Polarization-selective defect mode suppression in a deterministic aperiodic photonic crystal through plasmon excitation in an embedded array of metallic nanoparticles

Student Paper

Glukhov I.A.,[1,2] **Moiseev S.G.,**[2,3,4] **Dadoenkova Yu.S.,**[1,2] **Bentivegna F.F.L.**[1]

[1] Lab-STICC (UMR 6285), CNRS, ENIB, CS 73862, Brest Cedex 3, France 29238
[2] Ulyanovsk State University, 42 Leo Tolstoy str., Ulyanovsk, Russia 432017
[3] Kotelnikov Institute of Radio Engineering and Electronics of the Russian Academy of Sciences, Ulyanovsk Branch, 48/2 Goncharov Str., Russia 432011
[4] Ulyanovsk State Technical University, 32 Severny Venetz str., Ulyanovsk, Russia 432027
e-mail: glukhov@enib.fr

ABSTRACT

We show the possibility of a polarization-selective control of a defect mode in a multilayered photonic structure through the excitation of a surface plasmon resonance in a 2D periodic array of spheroidal metallic nanoparticles embedded in the structure. The system is a deterministic aperiodic photonic crystal, which allows to combine the resonances of the plasmonic and photonic subsystems in order to increase the sensitivity of the transmission spectrum of the structure to the constitutive parameters of the 2D nanoparticle array. Mode selectivity stems from the fact that the surface plasmon-assisted scattering of light by the nanoparticles strongly depends on the relative orientations of their anisotropy axis and the polarization direction of the incoming light.

Keywords: nanoplasmonics, 2D array of nanoparticles, photonic crystal

1. INTRODUCTION

A single metal nanoparticle (NP) can support localized surface plasmons, which causes a characteristic dip in its scattering spectrum. Similarly, a collection of identical metallic NPs ordered into two-dimensional or three-dimensional periodic arrays exhibit one or more narrow surface plasmon resonances. Consequently, by adjusting the constitutive parameters of an NP array (its period, as well as the dimension and shape of the particles) embedded in a photonic structure such as a photonic crystal (PC), one can achieve the polarization-sensitive control of the optical properties of the resulting composite system — mainly in the spectral region where the surface plasmon resonances take place.

In this communication, we propose to combine a 2D array of prolate spheroidal metallic NPs and a PC exhibiting defect modes in such a way that the frequencies of two surface plasmon resonances in the former coincide with two defect modes located in different photonic bandgaps of the transmission spectrum of the latter. Indeed, the prolate shape of the NPs ensures that two mutually orthogonal linear states of polarization of an incoming light beam parallel to their main axes excite plasmon resonances at different frequencies. Thus, it is possible to achieve separate, polarization-sensitive suppression of the defect modes of the PC and obtain a polarization-controlled dichroic filter. The fine tuning of the spectral positions and widths of the photonic bandgaps, of the frequencies of the defect modes they exhibit, and of the coincidence of these modes with the surface plasmon resonances in the embedded metallic NP array is made possible a so-called deterministic aperiodic multilayered photonic crystal in which the mathematical rules governing the sequence of layer thicknesses and positions provide the necessary adjustability

2. DESCRIPTION OF THE SYSTEM AND RESULTS OF CALCULATIONS

The structure is a resonant photonic cavity consisting of two multilayered dielectric reflectors separated by a dielectric layer D, as shown in Figure 1. A 2D array of silver NPs is located at the center of layer D. The reflector to the right of layer D is the mirror image of that to the left of that layer, so that the position of the NP array coincides with the center of the structure. The boundaries of all the layers are perpendicular to the z-axis of a Cartesian system of coordinates.

Each reflector is designed by overlapping two periodic distributed Bragg reflectors (DBRs) $(AB)^N$ and $(AB)^{N'}$ (with $N \neq N'$) made of alternate non-magnetic, isotropic, dielectric materials *A* (ZrO_2) and *B* (SiO_2). The layer thicknesses of the first DBR and those of the second DBR are chosen to satisfy the Bragg condition for two different vacuum wavelengths. The overlap of these two periodic DBRs results in a deterministic aperiodic Bragg reflector exhibiting two neighboring photonic bandgaps, each of which encompasses one or several defect modes as well as one of the surface plasmon resonance frequencies of the 2D array of metallic nanoparticles. The thickness of the central layer *D* is carefully adjusted in such a way that two defect modes of the aperiodic photonic crystal are close to the plasmonic modes of the 2D array.

