Rapid Communications

Magnetoplasmonic structures with broken spatial symmetry for light control at normal incidence

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As magnetized media by their nature have broken time reciprocity, the spatial symmetry of a material is also crucial and it imposes some restrictions on observed optical phenomena. Thus, for the normal incidence of light the spatial inversion symmetry makes transmitted and reflected light insensitive to the direction of the in-plane magnetization of the sample. To avoid this limitation, we propose here an approach based on a magnetoplasmonic structure with broken spatial symmetry. Combination of the specially designed spatial asymmetry with magnetism in the presence of optical losses provides a different effect, the transverse magnetophotonic transmittance effect, notable magnetooptical modulation of the optical transmittance at normal incidence enhanced by surface plasmon excitation. As the phenomenon is sensitive to asymmetry, it can serve as a powerful tool to study spin waves and currents in magnonic and optospintronic devices. The approach to marry the concepts of magnetoplasmonics and a lack of spatial symmetry is promising for the design of nanophotonics devices with outstanding properties.

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Light-matter interaction phenomena that depend on the applied magnetic field or magnetic order in the material are called magnetooptical (MO) effects. These effects are extensively used in various nonreciprocal devices such as optical isolators and circulators [1–3], for light modulation [4,5], and for sensing [6–8]. Thus, great effort has been made to design the artificial materials and structures that evince a significant MO response. One possible approach towards this is to combine magnetooptic and plasmonic materials [9–20]. Subwavelength gratings, either a metal grating deposited on a magnetic dielectric or a magnetic metal grating, can be employed for this purpose [17–19].

The transverse magneto-optical Kerr effect (TMOKE) is defined as a relative change in the reflected/transmitted light intensity induced by the reversal of in-plane magnetization in a direction perpendicular to the light incidence plane (Voigt geometry). Initially, the TMOKE was considered *in reflected* light [21]. However, the combination of magnetic materials and plasmonic nanostructures presents the possibility to observe the same effect *in transmitted* light as well [12]. Excitation of the surface plasmon polaritons (SPPs) at the plasmonic grating/ferromagnetic dielectric interface results in a significant increase in the TMOKE in comparison with those of the bare magnetic material. For both reflected and transmitted light, the TMOKE is related to the modification of boundary conditions for the light by a magnetic field and arises from the same physical origins.

For symmetry reasons, the TMOKE vanishes at normal incidence. For the SPP-assisted TMOKE, a similar feature is also inherent since the plasmon modes propagating in opposite directions are equivalent and compensate each other [12,18–26]. For the oblique light incidence, the equivalence of opposite SPP modes is broken and the TMOKE appears. This effect, its mechanism, and properties are discussed, for instance, in Refs. [12,18]. Namely, in Ref. [18] the authors report the peculiarities of the TMOKE enhanced by the first-order SPP mode in the symmetric magnetoplasmonic nanostructures. Note that magnetoplasmonic gratings considered so far have been symmetric in the lateral direction, i.e., in the grating plane.

Another case when the equivalence of counterpropagating SPP modes is broken takes place when the plasmonic grating is nonsymmetric, i.e., spatial symmetry is broken in the lateral direction. The nonsymmetric nonmagnetic plasmonic nanostructures have been studied thoroughly over the past decade [27–29]. It was shown that a specific design of these nonsymmetric structures results in enhancement of the plasmon resonance Q factor [30], wide-range tunability of the plasmon group velocity [31], and changes in the band-gap structure [32]. More important is the fact that in nonsymmetric structures the plasmon modes at normal incidence of light are excited with different efficiencies [33]. So far, the only kind of nonsymmetric plasmonic nanostructures with magnetic

