Resonant Magnetooptical Effects in Encapsulated 1D Plasmonic Crystals

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New approaches for the composition of efficient robust plasmonic crystals are very desired for practical applications as well as for the observation of new exciting effects at the nanoscale. Herein, both experimentally and theoretically resonant optical effects in encapsulated magnetoplasmonic crystals composed of a 1D gold grating sandwiched between two layers of iron garnet with slightly different dielectric properties are studied. It is demonstrated that depending on the geometry of the magnetic field application, various mechanisms provide resonant enhancement of the magnetooptical (MO) response of the structure; the strongest MO effect is attained for the case of waveguide modes propagating in iron garnet dielectric layer along the longitudinal magnetic field, when the magnetization-induced rotation of the polarization plane up to a few degrees is observed. The obtained results demonstrate high potential of magnetoplasmonic waveguides as stable and efficient plasmonic devices.

1. Introduction

The field of plasmonics attracts continuously high attention as a route toward subwavelength optical resolution and near-field enhancement at the nanoscale. Two main types of plasmon excitation are the localized and propagating surface plasmons, which appear as the result of the interaction of electromagnetic excitation are the localized and propagating surface plasmons, which appear as the result of the interaction of electromagnetic waves with conduction electrons in metal nanostructures or at interfaces or in a WG can be realized if the SPP phase matching conditions are satisfied, which are determined by the dielectric properties of the materials forming a particular structure. At the same time, if the plasmonic subsystem is a grating with the subwavelength period, quasi-phase-matching conditions support the excitation of propagating surface plasmon in the desired spectral range not restricted by the SPP dispersion of a continuous metal layer in a dielectric environment. Periodicity of such plasmonic structures brings about extra interference effects that lead to the appearance of the so-called plasmonic bandgaps and determines the term plasmonic crystals, or magnetoplasmonic crystals (MPC), if plasmonic part of the heterostructure is combined with a magnetic material. Similarly, magnetoplasmonic waveguides (MPWG) are the structures where plasmonic or dielectric subsystems are made of magnetic materials.
Dispersion properties of plasmonic WG and crystals can be substantially different, especially if the thickness of the plasmonic layer is small compared to the escape depth of light; in that case coupled plasmonic symmetric and asymmetric WG modes appear, the quality factor of the first one being relatively high. It was shown recently that high-quality resonant MPWG modes can be tuned by external magnetic field, which is attractive for a number of applications. A perspective type of MPWG is the encapsulated MPC first suggested in the study by Chekhov et al. and formed by a nanoperforated gold film sandwiched between dielectric iron garnet layers with close dielectric properties. It also demonstrates high-quality resonances in the magneto-optical (MO) response, while the described studies were carried out only for the transverse DC magnetic field and for the plasmon-polariton resonances. Here, we show further that the SPP excitation leads to a strong enhancement of the MO response in transmission through the MPWG for various geometries of the magnetic field application. In particular, longitudinal magnetization provides strong magnetic-field-induced tuning of the WG modes propagating in monocristalline iron garnet layer for different polarizations of the incident light. Strong light localization in MPWG under the SPP excitation is confirmed by the spectroscopy of optical second harmonic generation (SHG), which is a sensitive probe of local field and resonant effects as demonstrated, e.g., for plasmonic structures. The article is organized as follows. After short description of the fabrication and structure of encapsulated MPC, we discuss the experimental results on their optical spectra along and with the analytical description of their dispersion. In the next subsections, the spectra of MO effects in the Voigt, longitudinal, and Faraday geometry are presented, followed by the results of the spectroscopy of SHG and nonlinear MO effect. Finally, results of numerical modeling of the field distribution in the MPC confirms strong light localization under SPP and WG modes excitation.

2. Results and Discussion

The procedure of the MPC fabrication is described in detail in the Experimental Section. In brief, we studied the structures made on top of a epitaxial (Bi, Lu)₃(Fe,Ga)₅O₁₂ garnet grown on a monocristalline Gd₃Ga₅O₁₂ (GG) substrate. Gold grating with the period of 700 and 50 nm in thickness was covered by a 120 nm-thick polycristalline BiFe₂O₁₂ (BiIG) film. Figure 1a–c shows the scanning electron microscopy (SEM) images of the top view and cross sections of the structure, which confirm the high quality of the encapsulated MPC. Figure 1d presents the schematic view of the fabricated MPWG, which can support a set of resonant modes, including 1) coupled SPP in the gold grating; 2) WG modes in monocristalline 2.2 μm-thick garnet layer; and 3) in upper 120 nm-thick BiIG film.

