Anomalous Faraday Effect of a system with extraordinary optical transmittance

A. B. Khanikaev1*, A. V. Baryshev1, A. A. Fedyanin2, A. B. Granovsky2 and M. Inoue1, 2

1Toyohashi University of Technology, Toyohashi, 1-1 Hibari-Ga-Oka, Tempaku, Aichi 441-8580, Japan
2Lomonosov Moscow State University, Faculty of Physics, Leninskie Gory, Moscow, 119992, Russia

*Corresponding author: khanikaev@maglab.eee.tut.ac.jp

Abstract: It is shown theoretically that the Faraday rotation becomes anomalously large and exhibits extraordinary behavior near the frequencies of the extraordinary optical transmittance through optically thick perforated metal film with holes filled with a magneto-optically active material. This phenomenon is explained as result of strong confinement of the evanescent electromagnetic field within magnetic material, which occurs due to excitation of the coupled plasmon-polaritons on the opposite surfaces of the film.

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References and links
1. Introduction
Artificially structured metal films and surfaces have recently attracted significant attention due to experimental observation of the extraordinary optical transmission [1], theoretical prediction of spoof surface plasmon excitations [2] and prospects eventuated for potential applications for compact optical devices. Obviously, inclusion of the optically active components may endow these devices by additional functionality and flexibility. Application of electro-optically active materials, which are traditional for these purposes, is impractical because of DC field screening by conductivity electrons. On the other hand usage of magneto-optically (MO) active materials seems to be a reasonable approach.

Inclusion of MO components in perforated metal structures may result in some interesting features of MO response [3] as well as allow to control dynamically optical properties of such systems [4, 5]. Systems tunable by magnetization of a MO component and operating from microwave to optical frequencies were proposed in the past and already found applications. For example, in three port circulators and similar photonic crystal based structures [6] the non-reciprocity, which develops in a MO active component, is used to control electromagnetic energy flow. Representatives of another type of devices based on the non-reciprocal properties are phase shifters, unidirectional waveguides and optical isolators [7].

On the other hand MO properties are of significant interest per se. MO activity being very small in the most of the spectral ranges is strongly enhanced in the proximity of the resonances of bulk MO media. The nature prompts us to use artificially created resonances to enhance MO response. The idea of utilization of the resonances of various nature is not new and has a long history. According to our knowledge it was firstly proposed to explore plasmon-polariton associated resonances for enhancement of MO effects in Ref. 8, where authors studied MO response of the disordered metal-dielectric composites within the effective medium approximation. While demonstrating possibility of the enhancement of MO response, this idea encountered difficulties related to the disorder induced resonance broadening and absorption.

Artificial materials of different type, so-called magnetophotonic crystals, have also been recently proposed for MO applications [9]. In these structures resonant Bragg scattering results in accumulation and therefore strong enhancement of the Faraday rotation by the edge photonic states because of the pronounced multiple scattering regime in the proximity of the photonic band edges [10]. Another possibility to enhance MO effects is demonstrated by incorporation of a MO active defect into the photonic crystal. If the resonant state of the defect lay within the photonic bang gap of the photonic crystal [11, 12], the resonant transmittance of the light of the resonant frequency occur. In this case being trapped within the defect layer for a long time, light of the resonant frequency will also acquire huge values of the Faraday rotation.

In the present work, however, we go back to the idea of [8] to utilize artificially created plasmon-polaritons associated resonance. Recent development in the context of the works [1] and [2] allows us to vitalize this idea and demonstrate a huge enhancement of the MO response of structured metal films containing MO components.

2. Model description
The schematic representation of the perforated metal film with holes filled with a MO material is shown in Fig. 1. We utilize a theory developed in Ref. [13] for modeling of the extraordinary optical transmittance and generalize it to the case of MO active holes’ filler. We treat holes as waveguides with metallic boundaries and neglect interaction between waveguided modes of different order. Impedance boundary conditions are used to match these modes at the holes’ openings with free-space modes existing outside the structure. On the other hand we impose a requirement of the same periodicity in the $x$ and $y$ directions to allow extraordinary transmittance to appear for two orthogonal polarizations at the same frequency. Holes are chosen to be square because, as it will be demonstrated later, this gives maximal mode conversion.

