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Theoretical study of visible light refraction phenomena occurring at noble metal–air interfaces

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Based on the generalized reflection and refraction theory, the visible light wavelength-dependent refraction behaviors occurring at both Ag–air and Au–air interfaces are qualitatively attributed to the non-synchronized variations of electric and magnetic parameters of the light. Numerical results show that distribution of time-averaged Poynting vector of the transmitted light traveling through a wedge shaped noble metal film may be affected by width and divergence of the incident light beam, energy losses, and so on. Careful consideration of effects of multi-factors on the refraction phenomena are necessary to establish reasonable relationship among measured results by using different experimental methods. Our work may provide a new possible angle of view to understand the refraction phenomena occurring at noble metal–air interface.

1. Introduction

The noble metals play significant roles in the artificial metamaterials, resulting to the interesting negative light refraction [1–8], which has been assumed to be induced by the effects of the magnetic resonators [1], surface plasmon waves [2], Goos–Hänchen shifts [3], energy losses [4,5], and so on. Partly due to the configuration complexity of the metamaterials adopted, origins of the negative refraction phenomena have not been fully understood yet.

For simplicity, the pure noble metal wedge shaped films have been adopted to experimentally investigate light refraction properties at noble metal–air interface [5–7]. Several interesting and somewhat surprising results have been discovered. For an instance, the refraction index of Ag and Au films measured by using spectroscopic ellipsometer are close to each other when the incident light have free-space wavelength of $\lambda = 632.8$ nm, however, the power refraction index of Ag wedge shaped film obtained from the distribution of energy flow of the transmitted wave is significantly different from that of Au wedge shaped film [6,7]. In addition, difference of refraction behaviors between transverse magnetic (TM) and transverse electric (TE) polarized lights seem trivial in these experiments [6,7]. Here, we shall mention another experiment, in which all-angle negative refraction of TM polarized light and positive refraction of TE polarized light in Ag–TiO_2–Ag multilayered structures have been observed [8]. In principle, the refraction phenomena mentioned above are associated with reflection and refraction of light at the noble metal–dielectric interface, thus a common physics mechanism and similar refraction behaviors may be suggested from the view of reflection and refraction.

Several types of generalized laws of reflection and refraction have been proposed previously [9,10]. It is still somewhat difficult to predict theoretically the distribution of energy flow of the transmitted wave traveling through the lossy interface. For example, two sets of typical equations were developed to study the situations for the light entering from the dielectric medium to the metal [9] or vice versa [10]. Detailed calculations show wrongly that the light path or the pseudo-refractive index will not be reversible and continuous in all-angle conditions [6,7]. Therefore, theoretical study of light refraction phenomena occurring at the noble metal–air interfaces may be helpful for developing and testing the generalized theory of reflection and refraction.

In this work, we shall attempt to provide a new possible angle of view to understand the refraction phenomena occurring at noble metal–air interface. The remainder of the paper is organized as follows. In Section 2, the generalized reflection and refraction theory developed by us recently [11–13] and calculation model are briefly introduced. In Section 3, numerical results and discussions are presented. Finally, some conclusions are drawn in Section 4.

2. Theory and calculation model

The generalized reflection and refraction theory [11–13] developed by us have provided reasonable explanations for several

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refraction phenomena observed, e.g., the negative refraction at left-handed material (LHM)–air interface obey the Snell's law [12,14], whereas negative refraction may also be produced by heavily lossy wedge without negative refraction index [5–7,12], negative refraction of TM polarized light and positive refraction of TE polarized light in Ag–TiO_2–Ag multilayered structure [8,13], and so on.

For simplicity, we consider the case of a TM polarized harmonic homogeneous plane wave (HHPW) traveling through a noble metal–air interface. It is known that a noble metal can be represented by a complex scalar relative permittivity $\tilde{\varepsilon} = |\tilde{\varepsilon}| \exp(j\alpha_{\varepsilon})$ and a real scalar relative permeability $\mu = 1$, respectively [6–8,15]. (In this paper, the complex valued parameters are marked with "$\sim$".) Apparently, variation of electromagnetic wave parameters of $\tilde{E}(t), \tilde{D}(t), \tilde{H}(t)$ and $\tilde{B}(t)$ is usually non-synchronous in the noble metal or at the noble metal–air interface,. Thus the real valued boundary conditions with time terms are adopted as follows [11–13]:

$$\mathrm{Re}(\tilde{H}_i(t)) + \mathrm{Re}(\tilde{H}_r(t)) = \mathrm{Re}(\tilde{H}_t(t)), \tag{1}$$

$$a_i \mathrm{Re}(\tilde{H}_i(t)) \cos\theta_i - a_r \mathrm{Re}(\tilde{H}_r(t)) \cos\theta_r = a_t \mathrm{Re}(\tilde{H}_t(t)) \cos\theta_t, \tag{2}$$

$$b_i \mathrm{Re}(\tilde{H}_i(t)) \sin\theta_i + b_r \mathrm{Re}(\tilde{H}_r(t)) \sin\theta_r = b_t \mathrm{Re}(\tilde{H}_t(t)) \sin\theta_t. \tag{3}$$

where $a_\varsigma = \mathrm{Re}(\tilde{\eta}_\xi) - \mathrm{Im}(\tilde{\eta}_\xi)\mathrm{Im}(\tilde{H}_\varsigma)/\mathrm{Re}(\tilde{H}_\varsigma)$ (since $\mathrm{Re}(\tilde{E}_\varsigma(t)) = \mathrm{Re}(\tilde{\eta}_\xi \tilde{H}_\varsigma(t)) \equiv a_\varsigma \mathrm{Re}(\tilde{H}_\varsigma(t)), \tilde{\eta}_\xi = \sqrt{\tilde{\mu}_\xi \mu_0 / \tilde{\varepsilon}_\xi \varepsilon_0}$ is wave impedance), $b_\varsigma = \mathrm{Re}(\tilde{k}_\xi) - \mathrm{Im}(\tilde{k}_\xi)\mathrm{Im}(\tilde{H}_\varsigma)/\mathrm{Re}(\tilde{H}_\varsigma)$ (since $\mathrm{Re}(\tilde{D}_\varsigma(t)) = \mathrm{Re}(\tilde{k}_\xi \tilde{H}_\varsigma(t)) \equiv b_\varsigma \mathrm{Re}(\tilde{H}_\varsigma(t)), \tilde{k}_\xi = \frac{\omega}{c}\sqrt{\tilde{\mu}_\xi \tilde{\varepsilon}_\xi}$ is wave vector), $\varsigma = i, r, t$ refers to the incident, reflected and transmitted wave, and $\xi = 1, 2$ indicates the two media on both sides of the interface, respectively. According to Eqs. (1) and (3), we have $b_i \sin\theta_i = b_r \sin\theta_r = b_t \sin\theta_t$. Thus the generalized Snell's law including effects of energy losses is obtained as

$$\theta_r = \theta_i, \tag{4a}$$

$$\sin\theta_t = b_i \sin\theta_i / b_t = \sin\theta_i \frac{\mathrm{Re}(\tilde{k}_1)}{\mathrm{Re}(\tilde{k}_2)} \frac{1 + tg(\alpha_{k_1}) tg(\omega t)}{1 + tg(\alpha_{k_2}) tg(\omega t)}. \tag{4b}$$

Further, solving Eqs. (1) and (2), formulas for transmission and reflection coefficients may be obtained [11–13].

To take into account the effects of non-synchronized variation of electromagnetic wave parameters of $\tilde{E}(t), \tilde{D}(t)$, and $\tilde{H}(t)$, all possible direction relationships among electric and magnetic parameters of the incident, reflected and transmitted waves at the metal–air interface have to be considered [13]. A half of possible cases the normalized H_i towards inside are given in Fig. 1, the other similar cases correspond to the normalized H_i towards outside. Neglecting the imaginary part of noble metal permittivity in the visible range, the noble metal permittivity becomes a negative real number [15], which refers that direction of $\vec{D}(t)(\equiv \mathrm{Re}(\vec{\tilde{D}}(t)))$ in the noble metal is contrary to that of $\vec{E}(t)(\equiv \mathrm{Re}(\vec{\tilde{E}}(t)))$. It is found from Fig. 1(a) that, to satisfy the real valued boundary conditions 1–3, the refracted angle is negative. Fig. 1(b) presents the case that the time-dependent Poynting vector (TDPV) of the usual incident wave propagates away from the interface, and the usual reflected wave plays a role as real incident one [13], the refracted angle is negative respecting to the real incident wave. When imaginary part of metal permittivity is nontrivial, i.e., direction of $\vec{D}(t)(\equiv \mathrm{Re}(\vec{\tilde{D}}(t)))$ in the noble metal may also parallel to that of $\vec{E}(t)(\equiv \mathrm{Re}(\vec{\tilde{E}}(t)))$, it is clear from Fig. 1(c) and 1(d) that, in these cases, the refraction is positive respecting to the real incident wave. The details of refraction behaviors of HHPWs occurring at the lossy interface may refer to the Refs. [12,13]. It is demonstrated that negative refraction of TM polarized wave and positive refraction of TE polarized one may occur at the lossy interface when difference between the electric damped angle α_ε and magnetic damped angle $\alpha_\mu (= 0)$ of the lossy medium is significant. Decreasing the electric damped angle α_ε of the lossy medium, positive refraction of both TM and TE polarized waves may occur at the lossy interface. Noting the facts that α_ε of the noble metals decrease with decreasing wavelength of light, the predictions mentioned above are qualitatively in agreement with the wavelength-dependent refraction behaviors presented in Refs. [6,7].