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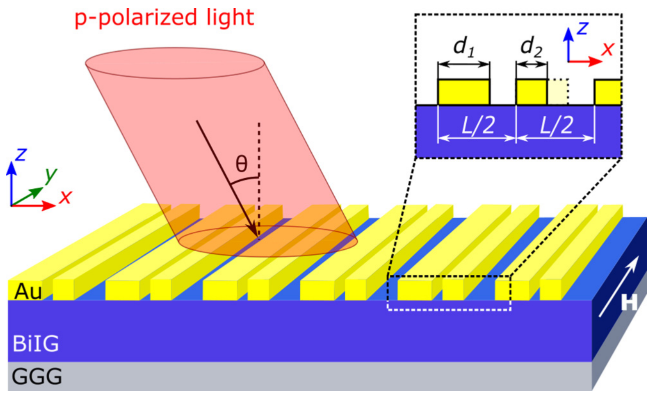

FIG. 1. Scheme of the addressed nonsymmetric magnetoplasmonic nanostructure.

constituents considered are chirooptical magnetoplasmonic nanostructures [34–36]. In particular, the chirooptical activity of such structures is governed by the applied magnetic field in Faraday geometry [35]. In addition, both magnetic and chirooptical properties of the system are tuned by separation and interaction between magnetic and chiral building blocks [36]. However, the chirooptical magnetoplasmonic nanostructures help to design Faraday and circular dichroism effects, i.e., only those effects that are present for smooth films as well.

Here we demonstrate that introduction of asymmetry in the magnetoplasmonic structures gives rise to the different magnetooptical effects, in particular to the modulation of light intensity at the normal incidence for opposite directions of the magnetization. This effect is forbidden in conventional nanostructures. The phenomenon can be referred to as a transverse magnetophotonic transmission effect. Its physical origin is in simultaneously broken excitation degeneracy and T symmetry for the plasmonic modes traveling in opposite directions. While the former is due to artificially designed frustration of spatial (P) symmetry of the structure in lateral direction, the latter is inherent in magnetic media.

To demonstrate the proposed concept, we consider a ferrimagnetic iron-garnet (BiIG) film on a nonmagnetic substrate covered with a nonsymmetric gold grating of period L (Fig. 1; see also the Supplemental Material [37]). The asymmetry of the structure emerges from the asymmetry of unit cells constituting the gold stripes separated by air grooves (inset in Fig. 1). Each cell includes a pair of gold stripes of widths d_1 and $d_2 \leqslant d_1$, whose left facets are shifted at a fixed distance $L/2$. In order to observe SPP excitation in both stripes with similar efficiency, we consider the structures with rather large stripe widths $d_1 \sim L/2$ and $d_1 - d_2 \ll L/2$. The asymmetry of the unit cell is thus caused by the difference of stripe widths d_1, d_2 and air grooves $L/2 - d_1$, $L/2 - d_2$ and thus can be characterized quantitatively as $P = \frac{d_1 - d_2}{L/2}$.

We consider three structures with the same $L = 1.2\,\mu$m and $d_1 = 0.5\,\mu$m. They differ in the width of the second stripe, (i) $d_2 = 0.5\,\mu$m, (ii) $d_2 = 0.42\,\mu$m, and (iii) $d_2 = 0.36\,\mu$m, so that the third grating has a larger value of the asymmetry parameter P (Fig. 2 and Fig. S1 in Supplemental Material [37]).

The nonsymmetric magnetoplasmonic nanostructure is illuminated by p-polarized light (Fig. 1) in an angular range from $\theta = -10^\circ$ to 10° and in the spectral range $\lambda = 0.5$–$1\,\mu$m. An angular and wavelength BiIG magnetic field $H = 200$ mT is applied parallel to the grating slits to saturate the film in plane [38]. We observe modulation of the transmitted light intensity $T(\mathbf{M})$ due to structure remagnetization and measure the effect by

$$\delta_T = 2\frac{T(\boldsymbol{M}) - T(-\boldsymbol{M})}{T(\boldsymbol{M}) + T(-\boldsymbol{M})}. \qquad (1)$$

The SPP mode is excited at the Au/BiIG interface under the phase-matching condition $\pm\beta = 2\pi/\lambda \sin(\theta) + m2\pi/L$, where β is the SPP propagation constant, λ is the wavelength of light in air, θ is the incidence angle, and m is an integer. In the addressed structure $m = \pm 3$ and $m = \pm 4$ in the visible spectral range. For a fixed λ there are SPP modes propagating in the forward and backward directions: SPP-f ($+\beta$) and SPP-b ($-\beta$). Symmetric gratings with $d_1 = d_2$ are a degenerate case and have period $L/2$, so the SPP excitation condition in them is valid only for even values of m; thus the $m = \pm 3$ SPP resonance is absent for this structure [Figs. 2(a) and 2(d)].

