Two ways of liquid crystal tunability of optical fishnet metamaterials.

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Abstract

In this work we propose two ways of tuning of the optical properties of a fishnet metamaterial infiltrated by liquid crystal. The first method is to control the hole mode of the structure via the reorientation of the liquid crystal molecules. We show that in this case the system is mainly sensitive to the refractive index change occurring inside the holes. The second technique is to tune surface-plasmon polariton modes. In this instance the structure becomes sensitive mainly to the refractive index change at the metal-liquid crystal interface. We demonstrate that controlling the surface modes one can achieve higher variation of the effective index (more than 300 times index enhancement), however transmission in such a system is lower than for the case of the hole mode control.

1. Introduction

A rapid development of nano-fabrication technologies has opened ways for the design of metamaterials in optics. The tunability of macroscopic metamaterial properties is one of the goals driving this research field, for the tunable structures could enable novel functionalities and applications.

Fishnet structure is one of the most popular designs for achieving negative refractive index in optical spectral range. Its structural geometry represents a periodic array of holes milled in a multilayer metal-dielectric-metal stack (Fig. 1). It was demonstrated that the fishnet design can exhibit a broad range negative refractive index accompanied by a high transmission [1].

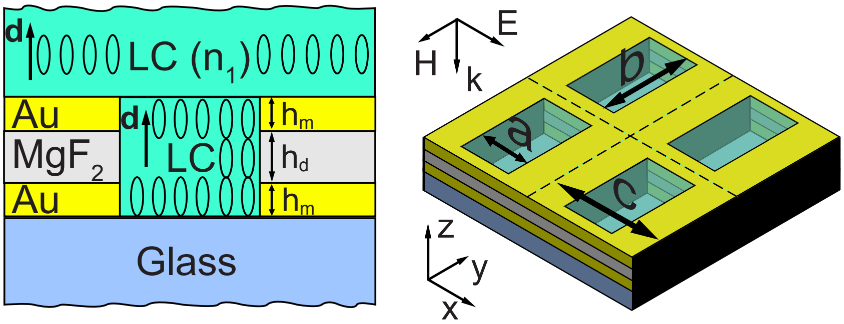

Fig. 1: Trilayer fishnet metamaterial on a glass substrate infiltrated by liquid crystal.

Transmission spectrum of a fishnet structure displays multiple resonant phenomena: hole mode and extraordinary optical transmission (EOT) peaks, spectral dips of surface and gap plasmon modes. By choosing appropriate geometrical parameters it is possible to place one or several of these spectral features in the vicinity of the negative index region. In general, resonances observed in a fishnet structure are quite broad, and their tuning requires a significant refractive index change of the surrounding medium. Such a strong index variation can be provided by liquid crystals (LCs) - highly anisotropic media which can exhibit index change of the order of 0.1. The index variation can be induced when LC molecules are reoriented by an external magnetic or electric filed as well as all-optically. Next we show that a fishnet structure infiltrated by LC can be tuned when the reorientation of the molecules causes the frequency shift of the hole mode.

2. Tunability via the hole mode control

Geometrical parameters of a fishnet structure can be chosen such that a broad transmission peak associated with the hole mode is located just below the gap plasmon resonance which is indicated by a dip in transmission spectrum [Fig. 2(a)]. In this case the channel plasmon is associated with a magnetic resonance which forms a region with negative permeability. The position of the hole transmission peak indicates plasma frequency, the point where permittivity crosses zero. The results of numerical simulations show that if the hole mode is located close enough to the gap plasmon mode, the change of LC refractive index in the hole can shift plasma frequency above the magnetic resonance causing effective index to switch from a negative to positive value.

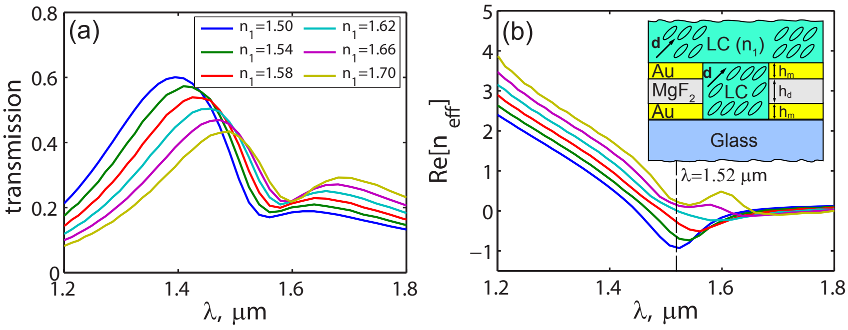

Fig. 2: (a) Simulated transmission spectrum of fishnet structure for different values of LC refractive index. (b) Extracted effective index. (inset) Schematic drawing of LC infiltrated fishnet. Geometrical parameters $h_d = 50$ nm $h_m = 30$ nm, $a = 0.19\,\mu$m, $b = 0.32\,\mu$m, $c = 0.57\,\mu$m.

