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Optics

Asymmetry of resonant forward/backward reflectivity of metal – multilayer-dielectric nanostructure

S.G. Ilchenko, V.B. Taranenko

Branch of Applied Optics at the Institute of Physics, NAS of Ukraine
10G, Kudryavska str., 04053 Kyiv, Ukraine
Corresponding author e-mail: svitlana-ilchenko@ukr.net

Abstract. Presented in this paper is an experimental and numerical study of direction-dependent asymmetry of resonant optical characteristics inherent to metal – multilayer-dielectric (MMD) nanostructure, which has much in common with the Tamm plasmonic configuration. We demonstrate that when a MMD structure is illuminated from opposite sides, there is a noticeable asymmetry of the forward/backward reflection resonances, contrasting with the strictly symmetrical transmission resonances indicating classical optical reciprocity. Comparative measurements were carried out on a metal film and a quasi-periodic dielectric structure, which are identical to the corresponding parameters of the MMD structure. Directional asymmetry of reflection and transmission is briefly discussed for a modified MMD structure with the Kerr nonlinearity.

Keywords: metal – dielectric structure, Tamm plasmon, surface mode, photonic crystal.

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1. Introduction

Transmission and reflection, fundamental optical properties, determine how light behaves when it interacts with materials. Creating nanoscale structured materials and fine-tuning their optical properties has opened up new possibilities for optical devices in a wide variety of applications. Engineered nanostructures, such as photonic crystals [1, 2] and metamaterials [3], enable to achieve asymmetry (non-reciprocity) of transmission and reflection relative to the incident light's orientation. The development of innovative structures designed to control and exploit asymmetries in the transmission or reflection of light plays a key role in the development of optical technologies. This control is essential for implementation of optical communication and signal processing functions [4], as well as fabrication of a variety of photonic components, including optical diodes and isolators [5].

In this study, we investigate the directional symmetry properties of optical transmission and reflection for a resonant MMD nanostructure [6–8], employing a combination of experimental and numerical methods. The MMD structure contains a thin metal film, the thickness of which is usually several tens of nanometers. This film is deposited on a transparent flat substrate, on top of which a quasi-periodic multilayer dielectric structure is also deposited (Fig. 1a). This configuration exhibits a close relationship to the optical Tamm plasmonic structure [9–11], which is a distributed Bragg reflector with a thin metal layer on its top.

The MMD structure was specially designed to operate in the total internal reflection from the surface of the upper dielectric layer. This particular configuration provides efficient excitation of leaky waveguide modes localized in the upper dielectric layer. Below the critical angle of incidence considered in this work, the MMD structure enable to excite surface Tamm optical modes at the metal – dielectric interface [11, 12]. In this study, we demonstrate that, when illuminating the MMD structure from opposite sides, a noticeable asymmetry in forward/backward reflection resonances emerges, contrasting with the strictly symmetric transmission resonances, indicating its optical reciprocity. For a deeper understanding, comparative measurements were performed on a metal film and a quasi-periodic dielectric structure, the parameters of which are identical to the corresponding parameters of the MMD structure. In addition, the directional asymmetry of reflection and transmission for a modified MMD structure with Kerr nonlinearity is discussed.

2. Materials and methods

The resonant plasmonic MMD structure that was fabricated for our study consists of a thin metal layer along with three pairs of high and low refractive index dielectric layers deposited on a silica substrate. Specifically, we utilized Nb_2O_5 ($n_H = 2.372$ at $\lambda = 532$ nm) as the high refractive index layers and SiO_2 as the low refractive index layers ($n_L = 1.461$ at $\lambda = 532$ nm). The dielectric layer thicknesses were multiples of $\lambda/4$ (90 and 140 nm, respectively), except for the final layer, which had its thickness doubled. The metal layer is composed of silver (Ag: $\varepsilon' = -9.293$, $\varepsilon'' = 0.872$ at 532 nm) and is 40 nm thick. The detailed sample structure and illumination scheme are illustrated in Fig. 1a. For comparison and reference purposes, we included two additional samples in our experiments. The first sample was a layer containing only metal (Ag), with a uniform thickness of 40 nm. The second sample was a quasi-periodic dielectric structure composed of alternating Nb_2O_5 and SiO_2 layers having the same configuration as the dielectric part of MMD structure. All three samples were carefully deposited on a flat transparent silica substrate with a refractive index of 1.461 at 533 nm, ensuring consistent and controlled experimental conditions for our investigations.