The main difference and very important property of anisotropic waveguides in comparison to their isotropic counterparts is a mode conversion that takes place at certain orientations of the optical axes. In addition to this property, magnetic waveguides possess nonreciprocity, i.e. when light propagates in opposite directions, mode conversion is different. For the case of longitudinal magnetization, anisotropy results in conversion of the orthogonally polarized modes [14] that can be considered as a rotation of the electric field vector. In this case nonreciprocity results in accumulation of the rotation for forward and backward propagating light.

![Fig. 1. Geometrical arrangement of a perforated metal film with magnetic holes. Red arrows show magnetization direction of a magnetic component.](image)

Since we treat the holes as a magnetic waveguides we need to consider the mode conversion that takes place. It can be done by introduction of the matrix notations and modification of the expressions of the theory presented in the Ref. [13] to the matrix form. The modified expression for transmission takes the form

\[
\hat{t}_f = \sum_{a,j,f} \hat{\tau}_{af}^l \hat{c}_a^l \left( \delta_{aj} - \hat{\rho}_{af}^l \hat{c}_a^l \hat{\rho}_{jf}^l \right)^{-1} \hat{\tau}_{jf}^l, \tag{1}
\]

where the reflectance and transmittance matrixes for reflection and transmission processes at the hole openings are introduced as

\[
\hat{\rho}_{af}^l = \rho_{af}^l \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}, \quad \hat{\tau}_{af}^l = \tau_{af}^l \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \text{ and } \hat{\tau}_{af}^l = \tau_{af}^l \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}, \tag{2}
\]

where expressions for scalar multipliers $\rho_{af}^l$, $\tau_{af}^l$ and $\tau_{af}^l$ can be found in Ref. 13, and $\hat{e}_a$ is the propagation matrix of the waveguide, which describes evolution of the phase and polarization state when guided mode is propagating along the hole and is considered later.

In the present work we consider the direction of magnetization directed in the z-direction (Fig. 1). This geometry is the most interesting because it allows for the most efficient mode
conversion in the homogeneous MO waveguides. For this geometry, the permittivity tensor of
the MO active filler of the holes takes the form

\[ \hat{\varepsilon} = \begin{pmatrix} \varepsilon_{11} & i\varepsilon_{12} & 0 \\ -i\varepsilon_{12} & \varepsilon_{11} & 0 \\ 0 & 0 & \varepsilon_{33} \end{pmatrix}. \]  

(3)

Non-diagonal elements of \( \hat{\varepsilon} \) are usually very small and can be treated as a perturbation to the
diagonal permittivity tensor \( \hat{\varepsilon}_0 \) of the non-magnetic case. I.e. modes of the magnetic
waveguide can be found starting from the known solution of the non-magnetic problem by
application of the coupled mode theory (CMT) [14, 15]. However, before applying CMT to
our problem we would shortly remind its main expressions and limitations to demonstrate its
applicability to the evanescent fields.

CMT assumes that the normal modes \( E_m^0(x, y) \exp(iq_mz - i\omega t) \), supported by the dielectric
medium characterized by the unperturbed permittivity tensor \( \hat{\varepsilon}_0 \), satisfies unperturbed wave
equation

\[ \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \omega^2 \hat{\varepsilon}_0 - q_m^2 E_m^0(x, y) = 0 \]  

(4)

are known. An arbitrary field existing in this medium can be expressed in terms of a linear
combination of the normal modes since they form a complete set. The dielectric perturbation
\( \Delta \hat{\varepsilon} \) causes an energy exchange between unperturbed modes. In order to take into account
influence of the perturbation one expresses the electric field vector of the electromagnetic
wave as an expansion in the normal modes of the unperturbed dielectric structure, where the
expansion coefficients depend on \( z \)

\[ E = \sum_m A_m(z)E_m^0(x, y) \exp(iq_mz - i\omega t). \]  

(5)

This approach is known in mathematics as the method of variation of constants. Substituting
the last expression into the wave equation of the perturbed problem

\[ \left[ \nabla + \omega^2 (\hat{\varepsilon}_0 + \Delta \hat{\varepsilon}) \right] E = 0 \]  