2.1. Transmission Spectroscopy of MPC Structure

Figure 1e, f shows the transmission spectra of encapsulated MPC as a function of the incident angle, θ, and the light wavelength, λ, recalled below as wavelength-angular spectra. One can see that the most pronounced features appear as transmission maxima or minima for the p- or s-polarizations of the probe beam, which are nearly linear functions of λ and θ and intersect each other at θ = 0. Sets of less pronounced asymmetric transmission maxima that are nearly equidistant in θ and λ are also detected, their period being smaller in the case of p-polarized probe beam. Observed MPWG transmission spectra were analyzed when considering SPP and WG modes excited through coupling with the incident light due to the presence of the gold grating; strong features at 800–1000 nm correspond to the second-order SPP mode. The approximation of the SPP dispersion within the model described in previous studies is shown by dashed lines in Figure 1e, f and corresponds to the excitation of two SPP modes in capsulated gold film. SPP excitation is evident for the p-polarized probe light, while the appearance of strong minima for s-polarized in nearly the same spectral range to the excitation of WG modes in BiIG capsulating layer, as confirmed by numerical modeling.

Periodic set of maxima at the wavelengths shorter than the features discussed above appears due to the excitation of WG modes in the 2.2 μm garnet layer through the diffraction of light at 1D Au grating. Slightly different periods of these WG modes for the p- and s- polarizations of the probe beam are due to different Fresnel coefficients in these cases. Finally, spectral interference provides the appearance of a set of low-quality transmission minima and maxima that are nearly independent on θ.

2.2. MO Effects in Encapsulated MPC

In order to reveal the magnetic field control over the plasmon excitation in the encapsulated MPC, we studied their MO response in the Faraday, Voigt, and longitudinal geometries of the DC magnetic field, applied correspondingly along the Z, Y, and X axes of the coordinate frame introduced in Figure 1d. The relevant wavelength-angular spectra and their cross sections for the angle of incidence θ = 10° are shown in Figure 2. The overall feature of these spectra is angular, or the sign reversal of the MO effect which is the general property of the MO response. One can see that the two SPP modes appear in the MO spectra in the Voigt geometry as strongly amplified magnetic contrast ρ₂0 in the wavelength range 800–900 nm, which changes its sign close to the SPP resonance. Similar while less pronounced features appear in the wavelength range 600–700 nm; they correspond to the third-order SPP in the encapsulated MPC. It is worth noting that the latter resonances are hardly seen in the transmission spectra contrary to the MO ones, thus confirming high sensitivity of magnetooptics to SPP resonances. The spectra of MO effects also reveal the resonance features associated with the excitation of WG modes in the epitaxial garnet layer, which intersect the SPP features and provide additional modulations of ρ₂0. At normal incidence the MO effect vanishes, which is typical for MPC.

In the longitudinal geometry of the applied magnetic field, the MO effect consisting in the polarization plane rotation of the probe radiation is the most pronounced for the WG modes propagating in the epitaxial garnet layer (shown in Figure 2b); it is
Figure 1. SEM images of a) top view and b,c) cross sections of encapsulated plasmonic crystals with the period of 700 nm; d) schematic view of the encapsulated MPC. e,f) Transmission wavelength-angular spectra of MPWG for p- and s-polarized probe beam.

Figure 2. Wavelength-angular spectra a) of magnetic contrast, \( \rho \), of the transmitted light intensity in the Voigt geometry; b,c) spectra of the polarization plane rotation angle of the probe beam under the application of the longitudinal magnetic field and in the Faraday geometry, respectively. d,e,f) Cross sections of the spectra shown in panels (a–c) for \( \theta = 10^\circ \).
accumulated similar to the case of the Faraday effect in bulk magnetic materials, while the SPP resonances are less evident. The sign of the effect depends on the direction of the WG modes' propagation and is an odd function of the angle of incidence. On the contrary, in the true Faraday geometry (Figure 2c) the magnetization-induced rotation of the polarization plane of light is of the same sign for positive and negative $\theta$ and tends to zero in the vicinity of the resonant modes of encapsulated MPC.

Panels d–f of Figure 2 demonstrate the cross sections of the MO spectra for the three geometries of the magnetic field application (Figure 2a–c), which show the spectral shapes of MO resonances of encapsulated MPC. Besides the enhancement of the MO response close to the resonant wavelength of the WG modes excitation, they show that the magnetic contrast for the counterpropagating SPP is of the opposite signs in the scheme of the Voigt effect and is accompanied by sharp drops with the sign reversal, which is perspective for sensing.