We performed research of the resonant properties inherent to the samples, when they were illuminated from opposite sides. The experimental setup involves positioning the sample in such a manner that the incident light first interacts with the coating side. We refer to this case as 'forward incidence' (Fig. 1a, I_f). Conversely, when the light is directed onto the substrate side first and then onto the structure, we refer to it as 'backward light incidence' (Fig. 1a), denoted as I_b. Our objective was to investigate whether the samples demonstrate equal transmission ($T_{f,b}$) and reflection ($R_{f,b}$) of light, if they are illuminated from the opposite sides.

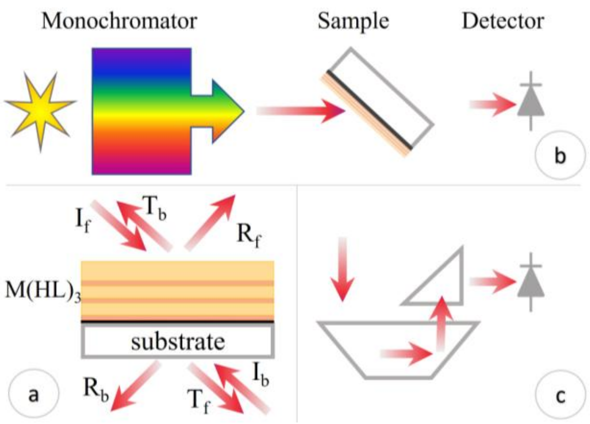

Fig. 1. Notations for transmission ($T_{f,b}$) and reflection ($R_{f,b}$) coefficients related to both forward (I_f) and backward (I_b) incidence of light beams onto the MMD structure (a). Experimental setup for measuring the transmission (b) and reflection (c) spectra, respectively.

We performed experimental measurements of the transmission (Fig. 1b) and reflection (Fig. 1c) spectra by using the spectrophotometer, specifically, SPEKOL 1500 from Analytik Jena AG UV/Vis. The prisms were positioned inside the spectrophotometer's chamber to capture the reflection spectra (Fig. 1c). Our measurements were performed over the wavelength range 500 up to 1100 nm.

To computationally simulate the resonant characteristics of the structures under investigation, we employed the scattering-matrix method, which effectively describes the propagation of plane waves in layered structures [13]. This method incorporates the Fresnel reflection and transmission coefficients at the layer interfaces, the layer thicknesses and their complex refractive indices. Note that using this method, in [8, 9] the presence of narrow spectral and angular dips in reflection from the studied MMD structure was demonstrated.

3. Results and discussion

Fig. 2 illustrates both the forward and backward transmission spectra of the studied structures, captured at the angle of incidence close to 45°.

