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## Multilayer thin film polarizer design for far ultraviolet using induced transmission and absorption technique

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### ABSTRACT

Good theoretical designs of far ultraviolet polarizers have been reported using a  $\text{MgF}_2/\text{Al}/\text{MgF}_2$  three layer structure on a thick Al layer as a substrate. The thicknesses were determined to induce transmission and absorption of p-polarized light. In these designs Al optical constants were used from films produced in ultrahigh vacuum (UHV:  $10^{-10}$  torr). Reflectance values for polarizers fabricated in a conventional high vacuum ( $\sim 10^{-6}$  torr) using the UHV design parameters differed dramatically from the design predictions. Al is a highly reactive material and is oxidized even in a high vacuum chamber. In order to solve the problem other metals have been studied. It is found that a larger reflectance difference is closely related to higher amplitude and larger phase difference of Fresnel reflection coefficients between two polarizations at the boundary of  $\text{MgF}_2$ /metal. It is also found that for one material a larger angle of incidence from the surface normal brings larger amplitude and phase difference. Be and Mo are found good materials to replace Al. Polarizers designed for 121.6 nm with Be at  $60^\circ$  and with Mo at  $70^\circ$  are shown as examples.

**Keywords:** far ultraviolet, multilayer, thin film, polarizer, induced transmission and absorption

### 1. INTRODUCTION

Analyzing the polarization of radiation in the far ultraviolet (FUV: 120-230 nm) spectral region has been of interest since the first report by Cole and Oppenheimer<sup>1</sup>. Many basic experiments in atomic and molecular physics require knowledge of the state of polarization of the light used as a probe in the experiment. The Lyman- $\alpha$  line ( $\lambda=121.6$  nm) has been very popular in many studies. In space, resonance scattering of solar chromospheric radiation that anisotropically illuminates neutral hydrogen atoms in the corona can produce linear polarization in the coronal Lyman- $\alpha$  emission of up to 20%. Magnetic fields in the corona should modify this polarization via the Hanle effect. Synchrotron radiation is also highly polarized, giving additional motivation to the search for a FUV polarizer.

At the shorter part of the FUV, transparent birefringent materials are not available and recourse must be had to reflection polarizers. A single metal surface at the Pseudo-Brewster angle of incidence is not enough for a high degree of polarization. Hamm et al.<sup>2</sup> designed a triple-reflection-polarizer (TRP) using gold coated mirrors. Because it had a polarization efficiency of 97% and maintained the direction of incident radiation, it was used by several authors<sup>3-5</sup>. The transmittance of the unpolarized light of such a system was about 4%. The merit of the metal multi-surface polarizer is that it works well in a broad wavelength region.

Some of present authors have used a concept of induced transmission and absorption to design a multilayer reflection polarizer in the FUV region. Using  $\text{MgF}_2$  and Al as a low absorbing and a high absorbing materials pair, high s-polarization reflectance and a high degree of polarization were obtained. In the designs, Al optical constants ( $N=n+ik$ ,  $n$ : refractive index,  $k$ : extinction coefficient) were used from films produced in ultrahigh vacuum (UHV)<sup>6</sup>. Reflectance values for polarizers fabricated in a conventional high vacuum using UHV design parameters differed dramatically from the design predictions<sup>7</sup>. Oxidation of the Al was suspected as a key cause of the discrepancy. This is a serious problem that has to be solved for successful fabrication of thin film devices based on theoretical designs. One approach to the above problem is to characterize the oxidized Al layer and include it in the design to optimize the performance<sup>8</sup>. Another approach is to use metals that are less likely to oxidize compared to Al. This is the approach taken in this report.

Three layer optical devices were designed as FUV polarizers and their performances were compared to  $\text{MgF}_2/\text{Al}/\text{MgF}_2$  devices. All metals with optical constants listed in Ref. 9, 10 were checked as replacements for Al. Calculated results for 121.6 nm are explained. The changes of polarizer performance are investigated as a function of the angle of incidence.

## 2. INDUCED TRANSMISSION AND ABSORPTION METHOD

In the FUV region, all thin film materials are absorbing. Unfortunately, absorption usually decreases reflectance and/or transmittance. Berning and Turner<sup>11</sup> showed that a reasonably thick metal film can be induced to transmit a surprising amount of energy of a particular wavelength when it is surrounded by suitably chosen interference film combinations. They called this technique induced transmission and applied it to a band pass filter design. This concept is used to design a FUV polarizer<sup>12</sup>.

