Coherent meta-materials and the lasing spaser

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In 2003 Bergman and Stockman introduced the spaser, a quantum amplifier of surface plasmons by stimulated emission of radiation [1]. They argued that, by exploiting a metal/dielectric composite medium, it should be possible to construct a nano-device, where a strong coherent field is built up in a spatial region much smaller than the wavelength [1, 2]. V-shaped metallic inclusion, combined with a collection of semiconductor quantum dots were discussed as a possible realization of the spaser [1]. Here we introduce a further development of the spaser concept. We show that by combining the metamaterial and spaser ideas one can create a narrow-divergence coherent source of electromagnetic radiation that is fuelled by plasmonic oscillations. We argue that two-dimensional arrays of a certain class of plasmonic resonators supporting high-Q coherent current excitations provide an intriguing opportunity to create spatially and temporally coherent laser source, the Lasing Spaser.

In the Lasing Spaser, identical plasmonic resonators impose the frequency at which the device will lase. They will draw energy from a supporting gain substrate. This ensemble of artificial classical electromagnetic resonators plays the role of the active medium in the lasing spaser, just as an assemble of essentially quantum inversely populated atoms plays the same role in a conventional laser. In the conventional laser the direction of emission is imposed by the external resonator, while its coherency is underpinned by the boson statistics of stimulated emission of atoms in the gain medium. In the lasing spaser the direction of emission is normal to the plane of the array. Here, strong trapped-mode currents in plasmonic resonators will oscillate in phase. However, the reason for coherence is not in the boson statistics of stimulated emission, but the fact that an in-phase collective oscillation of currents has the lowest losses and is therefore the easiest to excite. A small asymmetry in the plasmon resonator, which breaks the non-radiating...
nature of the trapped mode oscillation, will allow a fraction of the energy accumulated in current oscillations to be emitted by the spaser array into the free space. This is analogous to the leakage of radiation through the output coupler of a laser resonator. Therefore in contrast with the optical quantum generator, the Lasing Spaser is a classical device at all key levels apart from the provision of gain to the substrate active medium.

To create a Lasing Spaser a special type of metamaterial array of plamon resonators is needed. It should support high-Q current oscillations that have lowest total emission losses when all currents in the array oscillate in-phase. We will such media coherent metamaterials. We recently demonstrated that a high-quality mode of intense antisymmetric current oscillations may be excited in split ring resonators with weak asymmetry (ASRs). Strong oscillations in the rings will build up and exhibit long decay time only if the ring asymmetry is weak and resonators are arranged into a regular two-dimensional array. This is because the radiation losses associated with the electric and magnetic dipole emission of the oscillating antisymmetric currents are cancelled if the resonators are placed in an infinite regular array. Thus, the high-Q resonator is formed not by a single ASR plasmonic resonator, but by the entire array. Weak coupling of this current mode to free space occurs only due to the asymmetry in the split ring and may be controlled by design (smaller asymmetry gives lower coupling and higher Q-factor). Behavior of the weakly asymmetric split ring arrays is in sharp contrast with that of conventional metamaterials where the response is determined by the dipolar resonance of the individual elements of the structure, radiation losses are strong and depends weakly on their mutual interactions. We argue that laser action fuelled by trapped-mode spaser current oscillations could be achieved by exploiting the coherent nature and high-Q of the oscillations in an array of ASRs and result in light emission with high spatial coherence.

If the array of resonators is in contact with a gain medium, for instance when it is supported by a thin slab of gain material (see Fig. 1), then by introducing modest levels of gain in this high-Q system, radiation losses and Joule losses in the metal can be overcome. Various gain media such as optically and electrically pumped semiconductor structures with direct gap and quantum cascade amplification mechanisms or rare earth and semiconductor quantum dot doped dielectrics may be suitable for this purpose. We show below that on reaching the threshold value of gain, the intensity of the resonant wave reflected and transmitted through the structure increases dramatically. By combining a thin layer of a gain medium with a high Q-factor ASR array, it is possible to achieve orders of magnitude enhancement of single-pass amplification in comparison with the amplification of the bare gain medium layer.