Furthermore, we shall quantitatively address the light refraction phenomena observed at noble metal–air interfaces. Following the experiment device presented in Refs. [6,7], the model and coordinate axis x adopted in numerical simulations are shown in Fig. 2. Assuming the center of the incident light beam locals at $x_c = 1.2$ mm. The width ($w = 2$ mm) and divergence angle ($\theta_d < 0.3$ mrad) of the incident light beam are divided into $2N_1$ and N_2 equal parts, respectively. Choosing a position of $x = x_c + \frac{n_1 w}{2N_1}$ ($n_1 \in [-N_1, N_1]$) and an angle of $\theta_i = \frac{n_2}{N_2}\theta_d$ ($n_2 \in [-N_2, N_2]$) for the incident light, the time dependent refracted angle θ_t, fields of $H_\varsigma(t)$ and $E_\varsigma(t)$ at the interface are calculated by using formulas mentioned above, propagation of light in the layer of homogeneous film is taken into account by using the term of $e^{-\mathrm{Im}(\vec{k}) \cdot \vec{r}}$, ($r$ is the propagation distance of the light in the film) [13]. When the transmitted light arrive at the screen, the TDPV of transmitted light is given as

$$\vec{S}_\varsigma(x,t) \equiv \vec{E}_\varsigma(t) \times \vec{H}_\varsigma(t). \tag{5}$$

Further, the TAPV may be obtained

$$\langle \vec{S}_\varsigma(x) \rangle \equiv \sum_{t=0}^{T} \vec{S}_\varsigma(x,t) \Delta t / T_{period}. \tag{6}$$

The position of peak of TAPV is written as x_{peak}, according to the adopted model and coordinate shown in Fig. 2, the calculated power refracted angle $\theta_{t,S}^{cal}$ may be given as

$$\theta_{t,S}^{cal} = \theta_{wedge} - arctg\left(\frac{x_c - x_{peak}}{h}\right). \tag{7}$$

where $h = 20.55$ m is the distance between the wedge shaped film and the screen. Further, the power refraction index n_S^{cal} is obtained as

$$n_S^{cal} = \frac{\sin\theta_{t,S}^{cal}}{\sin\theta_{wedge}}. \tag{8}$$

3. Numerical results and discussions

In calculations, the permeability of the non-magnetic noble metal films is always taken as $\mu_m = 1$, the permittivity is given as $\tilde{\varepsilon}_m = \tilde{n}_m^2$, where $\tilde{n}_m$ is refraction index measured by using spectroscopic ellipsometer [6,7]. It is pointed out that the power refraction index obtained from distribution of the TAPV of the transmitted light traveling through the wedge shaped film is termed as n_S^{exp}.

We firstly focus on the case of a beam of visible light travel through a wedge shaped Ag film. Choosing the wedge angle as $\theta_{wedge} = 58.8$ μrad and the free-space wavelength of the incident light as $\lambda = 632.8$ nm, which corresponds to one of the experiments presented in Ref. [6]. The permittivity of the Ag film is taken as $\tilde{\varepsilon}_{Ag} = (0.216 + j3.881)^2 = -15.02 + j1.68 = 15.1e^{j0.96\pi}$ for the light with $\lambda = 632.8$ nm [6]. The Drude–Lorentz model with five Lorentz oscillators has been adopted to simulate the spectral