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Optical loss compensation in a bulk left-handed metamaterial by the gain in quantum dots

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A bulk left-handed metamaterial with fishnet structure is investigated to show the optical loss compensation via surface plasmon amplification with the assistance of the gain medium of PbS quantum dots. Simultaneously negative permittivity and permeability are confirmed at the telecommunication wavelength (1.5 μm) by the retrieval of the effective electromagnetic property. The dependence of enhanced transmission on the gain coefficient, as well as on the propagation layers, demonstrates that ultralow loss is feasible in bulk left-handed metamaterials.
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Three-dimensional (3D) optical metamaterials with artificial magnetic response will make the intriguing ideas, such as super imaging and cloaking, closer to actual truths.[1,2] The method to manufacture 3D optical metamaterials using a layer-by-layer technique, including fabrication processes of planarization, alignment, and stacking, has presented a breakthrough in building 3D optical metamaterials,[3] even for so-called stereometamaterial with flexible twists between layers.[4] As reported in literatures, left-handed metamaterial with fishnet pattern is one of the most popular artificial structures for the studies about negative refraction, cloaking, and magnetic plasmon polaritons.[5–8] In addition, the fishnet structure shows advantage for the processing of optical 3D metamaterial, what is required is simply an array of perforated holes on metal layers. Recently, negative index of refraction was demonstrated experimentally in optical frequencies by constructing a bulk metamaterial with 21 layers of alternating Ag/MgF_2 fishnet film.[9] However, metallic metamaterials in various shapes,[10–12] including the fishnet one, generally encounter heavy losses in propagating electromagnetic energies, particularly at optical frequencies.[13–16] Consequently, the issue of serious optical loss, needs to be addressed for a practical bulk metamaterial with a large number of stacks.

To compensate the propagation loss and thus pave the way toward bulk optical metamaterials, resorting to the active medium is a feasible way. In contrast to the general amplification process by a gain medium,[17,18] surface plasmon amplification by stimulated emission of radiation, shortened as "spaser,"[19,20] has the capacity to potentially reach the orders of magnitude enhancement around the resonant narrowband with a *moderate* requirement on the gain coefficient. Recently, a lasing spaser was proposed to create a confined version of a coherent source of electromagnetic radiation fuelled by plasmonic oscillations.[21–23] Obviously, surface plasmon amplification provides a way to overcome the propagation loss of electromagnetic waves in bulk metamaterials, since such artificial materials comprise metals and depend on resonance. For example, Sivan *et al.*[24] studied the compensation effect of the spatially inhomogeneous gain on the plasmonic losses in a negative-index material through a pump-probe configuration in the frequency domain. Although there are incremental studies regarding gain-assisted electromagnetic properties in literatures, few have been concerned about the *bulk* left-handed propagation with losses compensated by an optically active system. In this letter, we investigate the resonance enhancement at optical frequencies in an active bulk metamaterial by amplifying the surface plasmon. By taking into account the realistic metal and gain material, we demonstrate that the loss-compensated left-handed propagation is feasible for a large number of propagation layers at a moderate gain level.

Figure 1 shows schematically the bulk fishnet structure. The metal in fishnet pattern is silver subjected to Drude dispersion ($\omega_p = 1.37 \times 10^{16}$ s^{-1} and $\gamma = 8.5 \times 10^{13}$ s^{-1}, see Refs. 25 and 26), while the spacer is polymethylmethacrylate (PMMA) (optical index of refraction $n = 1.49$). The gain medium embedded into the PMMA spacer is PbS semiconductor quantum dots, for which the active characteristic can

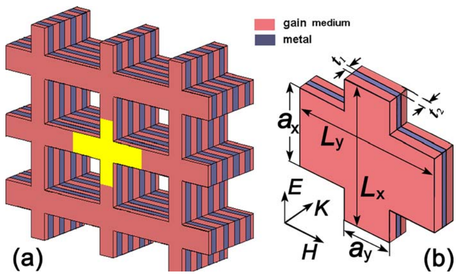

FIG. 1. (Color online) The schematic illustration of the bulk fishnet metamaterial. (a) Bulk fishnet metamaterial with four-layer metallic fishnet structure, the yellow area indicates the unit cell. (b) The unit symbols for the fishnet metamaterial with $a_x = 496$ nm, $a_y = 310$ nm, $L_x = L_y = 930$ nm, $t_1 = 62$ nm, and $t_2 = 46$ nm. Note that the gap between adjacent metal layers is $2 \times t_2 = 92$ nm when the stackable unit is cascaded to a multilayer structure.