In the degenerate case of a symmetric nanostructure ($P = 0$) the transmission spectrum is angularly symmetric with respect to $\theta = 0^\circ$ [Fig. 2(a)]. Plasmonic resonances are excited in the spectral range of 0.7–0.85 μm with $m = \pm 4$. They appear as typical Fano-shape resonances in the transmittance and the corresponding S-shape resonances in the MO effect spectra [see Fig. 2(d)]. At the normal incidence the magnetooptical effect is absent and $\delta_T = 0$.

A quite different situation appears for structures with broken spatial symmetry. Even for relatively small asymmetry the transmittance is no longer angularly symmetric with respect to $\theta = 0^\circ$; however, the asymmetry of the transmittance spectrum is very subtle [Fig. 2(b)] and becomes visible only if the relative difference between transmittance for $+\theta$ and $-\theta$ is calculated (Fig. S3 in [39]). Nevertheless, the magnetic field modulates the transmitted light intensity at normal incidence [Fig. 2(e)] and δ_T is positive for the $m = \pm 4$ mode, like the δ_T observed for oblique incidence at the SPP-f mode [Fig. 2(b)], and negative for the $m = \pm 3$ mode, like δ_T for the SPP-b mode excited at oblique incidence. So, a kind of "bridge" at $\theta = 0^\circ$ appears in the MO spectrum connecting the plasmon resonance branches of the SPP-f at the positive and negative values of the incident angle. Such MO modulation of light intensity at $\theta = 0^\circ$ indicates the nonequivalence of the excitation efficiency of SPP modes propagating in nonsymmetric gratings in opposite directions. Since nothing similar is observed either for smooth samples or for symmetric plasmonic structures, it makes sense to consider this phenomenon as a different MO effect: the transverse magnetophotonic transmission effect (TMPTE). Here "magnetophotonic" reflects the crucial role of the plasmonic nanostructure in the formation of the effect. The underlying physics will be discussed below.

The bridge is small and narrow when the asymmetry parameter P is rather small. For a higher asymmetric structure the angular asymmetry of the transmission spectrum becomes more pronounced [Fig. 2(c)] and the bridge in the MO spectrum is as wide as the plasmonic resonance for oblique incidence. Moreover, the TMPTE becomes comparable to the MO modulation at oblique incidence for a conventional symmetric structure [Fig. 2(f)].