We illustrate this concept by providing numerical analysis of amplification in the array of ASRs combined with a gain dielectric substrate. Two cases are considered: In the first case, resonant amplification is achieved in the mid-infrared part of the spectrum (at a wavelength of about 8 µm), where Joule losses in the metals can be neglected and only losses and gain in the isotropic dielectric substrate are taken into account. In the second case, we consider amplification at a wavelength of 1.65µm and take into account Joule losses in the metallic wires. In both cases, losses and gain in the substrate are assumed to be frequency independent. This simplifying assumption is valid when the metamaterial resonance is narrower than the gain line of the substrate and inhomogeneous spectral hole burning is insignificant. We also assume no depletion of gain in all operational regimes.

The unit cell of the modeled metamaterial structures is presented in Fig. 1. It consists of a planar sub-wavelength asymmetric metallic split-ring resonator (ASR) horizontally split in two wire segments of different lengths corresponding to arc angles β₁ and β₂, which are separated by equal gaps. The ASR-resonator is brought into direct contact with a dielectric slab, which could be a gain medium supporting the array. Arrays of such metal structures can be manufactured by e-beam write and photo lithography.

Figure 2 shows the transmission characteristics of the infrared ASR array for different levels of gain presented in term of the gain coefficient α. For negative values of α (lossy substrate) the metamaterial attenuates electromagnetic radiation. Gain in the substrate exceeding αth = 70 cm⁻¹ is sufficient to overcome losses at a frequency of about 35 THz (λ = 8.4 µm) and signal attenuation becomes signal amplification (see Fig. 3). This threshold level αth corresponds to amplification of only ~ 2.7% in a 2 µm thick active layer of the bare substrate. A further increase in the substrate gain leads to a rapid increase in resonant amplification in the metamaterial reaching the level of 42 dB (approximately μ = 1.6 × 10⁴ times) at α = 125 cm⁻¹. In a bare film such levels of gain will only lead to amplification of about 5%. Alongside the increase in gain, the width of the amplified spectrum collapses from 1200 THz at zero gain to Δν = 2 GHz at the amplification maximum. Further increases in gain lead to a rapid decrease in amplification. This is because gain broadens the amplification resonance in the same way that losses broaden absorption resonances, and achieving anti-phase oscillation of currents in the split ring arcs of the plasmonic resonator becomes more difficult as radiation losses increase.

Similar analysis has also been performed for a structure resonating at 1.65µ, where losses in the metal increase the threshold gain αth to ≈ 1800 cm⁻¹ and reduce the maximum level of achievable wave amplification to about 35 dB (approximately μ = 3.2 × 10³ times) (see Figs. 3 and 4). Here amplification peaks at a gain level of about α = 2550 cm⁻¹, which corresponds to amplification of 5.5% in the bare substrate film. Here the spectral width of
FIG. 2: Transmission spectra of the mid-IR planar ASR-metamaterial in the vicinity of the trapped-mode transmission resonance for different values of gain $\alpha$. The dashed arrow follows the transformation of the transmission resonance. The inset presents the transmission spectrum of the metamaterial with no losses/optical gain in a much wider frequency range, while the dashed box indicates the spectral domain that is covered by the main plot.

FIG. 3: Amplification (blue) and spectral width (red) of the resonant transmission peak in both near- and mid-IR ASR-metamaterials as functions of gain in the substrate.

FIG. 4: Transmission spectra of the near-infrared ASR-metamaterial in the vicinity of the trapped-mode transmission resonance corresponding to different values of gain, $\alpha$. Solid contour: region of unit transmission. The arrow line shows evolution of the trapped mode resonance frequency with increase of the gain.
the amplification resonance reduces from $3 \ THz$ to about $\Delta \nu = 500 \ GHz$ at the optimal level of gain and maximum amplification.