(6)

and assuming that dielectric perturbation is weak, so that the variation of the modal
amplitudes \( A_m(z) \) is slow and parabolic approximation

\[ \frac{d^2}{dz^2} A_m(z) \ll q_m \frac{d}{dz} A_m(z) \]  

(7)

is valid, one can finally get a system of coupled equations for amplitudes \( A_m(z) \)

\[ N_m \frac{d}{dz} A_m(z) = \frac{\omega^2}{2i\gamma_m} \sum M_{ml} A_l(z) \exp\left[i(q_m - q_l)\right], \]  

(8)

where \( N_m \) are the normalization constants and \( M_{ml} \) are overlap integrals determined by expressions

\[ N_m = \int |E_m^0|^2 \, dx \, dy, \]  

(9)

\[ M_{ml} = \int E_m^0 \Delta \hat{\varepsilon} E_l^0 \, dx \, dy. \]  

(10)

From this sketch of CMT one can see that its applicability is limited only by the validity of the parabolic approximation. It can be easily seen from expression (7) that this approximation is valid even for evanescent normal modes of the unperturbed problem, provided the perturbation \( \Delta \hat{\varepsilon} \) is small and attenuation rate determined by the imaginary part of \( q_m \) is big
enough. However, CMT will fail if absolute value of the \( q_m \) is small. In our problem this
happens when we are near cut off frequency of the waveguide. This limitation should be kept in mind when applying CMT for both propagating and evanescent regimes.

Here we use an additional approximation, which simplifies consideration much but is satisfactory for understanding the basics of phenomena and provides qualitative or even semiquantitative predictions. We suggest metal film to be perfectly conducting and consider only (i) the most slowly decaying waveguided modes and (ii) the first-order diffraction. Consideration of the higher order diffraction and waveguided modes introduces insignificant correction to intensity and frequency shift to the transmission spectra [13].

It is very important to emphasize here that the holes’ shape should be chosen appropriately in order to maximize mode conversion. For the case of the longitudinally magnetized magnetic waveguides this requirement is equivalent to the maximization of the overlap integral $M_{ad}$ that occur in CMT. On the other hand the overlap integral $M_{ad}$ takes maximal values when orthogonally polarized modes are degenerate due to symmetry with respect to 90 degrees rotation. Thus, the maximal mode conversion is expected, for example, for the square or circular apertures. Therefore, we choose the holes to be square with degenerate $x$- and $y$-polarized modes.

Expressions for two orthogonally $x$- and $y$- polarized most slowly decaying modes of the non-magnetic square waveguide are

$$E_{10}^0 = i E_{01} \frac{\pi}{a} \sin \left( \frac{\pi y}{a} \right) \exp(i q_c z - i \omega t),$$

$$E_{01}^0 = i E_{10} \frac{\pi}{a} \sin \left( \frac{\pi x}{a} \right) \exp(i q_c z - i \omega t),$$

where $q_c = (\varepsilon_1 \omega / c)^2 - (\pi / a)^2)^{1/2}$. Then, utilizing CMT we look for solution in the form

$$E = \sum_{i=10,01} A_i(z) E_i,$$  \hspace{1cm} (12)

and find a pair of coupled differential equations with a solution

$$\begin{pmatrix} A_{10}(z) \\ A_{01}(z) \end{pmatrix} = \begin{pmatrix} \cos \alpha z & \sin \alpha z \\ -\sin \alpha z & \cos \alpha z \end{pmatrix} \begin{pmatrix} A_{10}^0 \\ A_{01}^0 \end{pmatrix},$$  \hspace{1cm} (13)

where

$$\alpha = 4 \omega^2 \varepsilon_{1z} / (c^2 \pi^2 q_c)$$  \hspace{1cm} (14)

is parameter characterizing intensity of the mode conversion and vector $\begin{pmatrix} A_{10}^0 \\ A_{01}^0 \end{pmatrix}$ defines initial “polarization state” of the guided wave.

The parabolic approximation, which determines applicability of CMT, reduces to the condition $|\alpha| \ll |q_c|$ for this problem. In all the subsequent calculations we choose holes’ diameter small enough so that the cutoff frequency is far from frequency range of our interest and this condition is satisfied with very high precision.