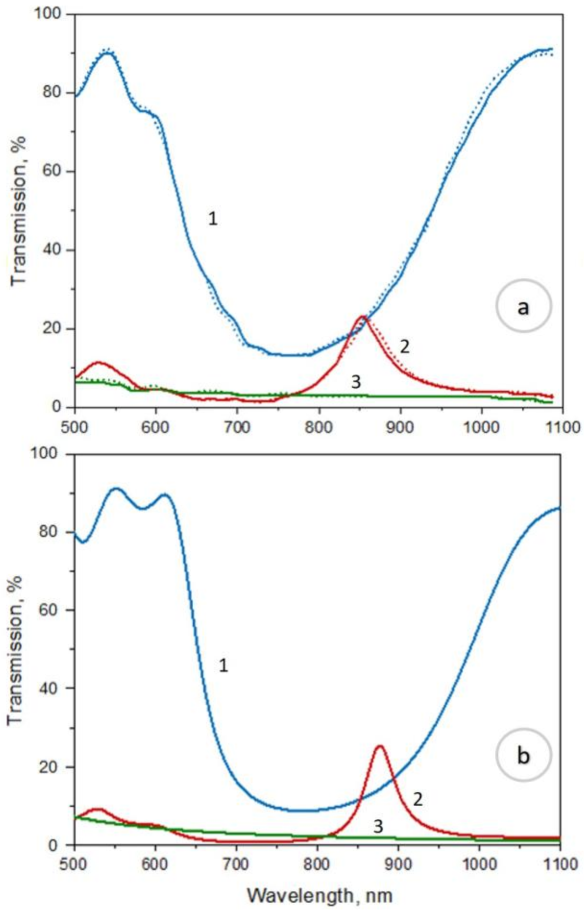

Fig. 2. Comparative display of experimental results (a) and corresponding calculated spectra (b) depicting the transmission spectra of multilayer dielectric (*1*, blue), metallic (*3*, green), and MMD (*2*, red) structures under the angle of incidence 45°. The solid lines represent spectra for forward incidence, while the dashed lines depict spectra for backward incidence.

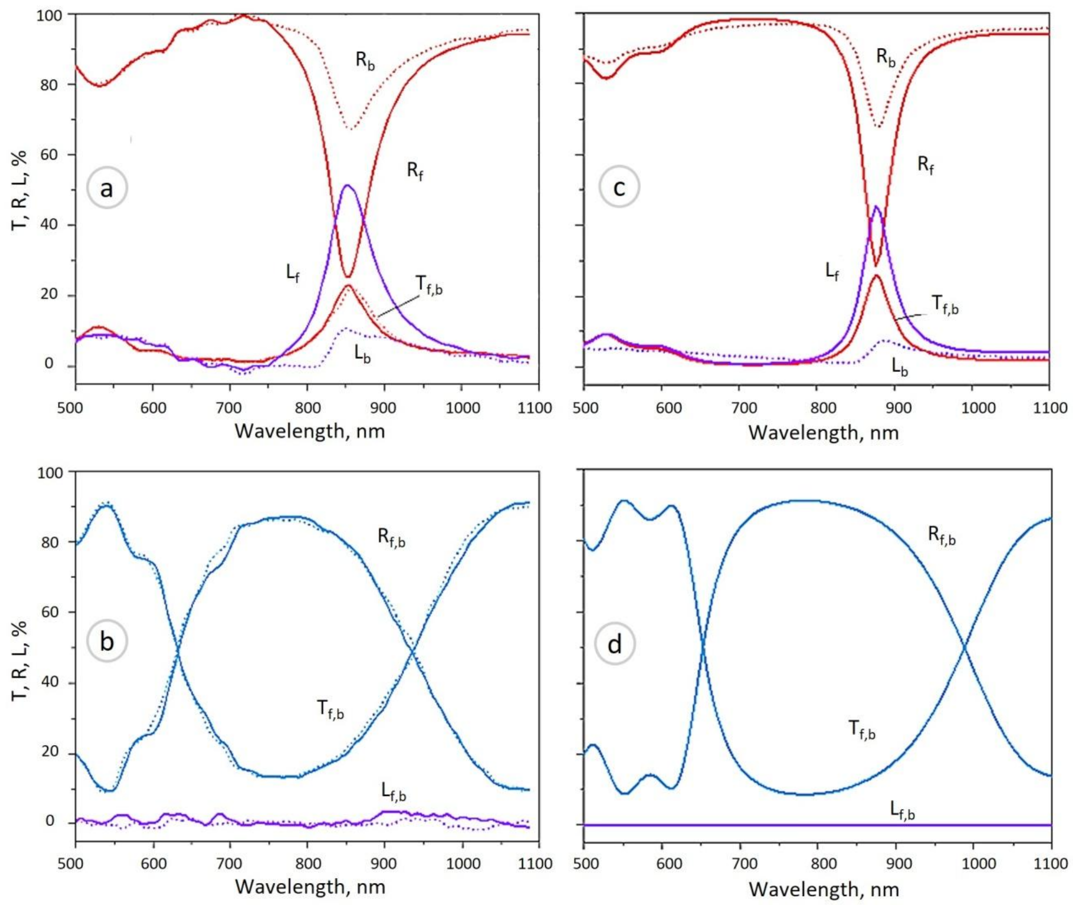

Fig. 3. Experimental (a, b) and corresponding calculated (c, d) spectral characteristics for MMD (a, c) and multilayer dielectric (b, d) structures. The solid lines represent transmission (*T*), reflection (*R*) and losses (*L*) spectra for forward incidence, while the dotted lines depict these spectra for backward incidence. (Color online)

It is worth noting that transmission measurements are usually carried out at a normal angle of incidence onto the sample, which is not possible in our experiment. Therefore, we measured the transmittance at the angle 45° (as shown in Fig. 1b) to ensure a correct comparison of the data with the reflectance measurements (Fig. 1c).

