

Polarization characteristics of subwavelength aluminum wire grating in near infrared

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Abstract Rigorous coupled wave analysis (RCWA) was used to investigate the polarization characteristics of subwavelength aluminum wire grating in near infrared. Upon exposure to the atmosphere, a layer of Al_2O_3 forms rapidly on the aluminum wires, so the effect of metal oxide layers on the polarization properties is modeled and analyzed. It is shown that subwavelength aluminum wire grating with oxide layers forming on the wires still offers excellent polarization properties. As the thickness of the oxide layer increases, the transmission coefficient increases, but the extinction ratio decreases. In addition, a magnesium fluoride (MgF_2) layer was proposed to deposit between the aluminum wires and the substrate to enhance transmission coefficient. The theoretical research shows that subwavelength aluminum grid grating has high transmission coefficient and extinction ratio in near infrared, as well as uniform performance with wide variations in the angle of incidence. These features with their small size make it desirable for use in optical communication and allow more compact component designs.

Keywords integrated optics, subwavelength gratings, polarization-sensitive devices, rigorous coupled wave analysis (RCWA)

1 Introduction

With the development of microfabrication technologies, grating nanostructures with period smaller than wavelength, known also as subwavelength optical elements (SOEs), have attracted more and more attention. They can be used as antireflection (AR) surfaces for visible and near-infrared spectrum application [1–4]. Another application

of such grating is to take advantage of the surface resonance effect induced by different thin layers and the coupling effect at a subwavelength grating to produce a resonance filter with high optical performances, such as flattop band shapes [5]. A third application is the polarization effect. This effect is enhanced by the presence of a subwavelength metal wire grid [6]. With good environmental stability and high reflectivity, gold is the most popular choice for the wire material [5,7,8], but a thin layer of a different metal such as titanium is often required because the gold will not adhere to the substrate. So the design and fabrication process are complicated. Aluminum adheres well to substrates, is relatively easy to deposit, and is commonly used by the semiconductor industry, making it very attractive for the wire material [9–11]. However, upon exposure to the atmosphere, a layer of Al_2O_3 forms rapidly on the aluminum wires, which will affect the polarization properties of the element [12]. In this paper, we model the oxide as a film with 5-nm thickness on the outer surface of the wire on all sides except the bottom and investigate the polarization characteristics of a subwavelength aluminum wire grating in near infrared using rigorous coupled wave analysis (RCWA) [13–15].

2 Principle and modeling

A schematic of the subwavelength aluminum wire grating is illustrated in Fig. 1. It consists of a series of fine parallel aluminum wires coated on transparent substrate. When the period of the grating is far smaller compared with the wavelength of incident light, light polarized parallel to the metal wires is reflected, and light polarized perpendicular to the wires is largely transmitted. The most common explanation of the wire-grid polarizer is based on the restricted movement of electrons perpendicular to the metal wires. If the incident wave is polarized along the wire direction, the conduction electrons are driven along

the length of the wires with unrestricted movement. The coherently excited electrons generate a forward traveling as well as a backward traveling wave, with the forward traveling wave canceling the incident wave in the forward direction. The physical response of the wire grid is essentially the same as that of a thin metal sheet. As a result, the incident wave is totally reflected, and nothing is transmitted in the forward direction. In contrast, if the incident wave is polarized perpendicular to the wire grid, and if the wire spacing is smaller than the wavelength, the Ewald-Oseen field generated by the electrons is not sufficiently strong to cancel the incoming field in the forward direction. Thus, there is considerable transmission of the incident wave. The backward traveling wave is also much weaker, leading to a small reflectance. Thus, most of the incident light is transmitted [16].