The simulations were performed by an FDTD commercial software RSoft (described in detail in [2]). Refractive indices for glass substrate and MgF_2 dielectric layer were taken as 1.5 and 1.38. Inside the hole the refractive index of LC changes from 1.5 to 1.7 which corresponds to n_o and n_e of liquid crystal mix E7 (Merck) at room temperature. The series of curves in Fig. 2 displays the evolution of transmission and effective index when LC molecules are reoriented from a vertical ($n_1 = 1.5$) to a planar ($n_1 = 1.7$) alignment. In the simulation the index is varied for LC inside the hole as well as in the upper semi-space. At the position of the effective index minimum ($\lambda = 1.52\,\mu$m) the change of LC index by 0.2 cases effective index variation of more than 1 which corresponds to a 5 time enhancement.

Another way to achieve the fishnet tunability is to find such geometrical parameters when the system becomes mostly sensitive to the refractive index change at the metal/LC interface. It turns out that it could be realised by utilising the surface-plasmon polariton (SPP) modes.

3. Tunability via surface-plasmon polariton modes control

Geometrical parameters of a fishnet structure can be chosen in such a way that there would be an EOT peak located near the magnetic resonance [Fig. 3(a)]. Since the phenomenon of extraordinary optical transmission is related to the excitation of the SPP, the refractive index change at the interface causes the shift of the transmission peak. As it can be seen from the plots displaying extracted effective index [Fig. 3(b)] the EOT maximum is also related to a sharp peak in n_{eff}. The shift of the EOT mode causes this maximum to move across the region of negative refraction. A sharp left slope of the peak provides a sensitive and rapid effective index change in the system. A solid curve in Fig. 3(c) displays n_{eff} variation versus the refractive index n_1 of the LC medium at a fixed wavelength $\lambda = 1.54\,\mu$m. As one can see the change of n_1 by just 0.01 causes the effective index change of the order of 3. Therefore, such a system turns up to be at least 60 times more sensitive than the geometry for the hole mode control [Fig. 3 (dash curve)]. Thus, refractive index enhancement with this design reaches more than 300 times.

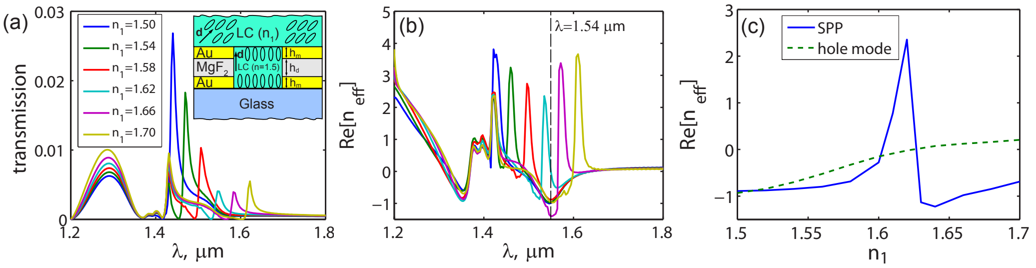

Fig. 3: (a) Simulated transmission spectrum of fishnet structure for different values of LC refractive index. (inset) Schematic drawing of LC infiltrated fishnet. The orientation of molecules inside the hole remains constant for all simulations and the refractive index in the hole is taken as 1.5. (b) Extracted effective index. Geometrical parameters $h_d = 35$ nm $h_m = 58$ nm, $a = b = 0.2\,\mu$m, $c = 0.95\,\mu$m. (c) n_{eff} versus the change of LC refractive index n_1 for surface-plasmon polariton (SPP) control case (solid curve) at $\lambda = 1.54\,\mu$m and hole mode control (dash curve) at $\lambda = 1.52\,\mu$m.

Unfortunately, we must point out that the transmission of the presented fishnet structure is not very high. Currently we are investigating whether it is possible to find geometrical parameters which will provide higher transmission without affecting the sensitivity.

4. Conclusion

We have analysed two different ways of achieving of the tunability of an optical fishnet metamaterial. In the case of the hole mode control we have shown theoretically that it is possible to achieve more than 5 times index enhancement, and the switching of the effective index from negative to positive value. However, to realise this in practice, the problem of the LC reorientation inside the hole has to be resolved. In contrast, surface-plasmon polariton modes are mainly sensitive to the index change at the metal interface. Controlling them it possible to achieve more than 300 times index enhancement, however, the improvement of the transmission properties of such a system would be desirable.

References

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