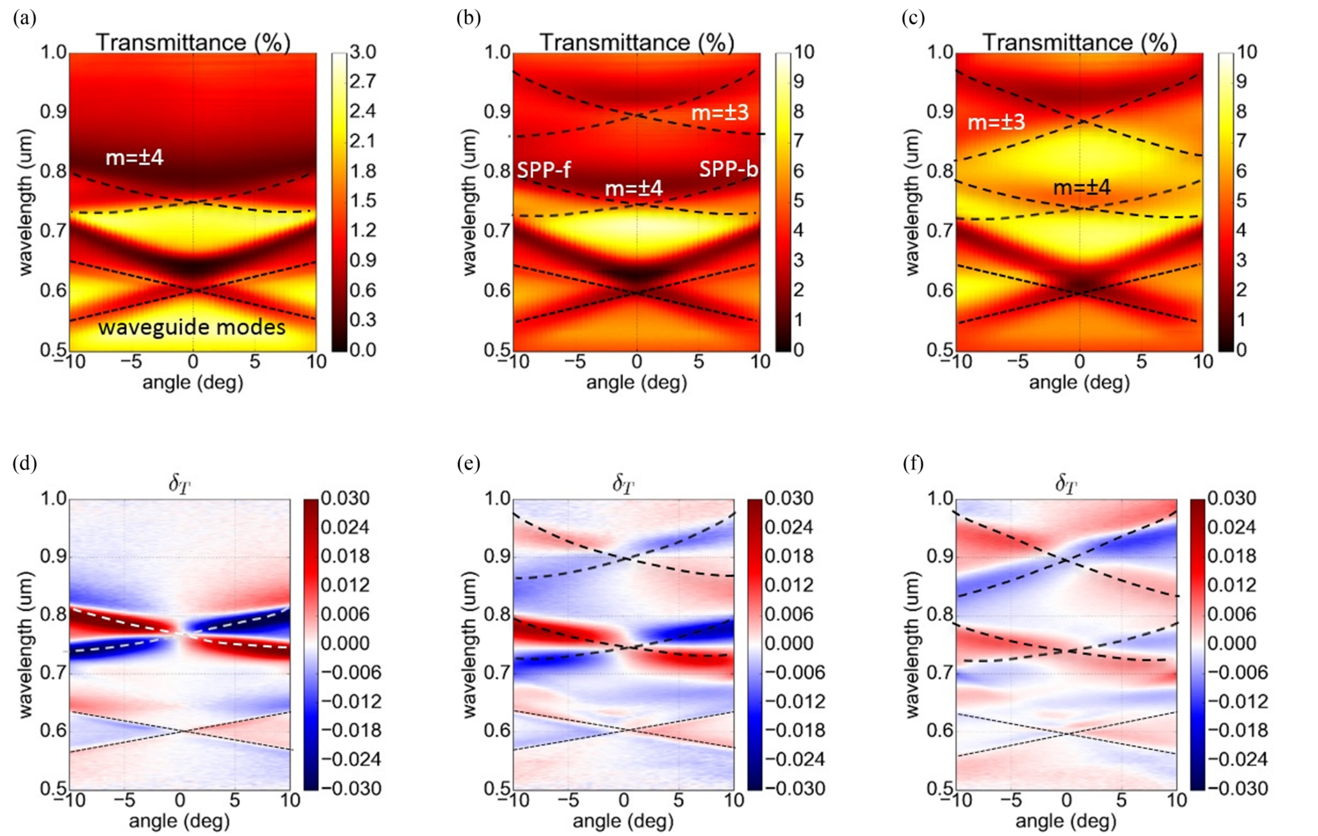

FIG. 2. Angular and wavelength resolved transmission spectra of the (a) symmetric and (b) and (c) nonsymmetric gratings. Dashed lines indicate SPP modes. Dotted lines refer to waveguide modes. Also shown are the angular and wavelength resolved magneto-optical modulations δ_T for (d) symmetric and (e) and (f) nonsymmetric gratings. The asymmetry parameter values are (a) and (d) $P = 0$, (b) and (e) $P \approx 0.12$, and (e) and (f) $P \approx 0.24$.

In addition, one can see that with an increase in the asymmetry parameter P, the MO spectrum becomes more and more angularly nonsymmetric with respect to $\theta = 0^{\circ}$. In particular, for plasmonic resonances of order $m = \pm 4$ excited in the spectral range 0.7–0.85 μm, δ_T at negative incidence angles is larger than for positive ones.

In addition, the SPP modes of the addressed structure support the waveguide modes in the spectral range of 0.55–0.68 μm [Figs. 2(a)–2(c)]. It should be noted that the waveguide modes also provide the TMPTE at normal incidence, see Supplemental Material [40]. This emphasizes the universal character of the reported effect.

To understand the origins of the TMPTE and the difference of its sign for different SPP resonances, the optical energy density and x component of the Poynting vector S_x averaged inside the magnetic dielectric film in considered structures are discussed below (see Fig. 3 and Supplemental Material [41]). The spectra of the averaged optical energy density [see Figs. 3(a)–3(c)] have the typical maxima indicating excitation of SPP modes. The sign of S_x corresponds to the propagation direction: $S_x > 0$ for SPP-f modes and $S_x < 0$ for SPP-b.