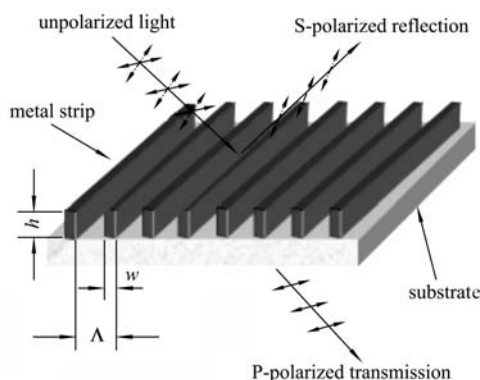


Fig. 1 Schematic of subwavelength aluminum wire grating

Because the grating period (Λ) is far smaller than the wavelength, the traditional diffraction theory is not fit for it again. Mainly, two approaches are used for modeling the microstructures. The first approach is effective medium theory (EMT). According to the theory, the whole structure behaves as if it were homogenous and equivalent to one birefringence film. Consider a one-dimensional grating composed of two materials of material with relative permittivity ε_1 and ε_2 with duty cycle f ($f = w/\Lambda$, w is the width of wire), under normal incidence, the effective indices for the TE (transverse electrical mode) and TM (transverse magnetic mode) polarizations of a subwavelength grating can be estimated from the zero-order EMT [17].

$$n_{TE} = [f\varepsilon_1 + (1-f)\varepsilon_2]^{1/2},$$

$$n_{TM} = [f/\varepsilon_1 + (1-f)/\varepsilon_2]^{-1/2}.$$

By choosing the material and adjusting the duty cycle f , a birefringence effect can be achieved that is much larger than that achieved with conventional optical materials.

The second approach is based on rigorous electromagnetic wave theory, called the RCWA. The RCWA, first introduced in Ref. [13] to analyze the diffraction properties

of TE-polarized light in lossless surface relief grating, can be summarized as follows. In the grating region, the optical fields are formulated in terms of spatial harmonics using the Fourier series expansions of the dielectrics constant. By substituting the components of these spatial harmonics into the wave equation, a sequence of coupled first-order linear differential equations can be generated. The equations can be solved in terms of their eigensolutions. The field distribution in the grating region can be represented by the superposition of these eigensolutions. Transmission and reflected diffractive field can then be derived by matching the appropriate boundary conditions. Subsequently, diffraction efficiencies are calculated for propagating transmitted and reflected diffraction orders. Energy conservation is used as a criterion for convergence of numeric solutions. Input parameter, namely the total number of diffraction orders, is increased until the precision, and the results themselves remain constant within the limits of the chosen numeric accuracy. The case of TM light polarization was treated in a similar manner, using the proper wave equation for this polarization and modifying the coupled wave equations for the case of metal grating.

For an aluminum wire grating, upon exposure to the atmosphere, a layer of Al_2O_3 forms rapidly on the aluminum wires. The layer is both adherent and relatively impervious so that, once formed, it protects the underlying metal from further oxidation. Polarimetric studies indicate that the surface oxide layer is from 2.0 to 5.5 nm thick but that thicker layers readily form in moist environments. Al_2O_3 is uniaxial with a small anisotropy of about 2% [11,12]. To investigate the effect of oxide layer on the polarization properties, we model the oxide as a film with 5-nm thickness on the outer surface of the wire on all sides except the bottom as shown in Fig. 2.

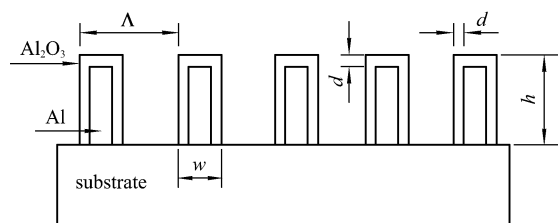


Fig. 2 Modeling of oxide layer

3 Simulation and optimization

For general transmissive polarization-sensitive devices, two parameters are used to characterize the polarizer's performance: transmission E_x and transmittance T_{TM} . T_{TM} is the power transmission coefficient for TM-polarized (electric-field vector perpendicular to the wire) light. E_x is defined as $-10\log(T_{TM}/T_{TE})$, in which T_{TE} is the power transmission coefficient for TE-polarized (electric-field vector parallel to the wire) light. The effects of the oxide

layer on the polarization properties of a subwavelength aluminum wire grating are shown in Fig. 3. The solid line is an ideal polarizer without oxide layer, while the dotted line is a polarizer with the same thickness ($h = 140$ nm), period ($\Lambda = 140$ nm), duty cycle ($f = W/\Lambda = 0.5$), but that includes a 5-nm-thick oxide layer ($d = 5$ nm). The substrate is assumed to be fused silica (refractive index $n = 1.46$). Optical properties of aluminum with complex refractive index at the incident wavelength are from Ref. [12]. It can be seen that the transmission coefficient increases, and the extinction decreases with the oxide layer forming on the aluminum wires. In the 0.8- to 2.0- μ m wavelength range, the transmittance ranges from 79% to 84%, and the extinction ratio ranges from 32 to 43 dB. For the fiber communication window of 1550 nm, the transmittance and the extinction ratio are 80% and 40 dB, respectively.