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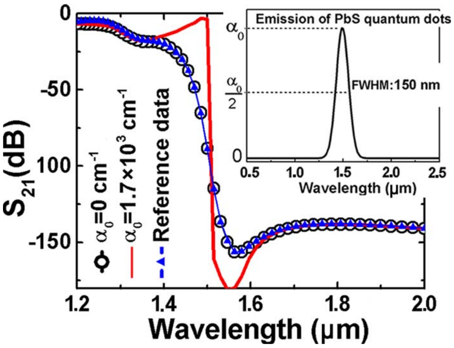

FIG. 2. (Color online) Transmission spectra of the ten-layer fishnet metamaterial with and without gain. The reference data are obtained with the same gain $\alpha_0 = 1.7 \times 10^3\ \text{cm}^{-1}$, but at an assumed emission wavelength 1.25 μm for the active quantum dots. The inset shows the gain profile of PbS quantum dots.

be described by a complex and frequency-dependent dielectric function,[17,18,21,27,28] with the gain coefficient $\alpha = (2\pi/\lambda)\text{Im}(\sqrt{\varepsilon' + i\varepsilon''})$, where ε' and ε'' are the real and imaginary parts of the permittivity for the active system, respectively. According to the emission property of PbS quantum dots, its gain profile can be described as a Gaussian distribution, with the maximum gain α_0 at 1.5 μm wavelength and a full width at half maximum of 150 nm. As for the value of maximum gain α_0 at 1.5 μm, it depends on the pumping power, density of quantum dots, and sample temperature.[29] In our numerical simulations based on the full-wave finite element method, the polarized incident wave with the electric field in the x-direction and the magnetic field in the y-direction is adopted by applying the perfect electric and magnetic boundaries, respectively.[25,30] The stackable unit cell in Fig. 1(b) is referred to as a one-layer fishnet structure since only monolayer metal is included. Analogously, the illustration in Fig. 1(a) is called as a four-layer fishnet structure.

Figure 2 shows the transmission results of the ten-layer fishnet metamaterial. It is evident that there is a resonant transmission near the telecommunication wavelength 1.5 μm with the introduction of the active medium of PbS quantum dots (solid line in Fig. 2). The large amplification does not result directly from the emission of the gain medium, as is verified by the reference data (triangular line in Fig. 2) obtained with the same maximum gain coefficient $\alpha_0 = 1.7 \times 10^3\ \text{cm}^{-1}$, but at an assumed emission wavelength of 1.25 μm for the PbS quantum dots. We can find from the reference data that such a gain level in itself is insufficient to reach an obvious enhancement as compared with the transmission spectrum without gain (circular line in Fig. 2). Thus, the reference data imply that the surface plasmon resonance from the metallic structure plays an important role in the sufficient transmission enhancement at a moderate gain level. Qualitatively speaking, the left-handed propagating field is fuelled by transferring the excited energy from the externally pumped quantum dots to the surface plasmon resonance of the metallic structure, thus compensating for the great metallic losses in terahertz frequencies. However, it is far from enough to attribute the resonance enhancement simply to an effect of loss compensation by the gain,[23] a full understanding of this combined system should take into account the strong coupling between the quantum-mechanical (active quantum dots) and electrodynamic (resonant metamaterial) systems. Note that the loss-compensated propagating field (no net amplification) in the metallic metamaterial is usually quite small in comparison with the strong pumping field; hence the potential feedback from the amplification field is assumed not enough to influence the active property of quantum dots.

