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Polarization properties of subwavelength metallic gratings in visible light band

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ABSTRACT Optical polarization properties of aluminum, gold and aluminum/gold subwavelength metallic gratings (SWMGs) are investigated numerically in the visible light band. Their performance as polarizing beam splitters are simulated with RCWA for varied metallic materials, grating depth and incident angle. Metallic waveguide theory is applied to explain the performance difference between Au and Al grating. A new type of Al/Au bimetallic is also investigated numerically for potential applications.

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1 Introduction

Metallic gratings with subwavelength period (subwavelength metallic gratings, SWMGs) have been widely researched for special optical applications based on their form-birefringence effect, such as polarizing beam splitters (PBS), anti-reflective polarizers, projection display, and so on. Moreover, their compact size and light weight are also advantageous to the miniaturization and integration of optical systems [1–4]. When incident light is linearly polarized such that the electric vector is parallel to the grating groove, the light is almost totally reflected as if the SWMGs were a flat metallic mirror. This state of polarization is called TE-polarization. When the incident light is linearly polarized such that the electric field is perpendicular to the grating groove, most of the light propagates through the grating. This state of polarization is called TM-polarized. When the incident light is unpolarized, the reflected light is mainly TE-polarized whereas the transmitted light is mainly TM-polarized. Based on these properties, the SWMGs can be used as a good polarizing beam splitter. Much of the research on polarizing beam splitting ability is carried in the infrared [1, 2, 5, 6]. In our work optical polarization properties of SWMGs are investigated in the visible light band. The performance of Al and Au gratings as PBS is investigated by rigorous coupled-wave analysis method (RCWA) whose period are 140 nm. The performance difference between Al and Au SWMGs is explained

by metallic waveguide theory, which is consistent with results calculated with RCWA. A new type of Al/Au bimetallic subwavelength grating is also investigated. Influence of the metal thickness ratios on the performance of this kind of grating is also researched by RCWA method.

The paper is organized as follow: The RCWA method and simulation model are introduced at first. The simulation results and discussions are presented in Sect. 3. Metallic waveguide theory is also introduced in this section to explain some of these results.

2 Numerical simulation method and model

2.1 Simulation method

Rigorous coupled-wave analysis (RCWA) has been widely used for the analysis and the design of diffractive structures. RCWA was developed initially for the investigation of holographic gratings. Later it was successfully applied to transmission and reflection arbitrarily profiled dielectric and/or metallic surface-relief gratings [7–9].

In the technique to analyze the diffraction from surface relief grating structures, the grating is divided into a large number of sufficiently thin planar grating slabs to approximate the grating profile to an arbitrary degree of accuracy. The light source used here is a unit-amplitude monochromatic plane wave with a wavelength λ and incident at an angle relative to the z -axis (as shown in Fig. 1). The electromagnetic field inside a grating with a complex dielectric function is given by wave equations derived from Maxwell's equation. Based on a full vector implementation, our RCWA routine reduces Maxwell equations to a simple eigenvalue problem. Well-known transmission-line methods were used to solve the required boundary-value problem [10, 11].

2.2 Simulation model

The schematic diagram of the Al and Al/Au grating is shown in Fig. 1 (left) and that of Au grating is shown in Fig. 1 (right). For aluminum gratings there is a protective layer (hafnium oxide) whose depth and refractivity index are 50 nm and 1.8. The substrate is made of common BK7 glass and its refractivity index is 1.53. The x -axis is perpendicular to the grating groove as shown in the diagram. The period and filling factors of all the gratings are 140 nm and 0.4, respectively. The