2.3. Optical Second Harmonic Generation Spectroscopy of Encapsulated MPC

Figure 3 shows the results of the SHG studies in the considered encapsulated MPC, the spectral range is limited by the tuning range of the Ti–sapphire laser used to pump the sample. One can see that close to the SPP resonances the SHG maxima have the Fano-type shape, the overall SHG signal being modulated by the interference of the fundamental beam in the epitaxial garnet layer. Resonant SHG enhancement is attributed to the increase of the local electromagnetic field close to the SPP resonances at the pump wavelength $\lambda$, as $I_{2\omega} \propto L(\lambda)^4$, where $L(\lambda)$ is the local field factor at the $\lambda$ wavelength. The WG modes are not pronounced in the SHG spectrum probably because of low spectral resolution of the SHG probe when using the femtosecond laser pulses with the spectral width of about 10 nm.

MO transversal SHG intensity effect in encapsulated MPC in the studied spectral range reveals the following main features: 1) the sign of the SHG magnetic contrast is opposite for the positive and negative values of the angle of incidence $\theta$, similar to the linear MO effect in the Voigt geometry; and 2) SPP mode that falls in the spectral range available for the SHG studies does not provide strong MO effect in the nonlinear optical response. We suppose that this is due to high symmetry of encapsulated MPC. Really, as all the constituting materials are centrosymmetric, the second-order nonlinear optical response in the electric dipole approximation appears due to the $\chi^{(2)}$ susceptibility associated with metal–dielectric interfaces,[28] BiIG/Au and Au/(Bi,Lu)$_3$(Fe,Ga)$_5$O$_{12}$, that are nearly mirror symmetric so that their nonlinear contributions should cancel each other.

![Figure 3. a) Wavelength-angular spectrum of the SHG intensity and b) its cross section at $\lambda = 870$ nm; c) analogous spectrum of the SHG intensity magnetic contrast, $\rho_{2\omega}$ and d) its cross section again at $\lambda = 870$ nm.](image-url)
other. Thus, despite the enhancement of the local electromagnetic field at the interfaces in the resonant SPP conditions, the SHG response is relatively small and does not produce strong SHG neither MO SHG effects.

2.4. Modeling of Electromagnetic Field Distribution in MPC

Calculations of the electromagnetic field distribution in encapsulated MPC were performed within the analytical approach as well as by numerical finite-difference time-domain method; dielectric constants of garnet and gold layers were taken from Johnson and Christy.\(^{[35]}\) Figure 4a,c shows the calculated absorption of the considered MPC, \(1 - T(\lambda, \theta) - R(\lambda, \theta)\), \(T\) and \(R\) being the reflection and transmission coefficients. One can see that in the case of p-polarized probe beam (Figure 4a) two strong absorption features appear that correspond to the second-order SPP excitation in encapsulated Au grating; these resonances are less pronounced for shorter wavelength due to the dispersion of iron garnet.

Figure 4b,d shows the distributions of the modulus of the electromagnetic field, \(|E| = \sqrt{E_x^2 + E_y^2}\), at normal incidence and of \(E_y\) at \(\theta = 15^\circ\), where the absorption of the structure is high. One can see that in these cases for \(\lambda = 860\) and 960 nm the nodes of the SPP modes correspond to the Au stripes of encapsulated MPC. At the same time, increased transmission happens when the SPP nodes coincide with the spacing between the Au stripes. So, the calculations confirm the plasmonic and WG nature of the observed features in the MPC transmission spectra.

3. Conclusion

In conclusion, we demonstrate resonant optical and MO response of encapsulated MPC made of 1D Au grating placed between the two garnet layers. We show both experimentally and by numerical modeling that such structures reveal a set of resonant modes, including second and third orders of SPP and two sets of the WG modes propagating in two garnet layers adjusting to the gold grating. Resonant enhancement of the MO effects is observed in the Voigt and longitudinal geometries of the DC magnetic field, induced by the modification of the SPP dispersion in the first case and by the nonreciprocal effects for the propagation of the WG modes in the second one.
The observed effects in a single plasmonic structure confirm that encapsulated MPC are promising for applications in magnetophotonics.