Two SPP modes are excited with equal efficiency for opposite incidence angles in the symmetric structure. However, for nonsymmetric gratings the equivalence of positive and negative directions along the x axis is broken and the considered $+\beta$ and $-\beta$ SPP modes of the same m are excited with different efficiencies.

For a small parameter of the asymmetry [Figs. 3(b) and 3(e), $P = 0.12$] the SPP mode running to the right is excited with greater efficiency and starts dominating the other SPP mode propagating to the left for $m = \pm 4$ and vice versa for $m = \pm 3$. As a result, at $\theta = 0^{\circ}$, the two counterpropagating modes no longer compensate one another and the optical energy flow to the right for $m = \pm 4$ (and to the left for $m = \pm 3$) emerges. A bridge can be seen in Fig. 3(e) that highlights that at normal incidence one mode prevails over the other, thus leading to the appearance of the TMPTE at normal incidence [Fig. 2(e)] whose sign corresponds to the one of the predominantly excited mode.

A further increase of the parameter P [see Figs. 3(c) and 3(f)] leads to a strongly nonsymmetric angular distribution of S_x. However, the sign of the TMPTE is again determined by the dominating SPP mode. The optical energy density and x component of the Poynting vector have the resonances on the waveguide modes as well; however, the magnitude of these resonances is negligible with respect to the SPP resonances.

In order to understand the relation between spatial symmetry breaking and the appearance of the TMPTE we also perform a theoretical analysis on a general basis for a homogeneous medium lacking space and time inversion symmetries. Though it is not directly applicable to the experimentally studied grating, it helps to reveal the underlying physics. The propagation of light in magnetic material with broken spatial symmetry along one direction can be described analytically