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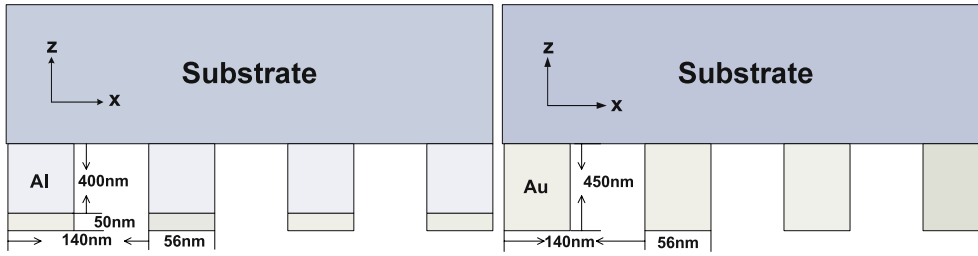


FIGURE 1 Schematic diagram of the subwavelength metallic grating. Al grating structure is shown in *left* and that of Au *right*

grating depth of Al is 400 nm with 50 nm thickness protective layer and the grating depth of Au is 450 nm. In our simulation model the light source is monochromatic plane wave. The refractive index of Au and Al are selected according to [12].

3 Results and discussions

3.1 Analysis by metallic waveguide theory

The normalized transmission and reflection efficiency vs. wavelength of Au and Al grating for TM and TE polarized light are calculated with RCWA and shown in Fig. 2. The numerical results shown that for Al grating reflection efficiency of TE polarized wave (Rte) is considerable larger than that of the TM-polarized wave (Rtm), and transmission efficiency of the TM-polarized wave (Ttm) is much larger than that of TE-polarized wave (Tte) during the whole visible light band. But for Au gratings, the difference between reflection and transmission for different polarizations is not large or constant in visible light band. So we can conclude that aluminum gratings are more suitable for use as a polarizing beam splitter in the visible light band than gold gratings. We believe that the performance difference between these two gratings is due to the different refractive index change vs. wavelength in the visible light band. The phenomena are explained by metallic waveguide theory in detail as follows:

The period of metallic grating simulated above is much smaller than $\lambda/2$ and plasmon cannot be excited under illumination of light in this kind grating [13, 14]. So the polarizing beam splitter ability of this kind of SWMG cannot be ex-

plained by excitation of the plasmon resonance surface waves. Metallic waveguide theory has been successfully used to explain the working mechanism of the SWMGs as a polarizing beam splitter [13]. In our paper metallic waveguide theory is used to explain the performance difference between Au and Al metallic gratings. One cell of the grating is treated as a part of the metallic waveguide, and the guide mode in such a waveguide is investigated. The field in such a guide can be written as a linear superposition of the so-called waveguide mode. The structure of this cell is shown in Fig. 3 with two metallic long slabs on each side and one dielectric gap in the center. Regions 2 and 3 of the refractive index n_2 consist of the same metal. The medium in region 1 is a homogeneous dielectric with a real refractive index n_1 . The width of the region is d . The incident wavelength is λ which varies from 400 nm to 700 nm. The mode eigenvalue function of this kind symmetrically metal enclosed waveguide are presented here. For TE mode:

$$\kappa_1 d = m\pi + 2 \arctan\left(\frac{\alpha_2}{\kappa_1}\right), \quad m = 0, 1, 2, \dots \quad (1)$$

For TM mode:

$$\kappa_1 d = m\pi + 2 \arctan\left(\frac{\varepsilon_1 \alpha_2}{\varepsilon_2 \kappa_1}\right), \quad m = 0, 1, 2, \dots \quad (2)$$

where $\kappa_1 = (k_0^2 \varepsilon_1 - \beta_m^2)^{-1/2}$, $\alpha_2 = (\beta_m^2 - k_0^2 \varepsilon_2)^{1/2}$, $k_0 = 2\pi/\lambda$, β_m is the propagation constant of TM_m mode or TE_m mode.