4. Experimental Section

Synthesis of Encapsulated MPC: As the template for the composition of MPC, we used monocrystalline (Bi,Lu)3(Fe,Ga)5O12 garnet of 2.2 μm in thickness grown by liquid phase epitaxy on commercial (111) Gd3Ga5O12 (CGO) substrate. On top of it, a 50 nm-thick gold film was made by repeated sputtering of an Au target by Ar+ beam with the energy of about 1000 eV. Such a procedure discussed in the study by Chekhov et al. helped to achieve the adhesion of gold to iron garnet, as well as to suppress the lateral diffusion of Au adatoms during annealing after the encapsulation. Capsulating BiIG layer was obtained by sputtering the Bi:Fe = 3:5 target by a beam of oxygen ions with the energy of up to 1200 eV after prolonged preliminary sputtering of the target to achieve an equilibrium phase state at the surface and in the bulk (the so-called leveling of the effect of preferential sputtering of the rapidly sputtered component).

BiIG was crystallized as a high-density polycrystalline layer through vacuum fast annealing in the atmosphere of 80%N2 + 20% O2 gas composition, temperature pulses of T = 590 C of several minutes in duration. Previously, we have shown that such conditions allow to form polycrystalline BiIG layer while keeping the periodicity of encapsulated gold grating. Scanning electron imaging of the samples was performed by FEI-650 or TESCAN electron microscopes.

Optical and Nonlinear Optical Methods: Wavelength-angular optical and MO spectra were obtained when illuminating the sample by a halogen lamp, its polarization being set by Glan prism. For the studies of MO effects, the samples were placed between the poles of permanent magnets producing DC magnetic field of 3 kOe, its direction being set by rotating the magnets around the samples by 180°. For the MO experiments in the longitudinal and Faraday schemes, we set the analyzer at 45° to the polarization plane of the probe beam. We measured the magnetic contrast ρmo = Iω−Iω∥, where Iω and Iω∥ are the transmitted intensities for the opposite directions of the applied magnetic field. In all cases, ρmo characterizes the efficiency of the MO effects that are intensity variation for the Voigt geometry or magnetic field-induced rotation of the polarization plane in the Faraday and longitudinal magnetic field geometries.

SHG experiments were made when using the Ti:sapphire laser (730–900 nm wavelength, pulse duration of 80 ps, mean power of 50 mW) as the source of the fundamental beam that was focused on the sample into a spot of about 50 μm in diameter. Transmitted SHG radiation was detected by a photomultiplier operating in the photon counting mode. Transversal nonlinear MO effect was studied similar to the linear one, while the measure of it is the SHG intensity contrast ρmo = Iω−Iω∥, Iω, and Iω∥ being the SHG intensities for the opposite directions of the magnetic field.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Keywords