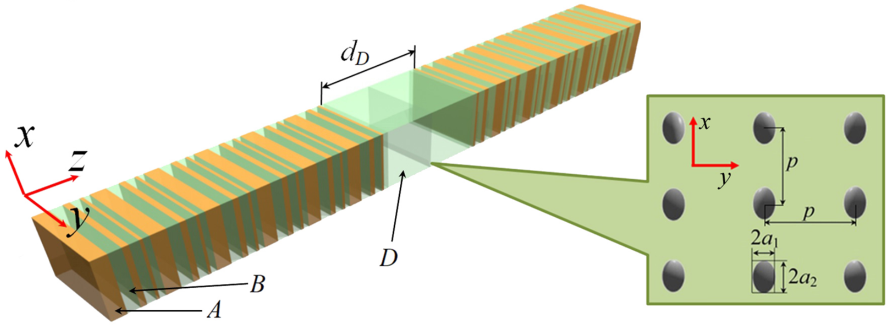

Figure 1. Schematic of the composite photonic structure. Two symmetrical deterministic aperiodic multilayered reflectors consisting of alternate A (in orange) and B (in green) layers are separated by a layer *D* (thickness d_D). A 2D array of spheroidal metallic nanoparticles, characterized by the dimensions $2a_1$ and $2a_2$ of the particles and the interparticle distance *p*, is located at the center of the structure.

The NPs are placed at the nodes of a 2D square lattice with period *p* that exhibits translational invariance along the *x*- and *y*-axes of the (*xyz*) Cartesian coordinate system, as shown in Figure 1. All NPs are prolate spheroids and similarly aligned, with their long axis parallel to the *x* -axis, and their shape is characterized by aspect ratio $\xi = a_1/a_2$, where $a_1 = 5$ nm and $a_2 = 2$ nm are the half-lengths of their polar and equatorial axes, respectively. The array acts as a polarizer whose spectral and polarization characteristics depend on the shape of the nanoparticles and the periodicity of the array [1].

The optical response of such a composite photonic structure can be calculated on the basis of a modified transfer matrix method, where the influence of the 2D array is described by a specific interface-like matrix whose elements are derived using a coupled-dipole approximation [2].

Figure 2 represents the transmittivity spectra of the structure under consideration in a visible and near-visible UV spectral range encompassing two neighbouring photonic bandgaps (henceforth referred to as the *lower-λ* and *higher-λ* bandgaps). As in regular PCs, these bandgaps result from the geometry of the reflectors. Defect modes appear in the bandgaps due to the presence of layer *D*, and their number and position in the spectrum are determined by the thickness and optical characteristics and internal structure of this composite layer.

Specifically, Figure 2(a) shows the transmittivity spectrum of the structure without 2D array of NPs at the center of layer *D*, which in this paper we assume to be SiO_2, *i.e.*, the same as that of layers *B*. The thickness of that layer is taken as $d_D \approx 485.4$nm. This value (as well as those of the thicknesses and refractive indices of all the layers of the structure) is chosen so that two defect modes (hereinafter called L_1 and L_2, located at approximately 375 nm and 412 nm, respectively) appear in the lower-λ bandgap and one (denoted *H*, at 609 nm) in the higher-λ one, in both cases away from the bandap edges. It should be noted that in this case the spectrum of the photonic structure does not depend on the state of polarization of the incoming electromagnetic wave, as the structure does not include any anisotropic element.

Figure 2(a) also shows (see green lines) the transmittivity spectrum of the sole 2D NP array embedded between two semi-infinite slabs of material *D*. The interparticle distance is taken *p* = 15 nm. Each NP is a prolate nanospheroid whose axes dimensions are 10 nm × 4 nm × 4 nm. The periodicity of the array and the dimensions of the NPs have been chosen so that this spectrum exhibits a broad dip inside the lower-λ (for *y*-polarized light) and the higher-λ (for *x*-polarized light) bandgaps, respectively. Those dips correspond to the polarization-sensitive excitation of a localized surface plasmon resonance in 2D array of the metallic NPs. Note that the transmission dip for *x*-polarized light is noticeably broader (FWHM ≈ 22 nm) than the dip observed for *y*-polarized light (FWHM ≈ 7 nm).

Figure 2(b) shows the transmittivity spectra of the structure when the 2D NP array is placed at its center for the *x*- and *y*-polarization states of the incoming wave. For either of these polarization states, the plasmon resonance excited in the NPs is broad enough to encompass one of the defect modes of the structure, which leads to a significant decay and a slight blue shift of that mode, provided the polarization state of the incoming wave is well chosen. Specifically, the defect mode affected by the presence of the NPs is the one in the higher-λ bandgap for *x*-polarized light, whereas it is the defect mode L_1 in the lower-λ bandgap for *y*-polarized light (Fig. 2(c)).