The transmissivity difference between the TM mode and TE mode has been qualitatively explained in [13], which

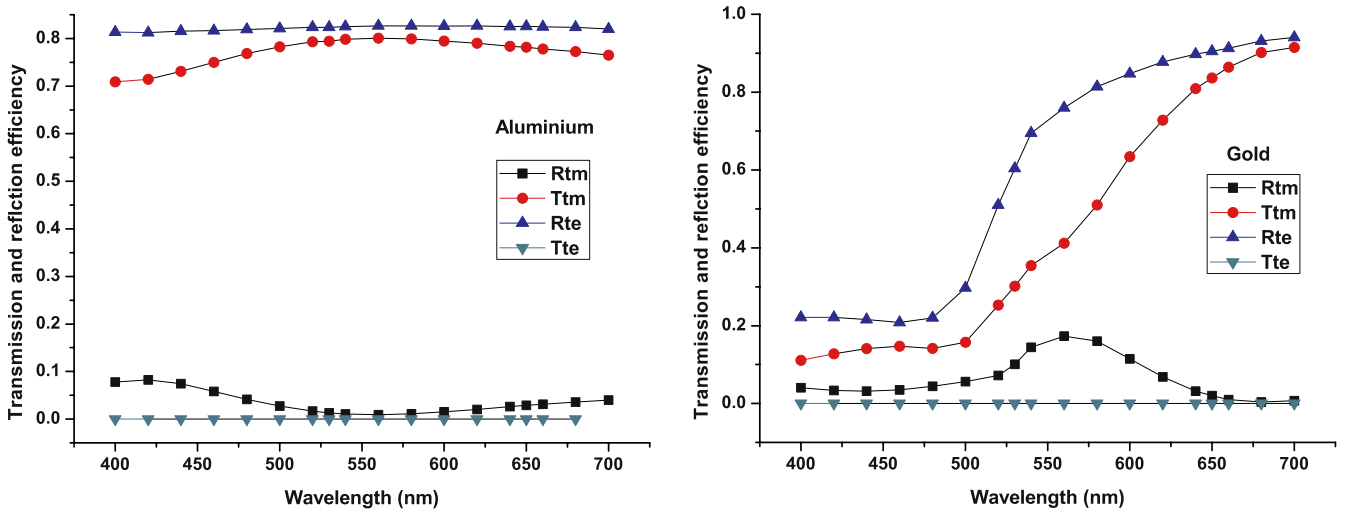


FIGURE 2 Normalized transmission and reflection efficiency of Al, Au, Al/Au grating vs. wavelength. Rtm, Rte, Ttm, Tte represent reflectivity of TM-polarized wave, reflectivity of TE-polarized wave, transmissivity of TM-polarized wave, transmissivity of TE-polarized wave, respectively

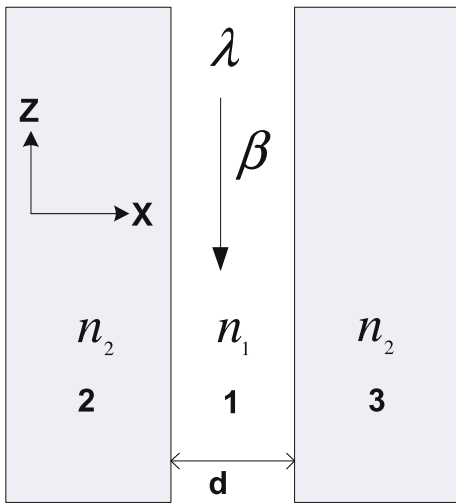


FIGURE 3 Structure of the long infinitely slab waveguide model, β is the propagation constant, λ is the incident wavelength, n_2 is the refractive index of metal in region 1 and 3, n_1 is the refractive of the air gap with width d

