Nonlinear effects in liquid-crystal-infiltrated fishnet metamaterials

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Abstract

We present our experimental studies of nonlinear properties of fishnet structure infiltrated with nematic liquid crystals. We observe that moderate laser powers cause significant changes in the optical transmission of the composite structures, and demonstrate that the nonlinear response of the design can be further controlled with a bias electric field, enabling the realisation of electrically tunable nonlinear metamaterials.

1. Introduction

Various applications of photonic structures require the ability to change their properties all-optically through a nonlinear change of their optical response. However, in materials occurring in nature, a sizable optical nonlinearity requires the use of ultra-high light intensities and powers, hindering the practical use of optical nonlinearities. An important approach for the enhancement of nonlinearity is offered by the significant field concentration and subwavelength confinement in plasmonic and metamaterial structures, employing the increased density of electromagnetic states near a metal surface [1]. Especially important is the case of field enhancement in metamaterial designs, because this can influence both their electric and magnetic nonlinear response. In this work, we show that by proper engineering of fishnet structure infiltrated with liquid crystals it becomes possible to achieve strong nonlinear response of their transmission at moderate laser powers.

The choice of liquid crystal infiltration is specially attractive because of the large optical anisotropy of liquid crystals (LCs) due to their molecular reorientation. As such, electrical control of the properties of plasmonic hole array infiltrated with LC has been experimentally demonstrated [2]. Liquid-crystal tunability of metamaterials was also suggested as a mean to achieve tunable refractive index [3, 4], and thermal and electric tunability of metamaterial structures were shown experimentally [5, 6]. Nevertheless, all-optical control of LC-infiltrated metamaterials has never been experimentally attempted. Here we employ the fishnet metamaterial structure infiltrated with LC and test experimentally their nonlinear response to incident light.

2. Fabrication and LC infiltration of the fishnet structures

In our experiments, we fabricate fishnet metamaterials using gold and MgF_2 as metal and dielectric layers deposited on a glass substrate [Fig. 1(a)]. For nanostructuring of the metal-dielectric layers, we

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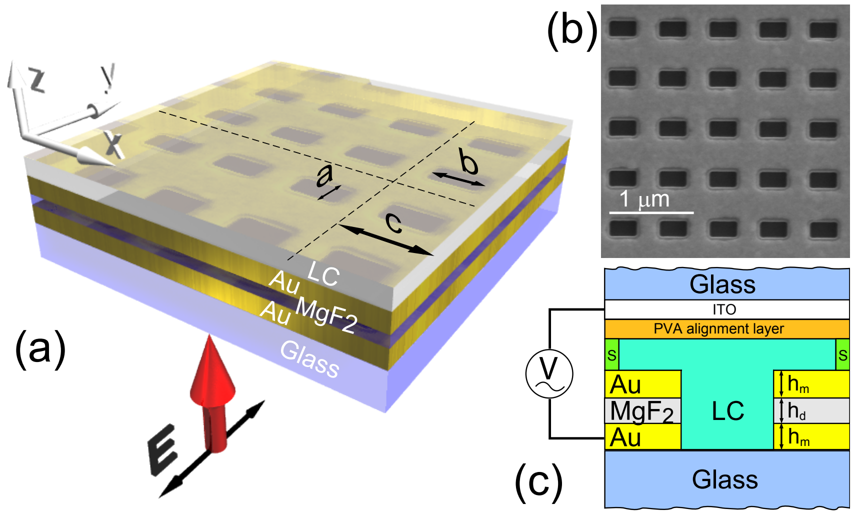

Fig. 1: (a) Schematic of the LC infiltrated fishnet metamaterial. (b) Scanning electron microscope image (top view) of the fabricated fishnet metamaterials. (c) Side view of the LC cell: S - 100 μm thick plastic spacers. Parameters for the fabricated Au-MgF_2-Au fishnet are $h_d = h_m = 50$ nm, $a = 190$ nm, $b = 350$ nm, and c=600 nm.

use focused ion beam milling, fabricating a typical fishnet structure as shown in the scanning electron microscope in Fig. 1(b). This sample is then infiltrated with E7 nematic LC (from Merck) making sure that the LC completely fills the holes of the fishnet. The presence of the LC inside the structure is verified by transmission measurements where the shift of the hole mode manifesting the infiltration is observed. The fishnet structure filled with the LC is sandwiched on the top with a glass substrate coated with a transparent indium tin oxide (ITO) electrode and a polyvinyl alcohol (PVA) layer for pre-alignment of the LC molecules. Furthermore, bias electric field can be applied between the top ITO electrode and the gold film for electrical control of the LC molecular alignment [Fig. 1(c)].