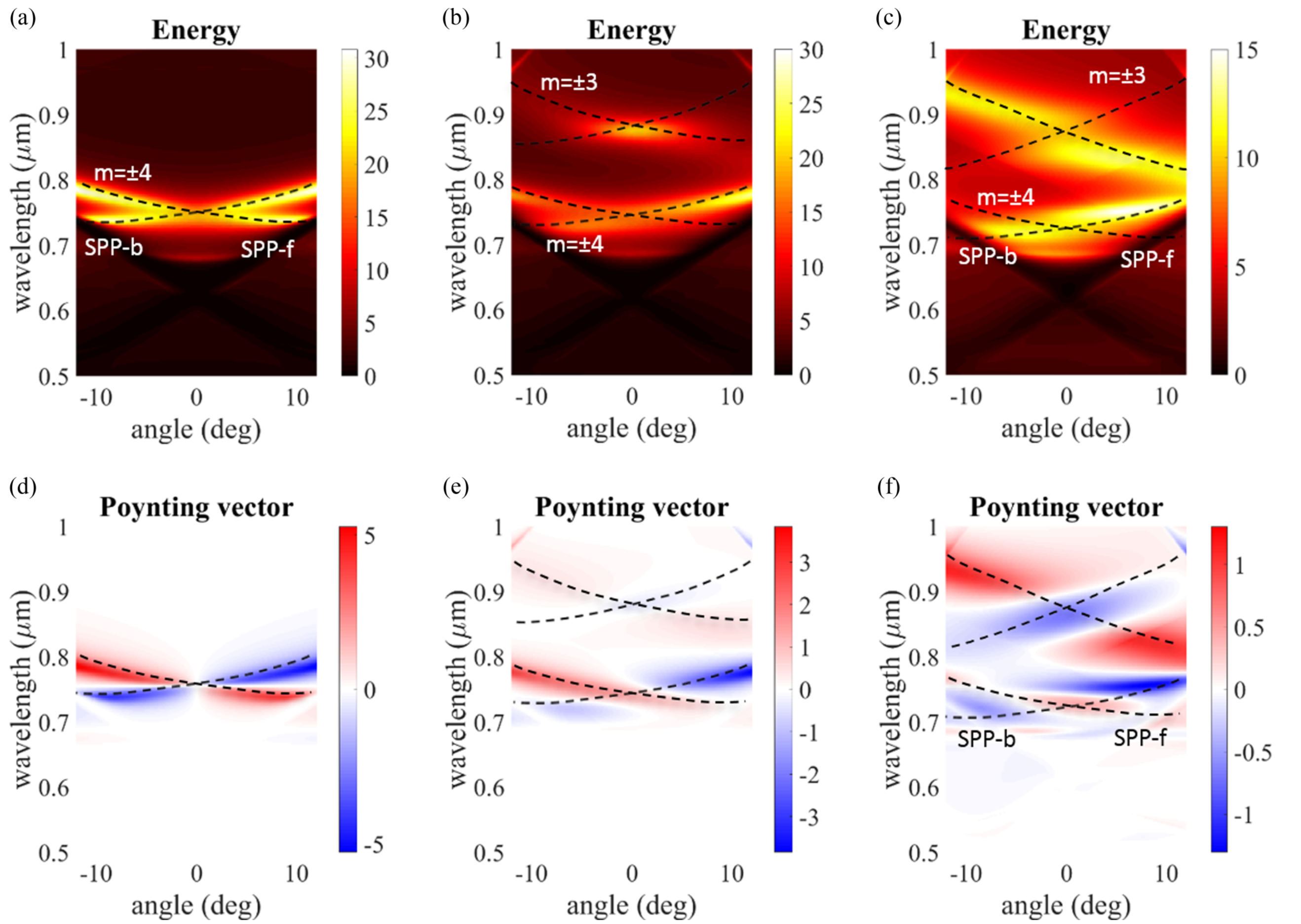

FIG. 3. Angular and wavelength resolved spectra of the optical energy density averaged in magnetic film of (a) symmetric and (b) and (c) nonsymmetric plasmonic gratings. Also shown are the angular and wavelength resolved spectra of the Poynting vector's x component averaged in a magnetic film of (d) symmetric and (e) and (f) nonsymmetric gratings. Both the energy density and S_x were calculated inside the iron-garnet layer and are given in arbitrary units. Dashed lines indicate the spectral positions of SPP modes, similar to those in Fig. 2. Both quantities were averaged inside the magnetic dielectric film of the structure excluding a thin 10-nm-thick layer near gold grating to avoid the contribution of hot spots near the edges of metal stripes. The rigorous coupled-wave analysis method was used for the calculations [42].

using the effective medium approach. The optical impact of transversal magnetization in a medium with permittivity $\varepsilon = \varepsilon' + i\varepsilon''$ is described by the gyration vector $\boldsymbol{g} = (0, g, 0)$ [21]. The broken spatial symmetry with respect to the $x \mapsto -x$ transformation in a general case is expressed in terms of a tensor $\hat{\kappa}$ with $\kappa_{ij} = 0$ except for $\kappa_{23} = i\kappa_{Ey}$ and $\kappa_{32} = i\kappa_{Ex}$ corresponding to an asymmetry parameter acting on the E_i component of the electromagnetic field and being zero for the symmetric medium. The constitutive equations are [43,44]

$$\mathbf{D} = \varepsilon\mathbf{E} + i[\mathbf{g}\mathbf{E}] + \hat{\kappa}\mathbf{H}, \quad \mathbf{B} = \mathbf{H} + \hat{\kappa}^{\dagger}\mathbf{E}, \tag{2}$$

where $\hat{\kappa}^{\dagger}$ denotes the complex conjugate tensor $\hat{\kappa}$. As p-polarized light does not have an E_y component, κ_{Ey} is not involved in further analysis. Hereafter, we define $\kappa_{Ex} = p$ for the convenience. We assume that both g and p are small compared to ε so that only linear terms are considered. The eigenmodes obtained by solving the Maxwell equations with constitutive equations (2) are

$$E_{\pm} = \begin{pmatrix} 1 \\ 0 \\ i\frac{\mp\sqrt{\varepsilon}p+g}{\varepsilon} \end{pmatrix}, \quad H_{\pm} = \begin{pmatrix} 0 \\ \pm\sqrt{\varepsilon} \\ 0 \end{pmatrix}, \tag{3}$$

where $\pm$ correspond to the waves propagating in the $+z$ and $-z$ directions and $n_{\pm} = \sqrt{\varepsilon} \pm \frac{gp}{\varepsilon}$ are dimensionless propagation constants.