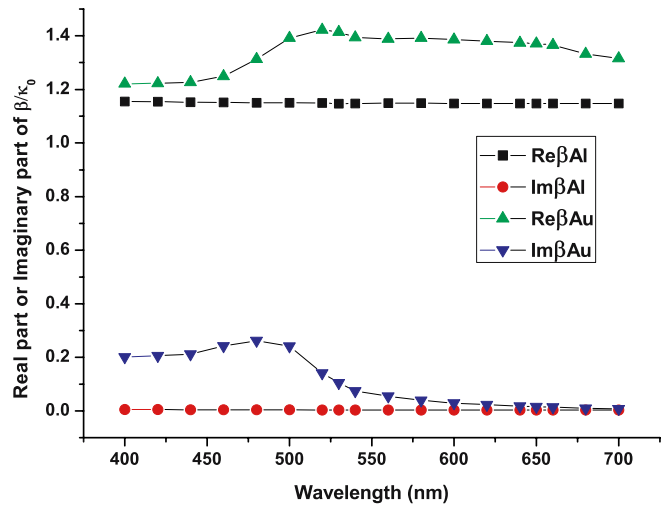


FIGURE 4 Propagation constants β_0/k_0 of Au and Al slab waveguide (TM mode). $\text{Re } \beta \text{Al}$, $\text{Im } \beta \text{Al}$, $\text{Re } \beta \text{Au}$, $\text{Im } \beta \text{Au}$ are real part, imaginary part of β_0/k_0 of Al waveguide, real part and imaginary part of β_0/k_0 of Au waveguide, respectively

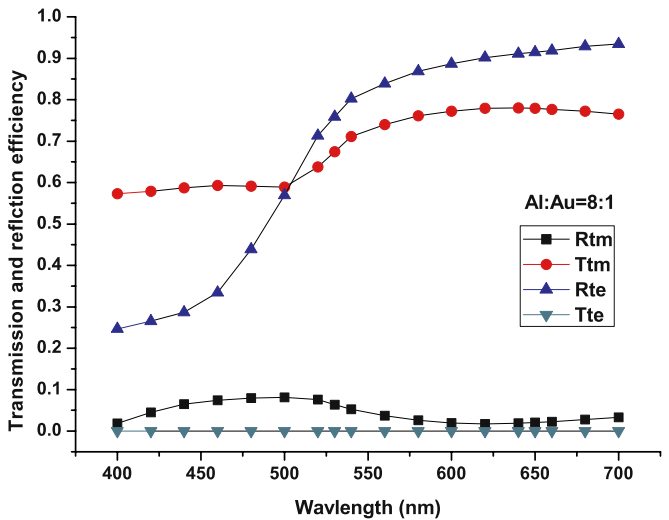
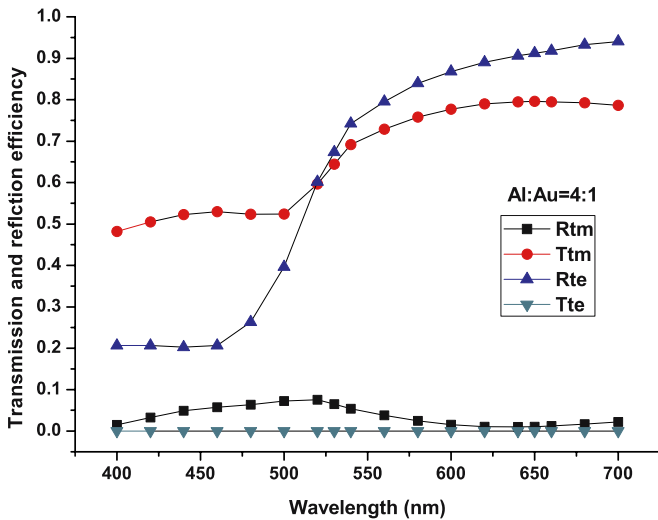
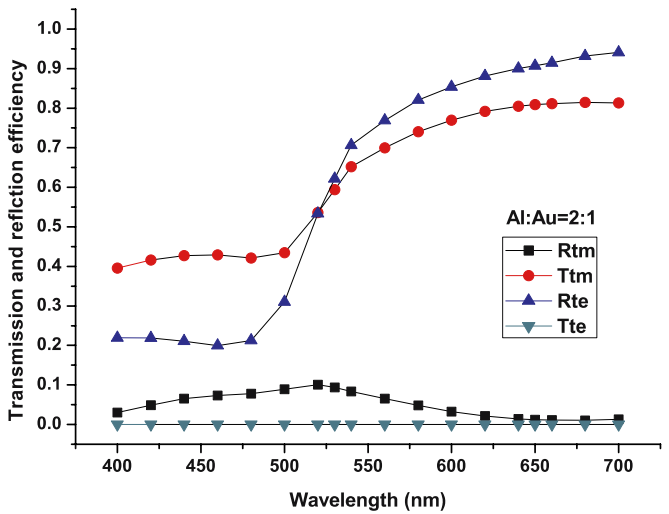
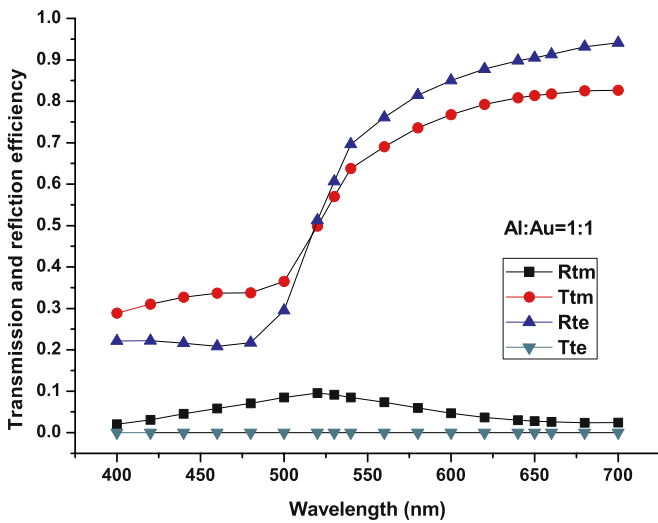