For the approximations considered here, expression (1) takes simple form resembling well-known Airy expression

$$\tilde{t}_{00} = \hat{t}_{12} \hat{e} \left( \hat{\delta} - \hat{\rho} \hat{\delta} - \hat{\rho} \hat{\delta}^{-1} \right)^{-1} \hat{t}_{12},$$  \hspace{1cm} (15)

where expression for $\hat{e}$ can be obtained from (11), (12) and (13); it has the following form
\[
\hat{e} = \begin{pmatrix} \cos \alpha h & -\sin \alpha h \\ \sin \alpha h & \cos \alpha h \end{pmatrix} \exp(i \alpha h),
\] 

where \( h \) is the film thickness.

Finally, knowledge of the transmission matrix \( \hat{t}_{\infty} \) allows us to evaluate the Faraday rotation angle of the transmitted wave [14].

3. Calculation results and discussion

Our calculation utilizing the theory derived in the previous section revealed a very unusual behavior of the Faraday rotation at around the frequency of the extraordinary optical transmittance. Calculations were performed for parameters of MO material corresponding to Bi:YIG (bismuth-substituted yttrium–iron–garnet) at 700 nm [11]. One can see from Fig. 2 that extraordinary optical transmittance occurs at around wavelength of 706 nm, which is right above lattice constant \( L \). Transmittance spectra are thoroughly studied and explained in Ref. 13. Therefore, we concentrate on the MO properties and only briefly remind the points of that work which are the most relevant for their explanation. The extraordinary optical transmittance occurs at frequencies where the denominator in Eq. (15) vanishes. It becomes possible only owing to the evanescent character of the modes inside the holes, which allows for removal of the restrictions on the real part or the modulus of \( \rho \). Two peaks in transmission spectra correspond to the two different resonances and two different values of \((\hat{\rho}^{\dagger} \hat{e})^2\) and are positioned around 703 and 709 nm. Strong enhancement of the Faraday rotation at frequencies of the peaks of high optical transmittance is evident from Fig. 2.

Comparison with the case of homogeneous Bi:YIG film of the same thickness as the structure under study, reveals about 18 and 8 times rotation enhancement for the left and right peaks, respectively.

Fig. 2. Transmittance and Faraday rotation of: (i) a perforated perfect conductor film with holes filled with Bi:YIG (shown by blue solid lines) and (ii) film of Bi:YIG of the same thickness (shown by green lines with circles). Calculations were performed for following parameters: film thickness of \( h=350 \) nm, lattice constant \( L=700 \) nm, holes' size of \( a=145 \) nm, \( \varepsilon_{11} = 5.59 + i 4.91 \times 10^{-9} \), and \( \varepsilon_{11} = 3.69 \times 10^{-7} \).
We explain this enhancement as the result of strong electromagnetic field confinement within MO holes, which occurs at the frequencies corresponding to the excitation of the surface plasmon-polaritons responsible for the extraordinary optical transmittance. Despite the exponential decay of the field in the holes, coupling of the plasmon-polaritons excited on the opposite surfaces of the film enables penetration of the light into MO active material and accumulation of the Faraday rotation due to multiple reflections from the holes’ openings. Therefore, amplification of the Faraday rotation is a consequence of the amplified path length of the light. In other words, the Faraday rotation measures the time of interaction of the light with the magnetic material [16]. On the other hand, increase in the interaction time results in the increase of the electromagnetic losses as well if MO material is absorbing. However, if losses in the metal are small, the structure under study brings possibility to have much higher Faraday rotation and comparable transmittance for much smaller thicknesses than in the case of the homogeneous material.

Note that this picture resembles very much the MO microcavity (Fabry-Perot etalon) [17, 18] with the only difference – in the present case modes propagation in holes are evanescent. This difference results in one very specific feature of Faraday rotation spectra in the structure under study. One can see from Fig. 2 that Faraday rotation behavior is very different from that found for the homogeneous Bi:YIG film. In addition to the above mentioned enhancement, the Faraday rotation reverses the sign at the frequency lying between the peaks in transmittance spectrum, while the sign of the Faraday rotation of the homogeneous film is the same in this frequency range. Such a peculiar behavior is explained as a result of the evanescent character of the waveguide modes responsible for the extraordinary optical transmission. As can be seen from expression (14), for evanescent modes the purely imaginary wave vector $q$ results in imaginary mode conversion parameter $\alpha$ and changes the nature of the sine and cosine functions in (16). This causes dramatic changes in the underlying physics of the phenomenon of the polarization transformation. Firstly, it is well-known that the Faraday rotation is determined by real part of the ratio $\frac{t_{01}^{21}}{t_{00}^{11}}$. In the case of homogeneous non-absorbing MO material it can be represented as