The reflectance and transmittance coefficients of light incident normally on a magnetic slab of thickness d possessing broken spatial symmetry could be calculated using the eigenmodes (3) and the boundary conditions for tangential components implying that E_x and H_y are continuous at the both interfaces. Since E_x, H_y, and the total phase $\varphi = k_0(n_+d + n_-d)$ are not affected by p, we find that the reflectance is independent of p: $R(g, p) = R(g = 0, p = 0)$. Therefore, the magnetooptical intensity effect related to light *reflected* from the material, the TMOKE, is absent at the normal incidence of light even if $p \neq 0$.

For the above-mentioned reasons, the asymmetry impact on transmittance occurs only due to the changes in imaginary parts of propagation constants which define absorption-related field decay, $T(p, g) = T(p = 0, g = 0)e^{-2\psi''}$, where the value ψ'' is determined as

$$\psi'' = \frac{k_0 d g p \varepsilon''}{|\varepsilon|^2}. \tag{4}$$

Thus, the TMPTE equals $\delta_T = -4\psi''$, so the MO light modulation requires simultaneously broken spatial inversion symmetry, application of the transversal magnetic field, and light absorption. This can also be shown based on the reciprocity theorem [45], which gives the most general way to analyze the magnetooptical response of the system (see [46], Table S1).

In addition, it should be stressed that to observe the TMPTE at normal incidence of light the spatial symmetry breaking and the time symmetry breaking (due to the magnetic field) must occur simultaneously in the same material. If the layer with spatial symmetry breaking is separated from the magnetized layer, the TMPTE would be zero at normal incidence. So, in the case of plasmonic structures, the TMPTE will almost vanish when the nonsymmetric gold grating is separated from the magnetic iron-garnet layer by a distance larger than the SPP penetration depth. This emphasizes the difference between usually studied magnetoplasmonic structures which provide only the enhancement of existing MO effects and the proposed magnetoplasmonic structure with artificial spatial asymmetry where the TMPTE fundamentally forbidden in other magnetic structures is observed.

To sum up, the magnetooptical properties of plasmonic nanostructures with spatial symmetry breaking have been investigated. In such nanostructures the in-plane asymmetry leads to inequivalence of SPP mode excitation even at normal incidence of light. The idea to introduce breaking of spatial symmetry in the magnetoplasmonic system leads to the magnetooptical effects prohibited in symmetric structures. In particular, the transverse magnetophotonic effect in transmission at the normal incidence appears. The effect was demonstrated for the SPP and waveguide modes.

The demonstrated approach and the revealed magnetooptical effect in nonsymmetric magnetic structures are important for various practical applications. As the phenomenon is sensitive to both magnetization and symmetry breaking, it can serve as a sensitive tool to study complex magnetization patterns in magnonics. For example, it can be utilized for reading magnetic bits using strongly focused light with wide angular spectra [see Fig. 3(f) and Fig. S5 in [39]]. The proposed magnetoplasmonic structure could be scaled down to tens of nanometers using asymmetric nanoantennas which would also have the nonzero magnetooptical response at normal and quasinormal incidence according to the theory presented in this Rapid Communication.

We have demonstrated the nonsymmetric coupling of incident light to magnetoplasmons propagating forward and backward. Recently, similar but nonmagnetic nonsymmetric structures were shown [47] to perform topologically enabled unidirectional emission of the guided wave to bulk radiation outgoing on a certain side of the slab. Combining topological photonics with the magnetic materials makes it possible to not only obtain the unidirectional light coupling, but also to control light via the observed magnetooptical effect. One might envision the appearance of topological magnetophotonics based on the structures considered here and alternative optoelectronic devices utilizing it.

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[39] See Supplemental Material at http://link.aps.org/supplemental/10.1103/PhysRevB.102.081405 for the transmission spectra of symmetric and nonsymmetric magnetic nanostructures.

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