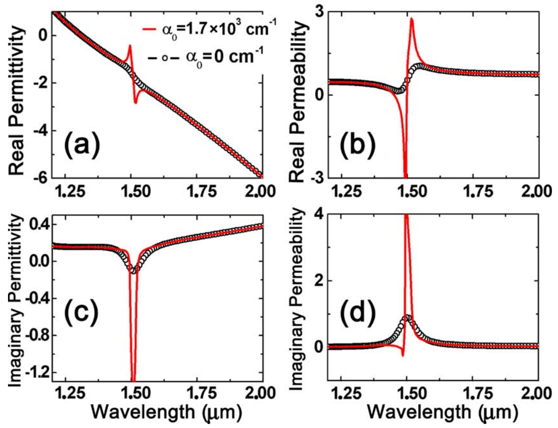

FIG. 3. (Color online) Retrieved constitutive parameters of the proposed fishnet metamaterial.

To further investigate the amplified optical resonance at the telecommunication wavelength and its left-handed property in the proposed bulk fishnet metamaterial, it is practical to use the retrieval procedure, since the fishnet periodicity is approximately $\lambda/10$ in the propagation direction. Without gain medium, the magnetic resonance near 1.5 μm is very weak, such that the real permeability loses its negative values [Fig. 3(b)]. In contrast, an amplified optical resonance with negative real permeability emerges at $\alpha_0 = 1.7 \times 10^3\ \text{cm}^{-1}$. Additionally, Figs. 3(c) and 3(d) show the dispersions of the imaginary permittivity and permeability, respectively. These effective electromagnetic properties are retrieved by considering that $\text{Im}(n) > 0$ and $\text{Re}(z) > 0$ and choosing the zero-order branch for the multivalued arccosine function. Aside from the simultaneously negative permittivity and permeability, it is confirmed in our simulations that the resonant mode has the same current distribution (not shown) as that of a left-handed fishnet metamaterial in microwave frequencies.[6]

As has presented earlier, the optical loss compensation of the left-handed propagation can be achieved in the ten-layer bulk fishnet metamaterial. However, whether or not the compensation effect is sustainable when the propagation thickness increases? What is the dependence of the bulk left-handed propagation on the gain coefficient? The numerical results in Fig. 4 can provide quantitative answers, from which it is found that, for a certain gain level, a constant compensation effect (i.e., a stable transmission independent of the propagation layers) can be achieved even if the propagation thickness is increased to a 50-layer fishnet. In comparison, for larger as well as smaller gain levels, the transmission deterioration near 1.5 μm would get increasingly severe with the propagation thickness, indicating that the elongation of the surface plasmon propagation cannot be overcompensated by the gain. Nevertheless, it should be emphasized that the transmission reduction above a certain critical value of gain, though in accordance with the literature,[21,31] may be attributed to an unrealistic consequence of the time-independent solution,[32,33] because physi-

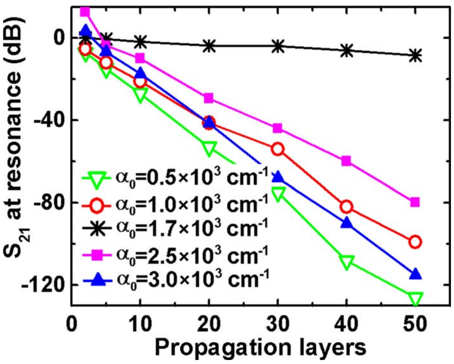

FIG. 4. (Color online) Dependence of the left-handed transmission on propagation layers and gain coefficient.

cally such gain coefficients could not be maintained in a steady state.

In summary, an optically active left-handed metamaterial in bulk fishnet stacks is numerically investigated by taking into account the realistic active medium of PbS quantum dots. It is indicated that tremendous losses in the optical left-handed metamaterial, which prevents the bulk propagation of electromagnetic waves, could be substantially reduced under a moderate gain level. In addition, the stability of the transmission magnitude can be established regardless of the propagation thickness. The results could be helpful for the experimental exploration of gain-assisted bulk metamaterials in the future.

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