$$\frac{t_{01}^{21}}{t_{00}^{11}} = \frac{\sin(\alpha h)}{\cos(\alpha h)}, \quad (17)$$

and is purely real since $\alpha$ in this case is also real. In the case of the structure under study this ratio can be approximately expressed for the small $\alpha$ from (15) as

$$\frac{t_{01}^{21}}{t_{00}^{11}} \approx \frac{\sinh(\rho h)}{\cosh(\rho h)} \cdot \left( \frac{1 + (\rho^{11} \exp(iq_h))^2}{1 - (\rho^{11} \exp(iq_h))^2} \right). \quad (18)$$

Because of presence of the imaginary unit the Faraday rotation now is determined by the imaginary part of the expression in the square brackets. Therefore it would be zero if there was no contribution from the additional multiplier responsible for the resonant behavior of the Faraday rotation at the frequencies of the extraordinary optical transmittance and reflecting excitation of the surface plasmons. Secondly, it appears that the imaginary part of this multiplier reverses sign at the frequency between two transmission resonances and this fact results in reversal of the Faraday rotation below this frequency. We remind that the double peak structure of transmittance originates only owing to resonant properties of the structure and exists for non-magnetic structures as well. It has no relation with the splitting of the eigenfrequencies for the left and right polarized modes in magnetic waveguide as it can be misunderstood at the first sight. Unusual behavior of the Faraday rotation is result of the subtle interplay of the resonant behavior responsible for the extraordinary transmittance and modification of the guided modes by MO activity.

It is worth mentioning that the very similar behavior of the Faraday rotation with change of the sign was discovered before [3, 8] for frequencies corresponding to the excitation of surface plasmon modes. One may therefore conclude that this behavior is inherent to MO
response associated with excitation of surface plasmons and evanescent and/or near-field. Thus, an advantage to obtain the Faraday rotation of the desired sign may arise in addition to its strong enhancement, if utilizing such structures with resonantly enhanced evanescent field.

To show possible routes for optimization of the structure under study, we analyzed dependence of the transmittance and Faraday rotation on the film thickness and size of the holes. As expected from expression for $q_f$ [Eq. (4)], in the case of the holes filled with dielectric of high dielectric constant, significant extraordinary transmittance exists even for very thick films (Fig. 3). With increase of the thickness both transmittance and Faraday rotation gradually decrease because of the increase of absorption in MO holes’ filler. At the same time, two peaks in transmittance are getting closer to each other in the same manner as was shown in Ref. [13]. Therefore, decrease of the Faraday rotation may also originate in compensation of the positive and negative rotations appeared at two picks when they start to intersect and overlap.

![Fig. 3. Transmittance and Faraday rotation spectra vs. the thickness of a perforated perfect conductor film with MO holes. Parameters used for calculations are the same as in Fig. 2.](image)

To find the best trade-off between the Faraday rotation and transmittance we calculated thickness dependencies of a figure of merit (FOM). The latter was defined as the product of the modulus the Faraday rotation angle and the square root of the transmittance ($|\theta_f| \sqrt{T}$) [14]. Figure 4 shows corresponding dependencies for the left and right resonances. One can see that the envelope of the FOM at the left peak gradually decreases with increase of the thickness, while at the right peak it has maximum at thickness of 290 nm. When thickness of the structure is small the FOM at the left peak is considerably higher than at the right peak because of huge rotation angles. At the same time the left peak is much narrower than the right one demonstrating that this difference originates in difference of quality of the resonances. Finally, FOM calculated for the homogeneous Bi:YIG film is up to two orders of magnitude smaller then for the structure under study. When the thickness is increased the left
peak is getting wider and FOM decreases and takes values close to those corresponding to the right peak and found in the homogeneous MO film.