iron garnet, magnetooptics, plasmonic waveguides, surface plasmon polaritons

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[1] S. A. Maier, Plasmonics: Fundamentals and Applications, Springer, New York 2007.
[2] J. A. Schuller, E. S. Barnard, W. Cai, Y. C. Jun, J. S. White, M. L. Brongersma, Nat. Mater. 2010, 9, 193.
[3] F. Wang, Y. R. Shen, Phys. Rev. Lett. 2006, 97, 206806.
[4] G. Lozano, D. J. Louwers, S. R. Rodríguez, S. Murrai, O. T. Jansen, M. A. Verschuuren, J. G. Rivas, Light: Sci. Appl. 2016, 2, e66.
[5] S. I. Azzam, A. V. Kildishev, R.-M. Ma, C.-Z. Ning, R. Oulton, V. M. Shalaev, M. I. Stockman, Jia-Lu Xu, X. Zhang, Light: Sci. Appl. 2020, 9, 90.
[6] G. M. Yankovskii, D. A. Baklykov, A. N. Shaimanov, I. A. Nechepurenko, A. V. Dorofeenko, A. A. Pischimova, I. A. Rodionov, P. N. Tanaanov, A. V. Baryshev, Opt. Mat. Express 2020, 10, 2643.
[7] V. V. Kornienko, A. N. Shaimanov, A. V. Baryshev, J. Appl. Phys. 2019, 126, 063102.
[8] V. A. Podolskiy, A. K. Sarychev, V. M. Shalaev, Opt. Express 2003, 11, 735.
[9] W. L. Barnes, A. Dereux, T. W. Ebbesen, Nature 2003, 424, 8240830.
[10] Y. R. Shen, F. de Martini, in Surface Polaritons (Eds: V.M. Agranovich, D.L. Mills), North-Holland, Amsterdam 1982, p. 629.
[11] S. Palomba, L. Novotny, Phys. Rev. Lett. 2008, 101, 056802.
[12] A. V. Zayats, I. I. Smolyaninov, A. A. Maradudin, Phys. Rep. 2005, 408, 131.
[13] L. Novotny, B. Hecht, Principles of Nano-Optics, 2nd ed, Cambridge University Press, Cambridge 2012.
[14] S. I. Bozhevolnyi, Plasmonic Nanoguides and Circuits, Pan Stanford, Singapore 2009.
[15] D. K. Gramotnev, S. I. Bozhevolnyi, Nat. Photonics 2010, 4, 83.
[16] R. F. Oulton, G. Bartal, D. F. P. Pile, X. Zhang, New J. Phys. 2008, 10, 105018.
[17] Y. Fang, M. Sun, Light: Sci. Appl. 2015, 4, e294.
[18] M. Inoue, M. Levy, A. V. Baryshev, Magnetophotonics: From Theory to Applications, Springer Berlin Heidelberg, New York 2014.
[19] G. Armelles, A. Cebollada, A. García-Martín, M. U. González, Adv. Opt. Mater. 2013, 1, 10.
[20] N. Maccaferri, I. Zubritskaya, I. Razdolski, I.-A. Chioar, V. Belotolov, V. Kapaklis, P. M. Oppeneer, A. Dmitriev, J. Appl. Phys. 2020, 127, 080903.
[21] R. M. Rowan-Robinson, J. Hurst, A. Ciuciulkaite, I.-A. Chioar, M. Pohlt, M. Zapata-Herrera, P. Vavassori, A. Dmitriev, P. M. Oppeneer, V. Kapaklis, Adv. Photonics Res. 2021, 2100119.
[22] V. I. Belotelov, I. A. Akimov, M. Pohl, V. A. Kotov, S. Kasture, A. S. Vengurlekar, A. V. Gopal, D. R. Yakovlev, A. K. Zvezdin, M. Bayer, Nat. Nanotech. 2011, 6, 370.
[23] A. L. Chekhov, P. V. Naydenov, M. N. Smirnova, V. A. Ketsko, A. I. Stognij, T. V. Murzina, Opt. Express 2018, 26, 21086.
[24] A. E. Khramova, D. O. Ignatyeva, M. A. Kozhaev, S. A. Dagesyan, V. N. Berzhansky, A. N. Shaposhnikov, S. V. Tomilin, V. I. Belotelov, Opt. Express 2019, 27, 33171.
[25] V. V. Temnov, G. Armelles, U. Woggon, D. Guzatov, A. Cebollada, A. Garcia-Martín, J. M. García-Martín, T. Thomay, A. Leitenstorfer, Nat. Photonics 2010, 4, 107.
[26] D. A. Sylgacheva, N. E. Khokhlov, A. N. Kalish, V. I. Belotelov, J. Exp. Theor. Phys. 2016, 123, 737.
[27] D. O. Ignatyeva, G. A. Knyazev, P. O. Kapralov, G. Dietler, S. K. Sekatskii, V. I. Belotelov, Sci. Rep. 2016, 6, 28077.
[28] Y. R. Shen, The Principles of Nonlinear Optics, Wiley, Hoboken, NJ 1984.
[29] V. L. Krutyanskiy, A. L. Chekhov, V. A. Ketsko, A. I. Stognij, T. V. Murzina, Phys. Rev. B 2015, 91, 121411(R).
[30] I. S. Parchenko, A. Stupakiewicz, S. Semin, A. I. Stognij, A. Maziewski, A. Kirlyuk, T. Rasing, ACS Photonics 2015, 2, 20.
[31] S. I. Bozhevolnyi, T. Søndergaard, Opt. Express 2007, 15, 10869.
[32] V. I. Belotelov, L. E. Kreikamp, I. A. Akimov, A. N. Kalish, D. A. Bykov, S. Kasture, V. J. Yallapragada, A. V. Gopal, A. M. Grishin, S. I. Khartsev, M. Nur-E-Alamat, M. Vasiliev, L. L. Doskolovich, D. R. Yakovlev, K. Alameh, A. K. Zvezdin, M. Bayer, Nat. Comm. 2013, 4, 2128.
[33] A. K. Zvezdin, V. A. Kotov, Modern Magnetooptics and Magnetooptical Materials, IOP Publishing, Bristol, UK 1997.
[34] A. R. Pomozov, A. L. Chekhov, I. A. Rodionov, A. S. Baburin, E. S. Lotkov, M. P. Temiryazeva, K. N. Afanasyev, A. V. Baryshev, T. V. Murzina, Appl. Phys. Lett. 2020, 116, 013106.
[35] P. B. Johnson, R. W. Christy, Phys. Rev. B 1972, 6, 4370.
[36] A. L. Chekhov, V. L. Krutyanskiy, V. A. Ketsko, A. I. Stognij, T. V. Murzina, Opt. Mat. Express 2015, 5, 1647.