-reflection dip was observed. The corresponding incident angle of 48° was chosen for all the subsequent spectral measurements with different concentrations of biomolecules. The differential phase corresponding to the measurement parameter.

**Supporting Information**

Supporting Information is available from the Wiley Online Library or from Supporting Information.

**Acknowledgements**

S.S. and A.K. contributed equally to this work. Authors acknowledge Prof. Aseem Mishra and Prof. Roop Mallik for the biomolecules and funding from the Department of Atomic Energy (DAE), India and the Department of Science and Technology (DST), India.

**Conflict of Interest**

The authors declare no conflict of interest.

**Keywords**

biosensors, perfect absorbers, phase singularity, point of darknesses, reusable biosensors

Received: November 16, 2020
Revised: March 9, 2021
Published online:

[1] H. P. Ho, W. W. Lam, S. Y. Wu, Rev. Sci. Instrum. 2002, 73, 3534.
[2] H. P. Ho, W. Yuan, C. L. Wong, S. Y. Wu, Y. K. Suen, S. K. Kong, C. Lin, Opt. Comm. 2007, 275, 491.
[3] J. Y. Lee, H. C. Shih, C. T. Hong, T. K. Chou, Opt. Comm. 2007, 276, 283.
[4] A. K. Sheridan, R. D. Harris, P. N. Bartlett, J. S. Wilkinson, Sens. Actuators B 2004, 97, 114.
[5] C. L. Wong, H. P. Ho, Y. K. Suen, S. K. Kong, Q. L. Chen, W. Yuan, S. Y. Wu, Biosens. Bioelectron. 2008, 24, 606.
[6] Y. P. Lee, J. Y. Rhee, Y. J. Yoo, K. W. Kim, Metamaterials for Perfect Absorption, Springer, Singapore 2016.
[7] I. E. Khodasevych, L. Wang, A. Mitchell, G. Rosengarten, Adv. Opt. Mater. 2015, 3, 852.
[8] C. Ji, K.-T. Lee, T. Xu, J. Zhou, H. J. Park, L. J. Guo, Adv. Opt. Mater. 2017, 5, 1700368.
[9] A. Nagarajan, K. Vivek, M. Shah, V. G. Achanta, G. Gerini, Adv. Opt. Mater. 2018, 6, 1800253.
[10] N. Liu, M. Mesoč, T. Weiss, M. Hentschel, H. Giessen, Nano Lett. 2010, 10, 2342.
[11] H. A. Atwater, A. Polman, Nat. Mater. 2010, 9, 865.
[12] V. G. Kravets, F. Schedin, R. Jailil, L. Britnell, R. V. Gorbachev, D. Ansell, B. Tackray, K. S. Novoselov, A. K. Geim, A. V. Kabashin, A. N. Grigorenko, Nat. Mat. 2013, 12, 304.
[13] K. Han, –C.-H. Chang, Nanomaterials 2014, 4, 87.
[14] J. Yang, F. Luo, T. S. Kao, X. Li, G. W. Ho, J. Teng, X. Luo, M. Hong, Sci. Light Appl. 2014, 3, e185.
[15] L. Cong, S. Tan, R. Yahiaoui, F. Yan, W. Zhang, R. Singh, Appl. Phys. Lett. 2015, 106, 31107.
[16] K.-T. Lee, S.seo, L. J. Guo, Adv. Opt. Mater. Carbon 2015, 2016, 108, 262.
[17] F. D. Nicola, P. Hines, M. D. Crescenzi, N. Motta, Carbon 2016, 108, 262.