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**Fig. 4.** Figure of merit vs. the thickness of: (i) homogeneous MO film at wavelength of 705 nm (green line) and (ii) perforated perfect conductor film with MO holes at the left (red line) and right (blue line) resonances, respectively. Parameters used for calculations are the same as in Fig. 2.

Dependence of FOM on the holes’ size $a$ is presented in Fig. 5. The upper limit for this parameter is determined by the criterion of validity of the couple mode approximation and was estimated to be approximately equal to $a \approx 147$ nm. At bigger values the cutoff frequency of the guided modes approaches the frequency range of the extraordinary transmittance giving rise to inapplicability of CMT.

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**Fig. 5.** Figure of merit vs. the holes’ size at the left (red line) and right (blue line) resonances, respectively. Parameters used for calculations are the same as in Fig. 2.
One can see from Fig. 5 that in order to optimize MO response of the structure the holes’ size \( a \) should be appropriately chosen. As expected, the maximal values of FOM correspond to bigger holes. Nevertheless at smaller values of \( a \) this dependence is also rather unusual and nontrivial and exhibits strongly undulating behavior caused by the interference of the evanescent guided modes. Appreciable transmittance and Faraday rotation exist and FOM riches the local maxima for some critical values of \( a \). Note that in general these values do not coincide for the left and right peaks. Summarizing we therefore conclude that the most optimal structure should have as big holes as possible while maintaining the evanescent character of the guided modes.

Let us remind that calculations presented here consider losses in MO material, but treat the metal as a perfect conductor. This simple model is expected to give very good prediction in the frequency regimes where the perfect conductor approximation is more justified (as for infrared, microwave and millimeter regimes). However, in the optical frequency range absorption of the electromagnetic radiation by metal will lower rotation angles and thickness of the film at which extraordinary optical transmittance exists. The same will be brought by imperfections in the holes shape and their non-uniformity. To understand changes in the Faraday rotation due to additional losses, we studied it dependence on the absorption in MO material filling the holes (Fig. 6). This transfer of the losses to the dielectric filler of holes does not introduce significant difference in the physics of the phenomenon if eigenstates of the guide can be represented by Eqs. (11) and (12). These expressions rather finely approximate real eigenstates at least in the case of good conductors in the frequency range under consideration.

![Graph](image)

Fig. 6. Transmittance and Faraday rotation vs. the absorption in MO holes’ filler. Parameters used for calculations are the same as in Fig. 2.
As expected, increase of the losses results in decrease of the transmittance and Faraday rotation angles. However, reduction of the Faraday rotation at the left peak, due to its higher quality, goes faster than that for the Faraday rotation at the right peak. Increase of the absorption does not cause such significant in the latter. However, the most important conclusion that can be done from comparison of the Fig. 2 and Fig. 6 is that the Faraday rotation enhancement is quite stable, and increase of the absorption by one order of magnitude results just in approximately three and two times reduction in Faraday rotation for the left and right peaks, respectively. Even for such strong absorption as for the upper curve in the Fig. 6 Faraday rotation is still one order of magnitude higher than that found in homogeneous film of the same thickness.

4. Conclusion

We developed a theoretical model for calculation of the MO Faraday rotation of subwavelength hole arrays with holes filled with an MO active material. Our calculations revealed the strong enhancement of the MO response at frequencies corresponding to the resonant extraordinary optical transmittance. This enhancement is the result of the light trapping within MO active holes’ filler which occurs owing to multiple scattering of the electromagnetic field from the holes’ openings. It was also found that Faraday rotation exhibits very unusual behavior in comparison with that found in homogeneous MO active materials. Faraday rotation changes the sign that does not occur in homogeneous materials, at least at the frequencies lying far away from natural resonances. This change of sign was explaining as a result of interplay of MO activity and the resonant interaction of light with the structure, which occurs at frequencies of the extraordinary optical transmittance.

In conclusion, nanostructured metal films bring possibility to obtain strongly enhanced Faraday rotation of the desired sign, and, therefore, would play invaluable role in MO applications. Moreover, the possibility to control the resonant wavelength of surface plasmon phenomena in these structures would allow one to have such unique MO properties at arbitrary desired frequency within the wide frequency range where surface plasmon excitations exist.

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