3. Experimental characterisation

In order to test the dependence of the optical transmission on light intensity, we illuminate the infiltrated structures from the substrate side by a laser beam at a telecom wavelength of 1550 nm. The experimental setup is depicted in Fig. 2(a). The particular pump wavelength is positioned on the long wavelength side of the transmission maxima indicating the plasma frequency of the structure. The laser is mildly focused onto the sample and the transmitted light is detected on a photo detector. First, we perform a reference measurement by testing the transmission of the entire stack of layers in the LC cell, but without the fishnet. In this test experiment we obtain a perfectly linear dependence of the transmission with power, regardless of the applied electric field.

However, this linear dependence dramatically changes if the fishnet structure is placed into the laser beam path [Fig. 2(b)]. In this case, we observe a drop (sub-linear dependence) in the transmission [see also Fig. 2(b-inset)] with increasing of the incident laser power. At low input powers the transmission through the infiltrated structure is $\sim 7\%$. As the power is increased, the transmission is reduced by approximately 30%. We also observe that the measured transmission drop is strongly dependent on the application of a bias electric field, indicating again that we have strong molecular re-orientation of the LCs inside the holes of the fishnet structure. This interplay between the optical and the bias electric fields induced LC reorientation demonstrates an important mechanism of electrically controlled optical nonlinearity in our fishnet structures.

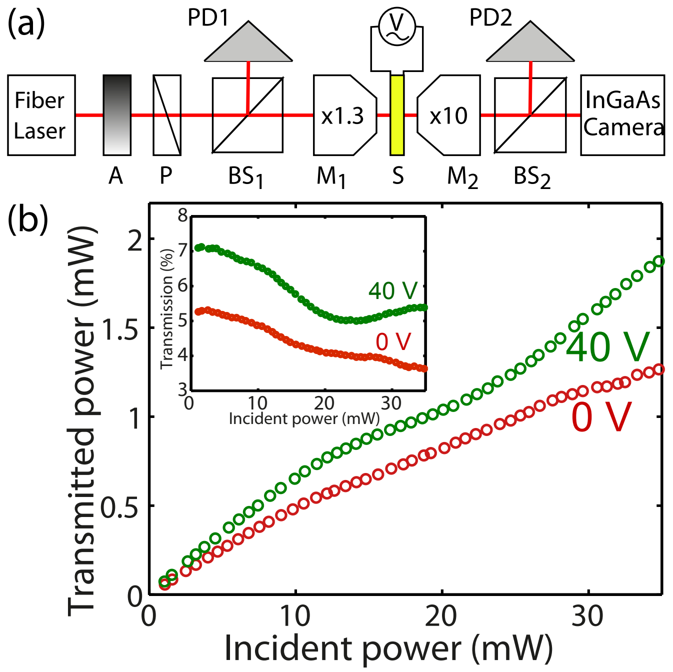

Fig. 2: (a) Experimental setup for nonlinear transmission measurement at 1550 nm. A - attenuator, PD_1, PD_2 - photodiode detectors, P -polarizer, BS_1, BS_2 -beam splitters, M_1, M_2 -microscope objectives. (b) Measured transmission at 1550 nm vs. input power for two bias voltages 0 V and 40 V. Dashed line - linear dependence. Inset: Normalized transmission vs. incident laser power.

3. Conclusions

We have fabricated and studied experimentally the fishnet metamaterial structures with strong optical nonlinearity due to their infiltration with nematic liquid crystals. We have observed a large shift of the optical transmission at moderate laser powers. Importantly, we have shown the possibility to control the nonlinear response of the fishnet structure by application of a weak bias electric field. Our results represent an important milestone in the development of optical metamaterials with enhanced nonlinear response, further opening novel possibilities for the realisation of optical materials with electrically-tunable nonlinearity.

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