[18] W. Wu, M. Ren, B. Pi, W. Cai, J. Xu, Appl. Phys. Lett. 2016, 108, 073106.
[19] J. K. Pradhan, S. A. Ramakrishna, B. Rajeswarana, A. M. Umarji, V. G. Achanta, A. K. Agarwal, A. Ghosh, Opt. Express 2017, 25, 9116.
[20] K. V. Sreekanth, S. Sreejith, A. Han, A. Mishra, X. Chen, H. Sun, C. T. Lim, R. Singh, Nat. Comm. 2018, 9, 369.
[21] D. Ye, Z. Wang, K. Xu, H. Li, J. Huangfu, Z. Wang, L. Ran, Phys. Rev. Lett. 2013, 117, 187402.
[22] J. Zhao, Y. Wang, Z. Zhu, W. Zhang, X. Yu, Opt. Lett. 2020, 45, 5464.
[23] Y. Ra’Di, C. R. Simovski, S. A. Tretyakov, Phys. Rev. Appl. 2015, 3, 037001.
[24] Z. Li, S. Butun, K. Aydin, ACS Photonics 2015, 2, 183.
[25] M. A. Kats, R. Blanchard, P. Genevet, F. Capasso, Nat. Mater. 2013, 12, 20.
[26] H. Song, L. Guo, Z. Liu, K. Liu, X. Zeng, D. Ji, N. Zhang, H. Hu, S. Jiang, Q. Gan, Adv. Mater. 2014, 26, 2737.
[27] J. Park, J.-H. Kang, A. P. Vasudev, D. T. Schoen, H. Kim, E. Hasman, M. L. Brongersma, ACS Photonics 2014, 1, 812.
[28] K.-T. Lee, S. Seo, J. Y. Lee, L. J. Guo, Adv. Mater. 2014, 26, 3624.
[29] M. A. Kats, F. Capasso, Laser Photonics Rev. 2016, 10, 735.
[30] K.-T. Lee, S. Seo, J. Y. Lee, L. J. Guo, Appl. Phys. Lett. 2014, 104, 231112.
[31] J. Zhao, M. Qiu, X. Yu, X. Yang, W. Jin, D. Lei, Y. Yu, Adv. Opt. Mat. 2019, 7, 1900646.
[32] R. Yang, C. Dai, C. Wan, G. Zheng, Z. Li, Opt. Mater. Express 2020, 10, 532.
[33] C.-S. Park, V. R. Shrestha, S.-S. Lee, E.-S. Kim, D.-Y. Choi, Sci. Rep. 2015, 5, 8467.
[34] C.-S. Park, S.-S. Lee, Sci. Rep. 2020, 10, 17727.
[35] A. Ghobadi, H. Hajan, B. Butun, E. Ozbay, ACS Photonics 2018, 5, 4203.
[36] M. Svedendahl, R. Verre, M. Käll, Light Sci. Appl. 2014, 3, e220.
[37] Y. Li, T. Yang, Z. Pang, G. Du, S. Song, S. Han, Opt. Express 2014, 22, 21403.
[38] https://www.lumerical.com/products/ (accessed: March 2021).
[39] Q. Li, Z. Li, X. Xiang, T. Wang, H. Yang, X. Wang, Y. Gong, J. Gao, Coatings 2019, 9, 393.
[40] R. M. A. Azzam, Appl. Opt. 1985, 24, 513.
[41] K. V. Sreekanth, M. Elkabbash, R. Medwal, J. Zhang, T. Letsou, G. Strangi, M. Hinczewski, R. S. Rawat, C. Guo, R. Singh, ACS Photonics 2019, 6, 1610.

[42] C.-S. Park, V. R. Shrestha, S.-S. Lee, D.-Y. Choi, Sci. Rep. 2016, 6, 25496.

[43] D. C. Carter, J. X. Ho, Adv. Protein Chem. 1994, 45, 153.

[44] Z. X. Guo, H. X. Shen, Spectrochim. Acta A 1999, 55, 2919.

[45] J. Zhang, K. Chen, Z. H. Fan, Adv. Clin. Chem. 2016, 75, 1.

[46] T. A. Scott, E. H. Melvin, Anal. Chem. 1953, 25, 1656.