FIGURE 5 Normalized transmission and reflection efficiency of Al/Au bimetallic grating vs. wavelength, from left to right the thickness ratio of Al and Au are 1 : 1, 2 : 1, 4 : 1, 8 : 1, respectively

shows the transmissivity of the TE-polarized wave is nearly zero and consistent with our results shown in Fig. 2. In our paper we explained the transmissivity difference of TM polarized waves between Au and Al gratings by using the metallic waveguide theory. The transmissivity difference of the TE mode can be deposited similarly. Because the width of grating (d) is much smaller than the incident wavelength (λ), only the TM_0 should be considered. The eigenvalue function for the TM_0 mode can be derived from (2):

$$\tanh\left(\frac{1}{2}\alpha_1 d\right) = -\frac{\varepsilon_1 \alpha_2}{\varepsilon_2 \alpha_1}, \quad (3)$$

where $\alpha_1 = -i\kappa_1$, $\kappa_1 = (k_0^2 \varepsilon_1 - \beta_m^2)^{1/2}$, $\alpha_2 = (\beta_m^2 - k_0^2 \varepsilon_2)^{1/2}$, $k_0 = 2\pi/\lambda$, β_m is the propagation constant of TM_m mode. From (3) propagation constants (β_0) for different λ can be solved by using a computer program and are shown in Fig. 4.

The curves of real part of β_0 for Al (Re β_{Al}) and imaginary part of β_0 for Al (Im β_{Al}) are more flat than that of Re β_{Au} and Im β_{Au} in the visible light band, which are similar to calculated results shown in Fig. 2. Known to all, if the propagation constant of a waveguide mode has a large imaginary part, the amplitude of the transmitted field exponentially attenuates along the propagation direction. The Im β_{Au} fluctuates slightly before 480 nm and is followed by a monotonic decrease, as a result the transmissivity changes little before 480 nm and follows with a monotonic enhancement. This deduction is consistent with results calculated by RCWA shown in Fig. 2. In Fig. 4, the imaginary part of β_0 for Al grating is smaller and more stable than that of Au grating, so the transmissivity of TM-polarized wave for Al grating is larger and more stable than that of Au grating, which is consistent with calculated results shown in Fig. 2. In conclusion, metallic waveguide theory can be used to explain the performance difference between Al and Au grating for the transmissivity of TM-polarized wave and is consistent with RCWA method.