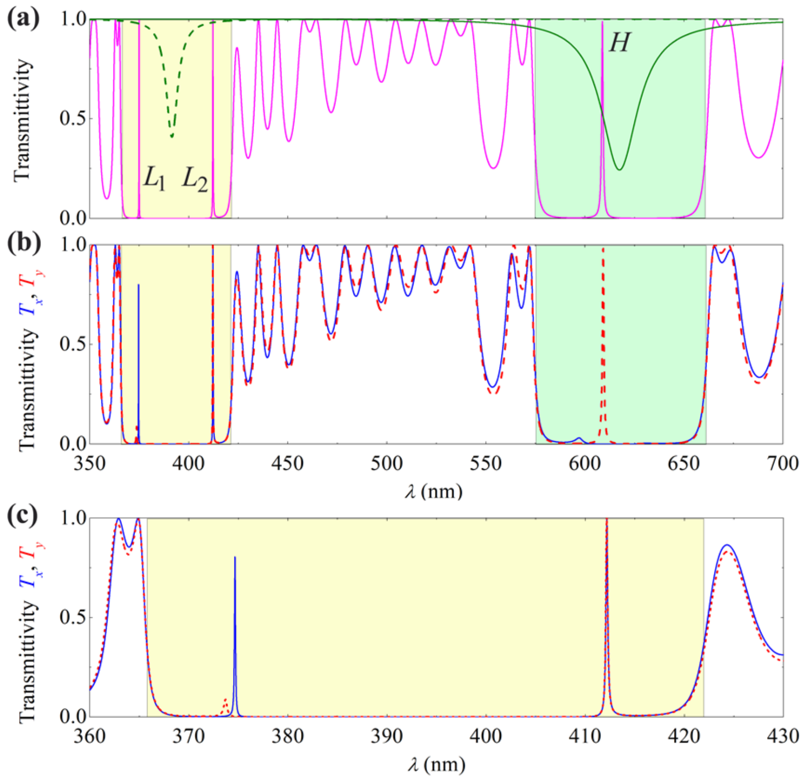

Figure 2. Transmittivity spectra of the photonic structure: (a) without 2D array of NPs (magenta line) and for any polarization state of the incoming lightwave; (b) after inclusion of a 2D array of NPs and for x-polarized (blue solid line) and y-polarized (red dashed line) incoming lightwave; (c) zoom on the lower-λ bandgap. The two defect modes in the lower-λ bandgap and the defect mode in the higher-λ bandgap are denoted L_1, L_2, and H, respectively. The green curves superimposed to the spectrum in (a) show the transmittivity dips due to surface plasmon resonance in the sole 2D NP array embedded into SiO_2 for x-polarized (green solid line) and y-polarized (green dashed line) incoming light, respectively.

3. CONCLUSIONS

We have made the theoretical demonstration that it is possible to achieve the separate, polarization-sensitive suppression of two narrow defect modes located in different bandgaps of an aperiodic photonic crystal by exciting surface plasmon resonances in a 2D array of metallic spheroidal nanoparticles embedded in the structure. Adjusting the frequencies of the defect modes can be done by carefully designing the photonic crystal, while their polarization-sensitive suppression is obtained through the choice of the constitutive parameters of the nanoparticle array (spatial period, dimensions and aspect ratio of the particles, and choice of metal). Our results point to potential applications, such as polarization-sensitive photon detectors, or spectral filters.

ACKNOWLEDGEMENTS

This work is supported in part by École Nationale d'Ingénieurs de Brest, France (Project HF-CCCP), Conseil Régional de Bretagne, France (Projects PhotoMag and SPEACS), the Ministry of Science and Higher Education of the Russian Federation, and the Russian Foundation for Basic Research (RFBR) (Project No. 18-42-730007).

REFERENCES

[1] S. G. Moiseev *et al.*: Spectra of the photonic crystal structure with a monolayer of metallic nanoparticles, *J. Appl. Spectrosc.*, vol. 85(3). pp. 511-516, July 2018.

[2] S. G. Moiseev *et al.*: Polarization-selective defect mode amplification in a photonic crystal with intracavity 2D arrays of metallic nanoparticles, *J. Opt. Soc. Am. B*, vol. 36. pp. 1645-1652, June 2019.