We argue that since the radiation losses in the metamaterial are at a minimum when all currents in individual oscillators oscillate coherently at the resonance frequency, the current oscillation will self-start coherently in all rings of the array if sufficient gain is provided. Such oscillations will produce a spatially and temporally coherent diffraction-limited beam of optical emission normal to the array, transforming optical amplifier into lasing spaser. This will happen without the need for an external resonator: coherence and narrow-diversion of the output will be ensured by the low-loss condition. From the properties of the metamaterial array as an amplifier we can expect that on reaching a threshold gain the system will start lasing coherently across the whole array. With increasing gain the output intensity will increase rapidly while its spectrum will narrow dramatically. In reality, the output intensity of the lasing spaser is likely to be limited by saturation in the gain medium and heat management problems.

The small scattering losses of the current in the metamaterial array make the levels of threshold gain and gain needed to achieve peak amplification of 35-40dB practically attainable. Indeed it was recently demonstrated that quantum well structures can provide high values of gain of the order of $10^3 \ cm^{-1}$, which is similar to the threshold value required for an ASR array operating at 1.65 $\mu m$. Furthermore, quantum cascade amplifiers can readily provide the gain values needed in the mid-infrared case, since attainable gain coefficients in this wavelength range exceed 100 $cm^{-1}$. This easy-to-achieve threshold gain condition gives a crucial advantage over the recent suggestions to combine amplifying media with nano-shell and horseshoe resonant elements to create a compact plasmonic nanolaser which is much smaller than the wavelength. There the high dipole radiation losses of plasmonic resonator make the threshold gain level extremely difficult to achieve.

The lasing spaser allows high amplification and lasing in a very thin layer of material with a modest gain level, making it a very practical proposition. The thin-layer geometry is a desirable feature for some highly-integrated devices and from the point of view of heat management and integration. Here the amplification/lasing frequency is determined by size of the ring and may be tuned to match luminescence resonances in a large variety of gain media such as rare-earth elements, quantum-cascade amplifying media and quantum dots. All together this makes the lasing spaser a generic concept for many applications.

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**Method**

In the mid-IR version of the planar metamaterial the unit cell has a lateral dimension of 1.5 $\mu m$, while the split ring has a radius and line width of 0.6 and 0.05 $\mu m$ respectively, and $\beta_1 = 160^o$, $\beta_2 = 151^o$. The thickness of the active layer on the support substrate is 2 $\mu m$ and its dielectric constant (real part) $\epsilon' = 10.9$. The optical response of such metamaterial structure was analyzed in the 20-50 $THz$ frequency range (6 - 15 $\mu m$) using the method of moments. This numerical method involves solving an integral equation for the surface currents induced in the metallic pattern by the incident electromagnetic wave, then calculating the scattered fields produced by the currents as a superposition of partial spatial waves. The metallic pattern is therefore treated as a very thin perfect conductor (which is acceptable for most metals in the mid-IR), while the gain (losses) in the substrate is introduced through the imaginary part of its dielectric constant and assumed to be isotropic.

In the metamaterial structure designed for the near-IR domain, the diameter of the ASR-resonator is 140 $nm$, with a unit cell of $210 \times 210 \ nm$. The angular lengths of the metallic wire segments correspond to angles $\beta_1 = 160^o$, $\beta_2 = 125^o$, while the size of their cross-section is $20 \times 50 \ nm$. The metal of the nano-wires is assumed to be silver with a dielectric constant described by the Drude model. The substrate is 100 $nm$ thick with $\epsilon' = 9.5$, and gain is introduced through the imaginary part $\epsilon''$ of the substrate’s dielectric constant, which is related to the gain/attenuation coefficient $\alpha$ by $\alpha = \frac{2\pi}{\lambda} Im(\sqrt{\epsilon' + i\epsilon''})$. The transmission properties of this active nano-structure were numerically modeled in the 500 $nm$ – 3 $\mu m$ wavelength range using a true 3D finite element method for solving Maxwell’s equations, which also enabled us to study the effect of gain anisotropy.

* URL: [www.nanophotonics.org.uk/niz](http://www.nanophotonics.org.uk/niz)
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