3.2 Al/Au bimetallic grating

A new type Al/Au bimetallic grating is also numerically investigated in our paper. The structure of this kind of Al/Au bimetallic grating is shown in Fig. 1 (left), which is similar to that of Al grating, except that the protective layer is replaced with Au films. To investigate the influence of the Au layer on the performance of this kind of bimetallic grating, we change the thickness ratio of Au and Al layers from 1 : 1 to 1 : 8. The simulation results are presented in Fig. 6. The

curves of R_{tm} , R_{te} and T_{te} change slightly with the thickness ratio, but the curve of T_{tm} from 400 nm to 500 nm drives up as the ratio decreases. Moreover, simulation results also show that the existence of the Au layer of Al grating influences the R_{te} very greatly even with a very small ratio, such as 1 : 8. When comparing Fig. 5 with Fig. 2, we find that the shape of curves for Al/Au bimetallic grating is between that of Al and Au grating, so we can obtain differently shaped curves by tuning the thickness ratio of Au and Al. And also for SWMGs working at constant wavelength, the reflectivity and transmissivity for different polarization can be tuned by change the thickness ratio.

3.3 Effect of incident angle and grating depth on the performance of SWMGs

The normalized transmission and reflection efficiency of TM-polarized and TE-polarized wave vs. incident angle are also calculated with RCWA. The model in Fig. 1 assumed an illumination with a TM-polarized or TE polarized monochromatic wave at fixed wavelength $\lambda = 650$ nm as the incidence angle θ is scanned with an angular resolution of 0.01° . The wavelength 650 nm was selected because it lies in the communication window of polymer optics. The simulated results were shown in Fig. 6. The curves of R_{tm} , T_{tm} , R_{te} and T_{te} are very flat in the wide band incident angle (0° to 50°), which reveal that the Al grating perform stably in spite of the incident angle. For Au gratings, R_{tm} increase slightly with the incident angle in contrast with the T_{tm} . When compared three diagrams in Fig. 6, we find that curve of Al/Au vs. incident angle is between that of Al and Au grating.

The normalized transmission and reflection efficiency of TM and TE wave vs. grating depth are also simulated with RCWA. The Al thickness of Al or Al/Au gating is tuned from 100 nm to 800 nm and for Au grating the thickness of Au is the same change. The simulation results are shown in Fig. 7. The grating depth has less influence on the reflectivity and transmissivity of TE-polarized wave than that of TM-polarized wave. This phenomenon may be explained briefly as follows: The electric field of the TM-polarized wave is perpendicular to the grating groove, which will induce the restricted movement of electrons perpendicular to the metallic wires. If the grating depth changes, the interaction area between the incident TM-polarized field and metallic grating changes and so does the number of restricted moving electrons changes; as a result, transmissivity and reflectivity also change. But for