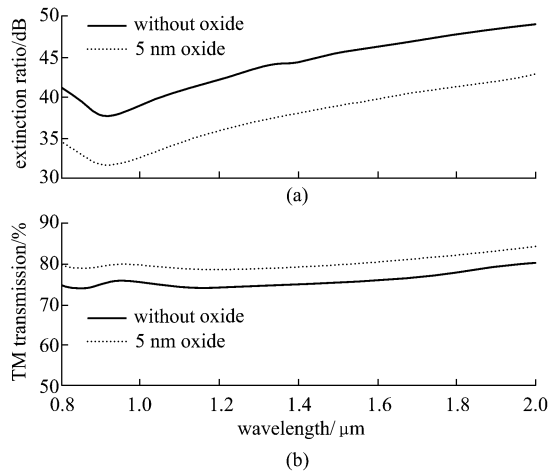


Fig. 3 Effect of oxide on polarization properties of a subwavelength aluminum wire grating at normal incidence. (a) Extinction spectrum; (b) TM transmission spectrum

Furthermore, as the thickness of the oxide layer increases, the transmission coefficient increases, but the extinction ratio decreases (shown in Fig. 4). The effect of

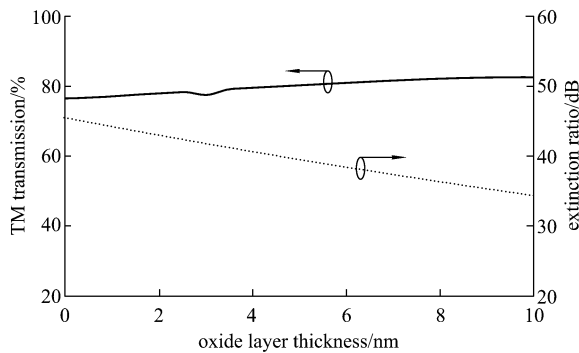


Fig. 4 TM transmission and extinction ratio as a function of oxide layer thickness, normal incidence, and wavelength of incident light is 1550 nm

oxide layer can be attributed almost entirely to the reduction in wire width and height. As the width of the wires is reduced, the wires are narrower for the TM field, and the electrons have less space in which they can vibrate, so the TM transmission coefficient increases. For the TE field, the wires are wider; it is easier to excite electrons to move up and down the wires, so the TE transmission coefficient decreases. The opposite occurs if the width of the wires is reduced. As a result, the T_{TM} and T_{TE} both increases with the oxide layer forming on the wires. However, the increment in T_{TE} is proportionately higher than that in T_{TM} , leading to a decrease in the extinction ratio.

As can be seen from Fig. 5, the polarization properties improve with an increase in the angel of incidence. There are two factors to this improvement. One is simply the polarization dependence of the reflection and transmission of light from the substrate. The transmission of TE light is naturally reduced as the incident angle is increased. Likewise, the transmission of TM light naturally increases as the incident angle increases to the Brewster angle, after which, it drops rapidly. The other factor is that the effective thickness of the grating region increases with increasing incident angle. Because the TE light sees the grating region as an absorbing material, increasing its effective thickness increases the TE attenuation. Similarly, because the TM light sees the grating region as a dielectric material, the increased effective thickness also changes the transmission properties of the grating in a similar manner to any other thin film. The combination of these two effects leads to the improvements in polarization properties with increasing incident angle. The improvements do not continue indefinitely, however. At higher angles of incidence, the TM transmission coefficient reaches a maximum and then rapidly declines. This is due to the passing of the Brewster angle of incidence and having the ± 1 diffracted orders start to propagate, stealing energy away from the zero order. However, because the TE transmission continues to fall,