There is a clear correlation between the experimental spectra (Fig. 2a) and the calculated data (Fig. 2b), even though unpolarized beam was used in the experiment, while the calculations were made for linearly TE-polarized plane waves. The main result here is that for each sample, including the MMD structure, symmetric transmittance curves are observed for both forward (T_f) and backward (T_b) configurations of incidence. In calculations, the curves of the forward and backward transmission spectra overlap perfectly (Fig. 2b), and in experiment these curves coincide within the limits of measurement error (Fig. 2a).

Fig. 3 serves for a comparative analysis of the transmission ($T_{f,b}$), reflection ($R_{f,b}$), and losses ($L_{f,b}$) spectra between the MMD structure and a multilayer dielectric sample. The absorption spectrum, indicative of losses, was derived from the experimental data by using measurements of transmission and reflection ($L_{f,b} = 1 - T_{f,b} - R_{f,b}$). Notably, within the wavelength range from 750 up to 1000 nm, the experimental data agree well with the calculated ones. $T_{f,b}$ spectra maintain symmetry in both forward and backward measurement configurations for both structures. In the case of multilayer dielectric sample, $R_{f,b}$ spectra exhibit symmetry and complementarity to $T_{f,b}$ spectra, resulting in zero losses across the entire measured wavelength range. However, a notable asymmetry emerges in the $R_{f,b}$ and $L_{f,b}$ spectra for the MMD structure, as depicted in Figs 3a, 3c. This observation underscores distinctions in the behavior of light interaction with the MMD structure compared to the multilayer dielectric sample.

The observed asymmetry of reflection spectra for MMD structure is related to a surface optical mode referred to as the Tamm mode [11] that is excited by incident light with both TE and TM polarizations near the interface between the metal and dielectric layers. The Tamm mode gives rise to a distinct absorption resonance band within the stopband of the photonic crystal, leading to a prominent peak in the transmission spectrum (Fig. 2, red lines, *2*). This absorption resonance serves as a characteristic signature of the Tamm plasmonic structure and holds significant promise for various optical applications and devices.

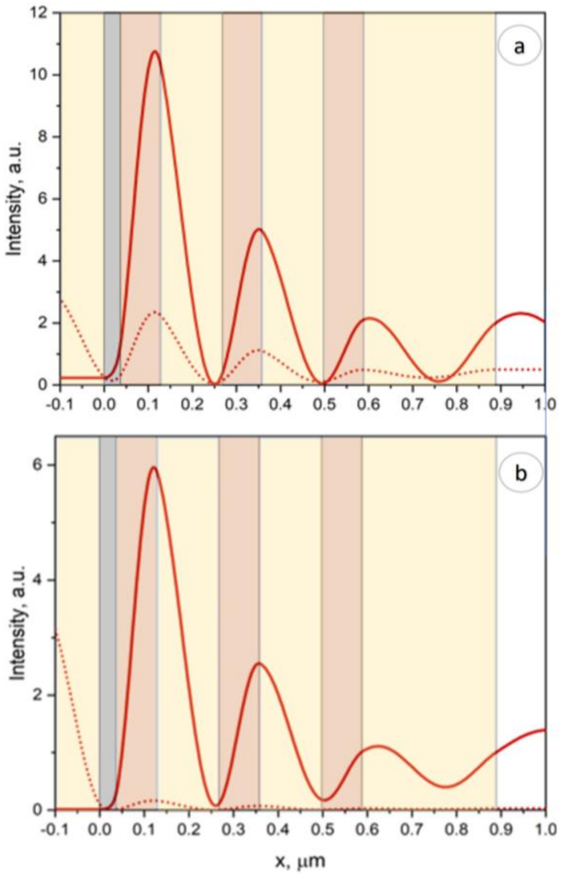

Fig. 4. Computed representation of resonant light intensity distribution across MMD structure, showing the impact of (a) silver (Ag) and (b) aluminum (Al). The dielectric configurations within the MMD structures remain consistent with those presented in Fig. 1. Solid and dotted lines correspond to forward and backward incidence of light.