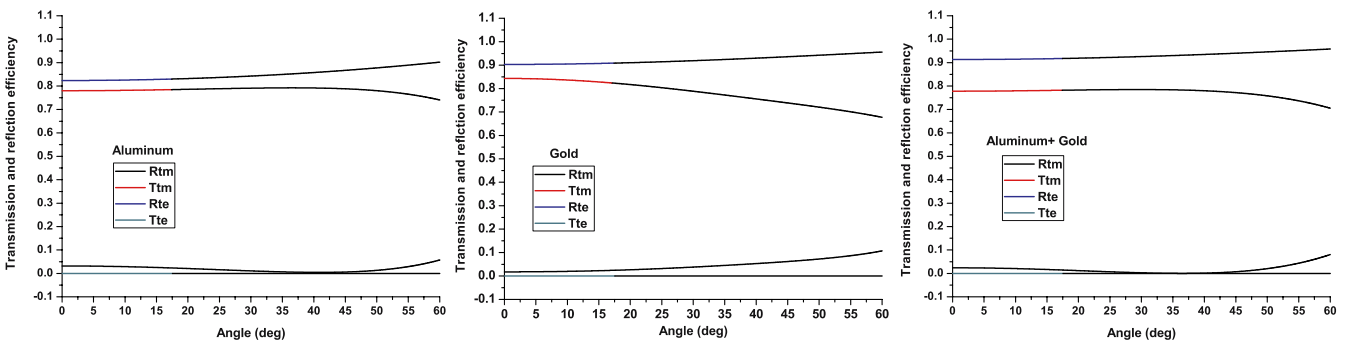


FIGURE 6 Normalized transmission and reflection efficiency of Al, Au, Al/Au grating for TM and TE polarized wave vs. incident angle

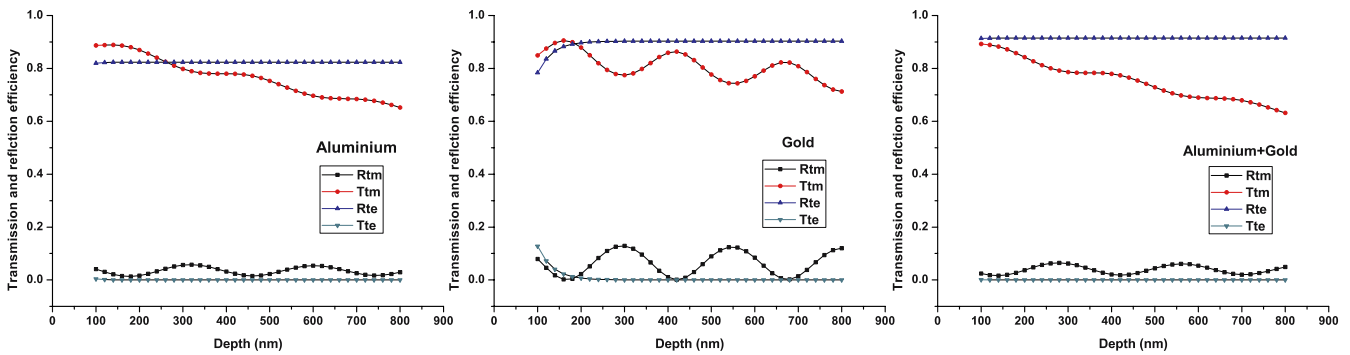


FIGURE 7 Normalized transmission and reflection efficiency of Al, Au, Al/Au grating for TM and TE polarized wave vs. grating depth

a TE-polarized wave, its electric field direction is parallel to the grating groove and so will not induce restricted electron movement perpendicular to the metallic grooves. Also most of the electric energy is totally reflected as analyzed by metallic waveguide theory [13], as a result the grating depth change has little influence on the transmissivity and reflectivity.

The Rtm of these three kinds of gratings change periodically with the grating depth. The fluctuation of the gold grating is the largest. Ttm of these gratings fluctuate periodically and decrease slightly with grating depth because of the enhanced optical absorption of metal. This kind of periodical fluctuation can be analyzed based on the waveguide mode in the grating. As analysis above showed, SPs cannot be excited in this kind of grating, and the transmission and reflection process are associated with waveguide modes. The simulation results show that the influence of the grating depth on the performance of the Al grating is the least.

4 Summary

Subwavelength metallic gratings made of different materials are investigated numerically in the visible light band. A new type of Al/Au bimetallic grating is also investigated numerically. The performance of these Al, Au, Al/Au subwavelength metallic gratings as polarizing beam splitters in visible light band are compared. Calculated results show that the Al grating performed best. Metallic waveguide theory is also introduced to explain the performance difference be-

tween the Al and Au grating. All the simulation results help to illuminate optical properties of metallic grating and optimized its application in integrated optics and so on.

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