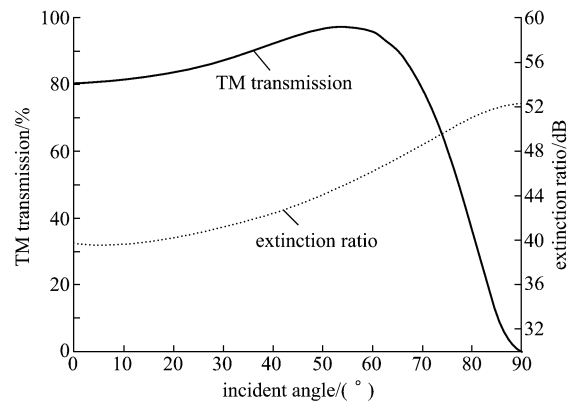


Fig. 5 TM transmission and extinction ratio as a function of incident angle ($\Lambda = 140$ nm, $h = 140$ nm, $d = 5$ nm, $w = 75$ nm, normal incidence, and wavelength of incident light is 1550 nm)

the extinction ratio continues to increase monotonically with increasing incident angle [11].

Furthermore, to enhance TM transmittance, an antireflection layer can be deposited between the metal wires and the substrate (shown in Fig. 6). The effect of additional magnesium fluoride (MgF_2) layer on the polarizer is shown in Fig. 7. It has shown that the antireflection layer can improve the performance of the subwavelength aluminum wire grating and the effect depends on the other parameters. It is another tool for customizing the performance of a polarization-sensitive device for specific applications.

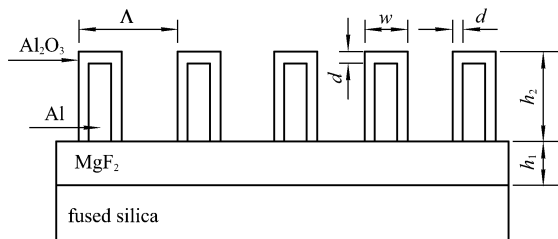


Fig. 6 Schematic of subwavelength aluminum wire grating with an additional magnesium fluoride layer

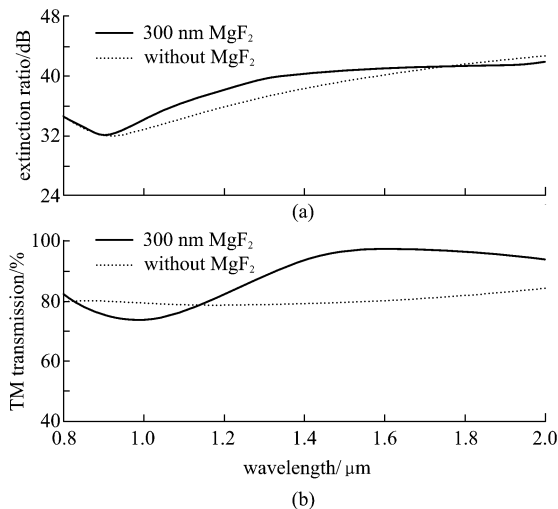


Fig. 7 Effect of MgF_2 layer on polarization properties of a subwavelength aluminum wire grating ($\Lambda = 140$ nm, $h = 140$ nm, $d = 5$ nm, $w = 75$ nm, and normal incidence). (a) Extinction spectrum; (b) TM transmission spectrum

4 Conclusion

In conclusion, the actual oxide layers forming on the aluminum wires have only a small effect on the performance of the polarization-sensitive devices. With the oxide layer forming on the aluminum wires, the TM transmission coefficient increases, and the extinction ratio decreases. The device with oxide layer still offers excellent

polarization properties. In addition, to improve the polarization properties, a magnesium fluoride layer was proposed to deposit between the metal wires and the substrate. The results show that polarization-sensitive device has high transmission coefficient and extinction ratio over near-infrared spectrum, as well as uniform performance with wide variations in the angle of incidence. These features with their small form factor make this device desirable for use in optical communication as well as other polarization optics applications.

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