Fig. 4 shows distribution of light intensity within the layers of the MMD structure depending on the incident light directions. In both incident light directions, light energy becomes concentrated near the interface between the metal layer and the multilayer dielectric structure. Nevertheless, in the forward direction, the localized light intensity surpasses that in the backward direction, leading to more pronounced absorption in the metal layer. Since the transmittance is the same in both directions of incident light, the asymmetry of the absorption spectrum leads to a corresponding asymmetry of the reflection spectrum (Figs 3a, 3c).

Fig. 4 shows that the directional asymmetry in the distribution of light intensity throughout the depth of the MMD structure is dependent on the optical properties of employed metal layer. In the case of an MMD structure with an aluminum (Al) layer ($\varepsilon' = -40.329$, $\varepsilon'' = 12.053$ at 532 nm) of identical thickness, the directional asymmetry in intensity becomes more pronounced when being compared to the MMD structure featuring a silver layer (compare Figs 4a and 4b).

Finally, let us briefly discuss the impact of directional asymmetry within the intensity distribution of transmission and reflection coefficients for the case of modified MMD structure with Kerr nonlinearity, enabling bistable switching of reflectivity [14, 15]. Because of the large directional asymmetry of localized light intensity, bistability may occur in the forward direction but not in the backward direction. Then, with a constant incident light intensity, the reflection coefficient manifests three distinct values – two in the forward direction and one in the backward direction. Remarkably, a transmission asymmetry also emerges.

4. Conclusions

In summary, this study sheds light on the directional features of the resonant optical characteristics inherent to the metal – multilayer-dielectric nanostructure, offering valuable information about its behavior under different lighting conditions and considering Kerr nonlinearity.

The study deals with the directional asymmetry of resonant optical properties in a metal – multilayer-dielectric nanostructure, closely resembling the Tamm plasmonic multilayer configuration. The study includes both experimental and numerical approaches. It is noteworthy that the study revealed a distinct asymmetry in the forward/backward reflection resonances when the MMD structure was illuminated from its opposite sides. This contrasts sharply with strictly symmetrical transmission resonances, emphasizing classical optical reciprocity.

To provide a comprehensive understanding, comparative measurements were performed on a metal film and a quasi-periodic dielectric structure, both possessing parameters identical to those of the metal – multilayer-dielectric structure. The directional asymmetry observed in reflection and transmission for the metal – multilayer-dielectric structure is further examined in the context of Kerr nonlinearity.

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Authors and CV

Svitlana Ilchenko, PhD, Researcher of the Branch of Applied Optics at the Institute of Physics, NAS of Ukraine. Area of scientific interests is optics, laser physics and plasmonics.
https://orcid.org/0000-0001-6924-2225

Victor Taranenko, Dr Sci., Professor, Director of the Branch of Applied Optics at the Institute of Physics, NAS of Ukraine. Area of scientific interests is nonlinear optics, laser physics, holography.
E-mail: victor.taranenko@iao.kiev.ua
https://orcid.org/0000-0003-3193-9267

Authors' contributions

Ilchenko S.G.: formal analysis, investigation, validation, visualization, writing – original draft.
Taranenko V.B.: conceptualization, formal analysis, investigation, validation, visualization, writing – review & editing.

Асиметрія при резонансному прямому/зворотному відбитті від наноструктури метал – багатошаровий діелектрик

С.Г. Ільченко, В.Б. Тараненко

Анотація. Представлено експериментальне та чисельне дослідження залежної від напрямку асиметрії резонансних оптичних характеристик наноструктури метал – багатошаровий діелектрик (МБД), яка має багато спільного з плазмонною конфігурацією Тамма. Продемонстровано, що коли структура МБД освітлюється з протилежних сторін, існує помітна асиметрія резонансів при відбитті вперед/назад, що відрізняється від строго симетричних резонансів пропускання, що вказує на класичну оптичну взаємність. Порівняльні вимірювання проводились на металевій плівці та квазіперіодичній діелектричній структурі, які ідентичні відповідним параметрам структури МБД. Асиметрія за напрямком відбиття та пропускання коротко обговорюється для модифікованої МБД структури з нелінійністю Керра.

Ключові слова: структура метал – багатошаровий діелектрик, плазмон Тамма, поверхнева мода, фотонний кристал.