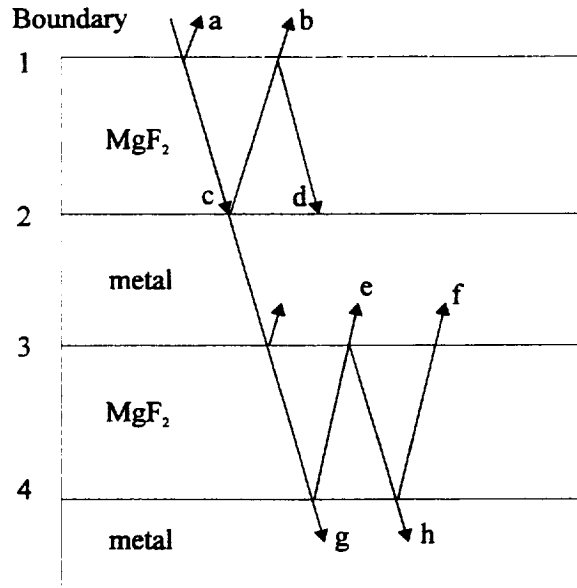
The first step in our approach is the design of a multilayer that has a very low p-polarization reflectance. This can be achieved by inducing transmission and absorption for this polarization state. However, the multilayer must also have a large s-polarization reflectance to be a good polarizer. For an oblique angle of incidence, the Fresnel reflection and transmission coefficients have different values for the s and p-polarization states. The Fresnel coefficients are complex numbers for absorbing film materials, and amplitude changes as well as phase angle changes are different for the two polarizations. The differences are large at the boundary between high and low absorbing materials. Therefore, we can design a good polarizer using a high and low absorbing materials.

In the FUV region, LiF is the lowest absorbing material, but it is hygroscopic and unsuitable for practical use<sup>13</sup>. The most attractive low absorbing material in this region is  $\text{MgF}_2$ <sup>14</sup>. We use  $\text{MgF}_2/\text{metal}/\text{MgF}_2$  three layer structures on a thick opaque metal substrate. The top  $\text{MgF}_2$  layer is used as a transmission induced layer for the p-polarization state. The role of the top  $\text{MgF}_2$  layer is to maximize the amount of the p-polarized light that can pass through the center metal layer. The bottom  $\text{MgF}_2$  layer acts as a transmission and absorption induced layer. Because of the differences in Fresnel transmission and reflection coefficients between two polarizations, these two  $\text{MgF}_2$  layer work differently for the s-polarization state. Therefore, we can achieve a high degree of polarization.

The film thicknesses are estimated using the method of summation<sup>15</sup>. In analyzing a multilayer thin film, the summation method is more straightforward than matrix methods. It can trace step by step every reflected and transmitted wave, and can select important waves among all the multiply reflected waves. Important waves are those which have much larger amplitudes than other waves at a specific point. The thin film thickness is estimated by considering the phase difference between important waves.

Fig. 1 shows the light waves considered to determine the thin film thicknesses. At the top  $\text{MgF}_2$  layer, the transmission of the p-polarized light is maximized by making the reflected light (a and b in Fig. 1) interfere constructively because only two boundaries are above the center metal layer and the amplitudes of the Fresnel reflection coefficients are quite different at these two boundaries. In this way, the electric fields that reach the second boundary can interfere destructively (c and d in Fig. 1), and this gives a small reflected amplitude from that boundary (b in Fig. 1). Even though this reflected light interferes constructively with the light reflected from the first boundary, the sum is smaller than any other case. In Fig. 1, the wave d passes through the top  $\text{MgF}_2$  layer twice, and is reflected at the first and second boundary after it starts from c. The thickness of the top  $\text{MgF}_2$  layer is determined to make the sum of the phase changes of this round trip equal to  $\pi$ .

The bottom  $\text{MgF}_2$  layer is sandwiched by high reflecting metal layers and is designed for use as a transmission and absorption induced layer for p-polarization. In order to induce absorption, the sum of the waves going up to the central metal layer must have a large amplitude. This is achieved by making the waves interfere constructively. For this purpose, e and f waves are taken as the important waves in Fig. 1. For the transmission induced layer, the g and h waves are important. If these waves interfere constructively, they will have large amplitudes when they go into the substrate. As a result, this three layer structure has a large transmittance for p-polarization. The constructive interference between e and f and between g and h are achieved simultaneously because the bottom  $\text{MgF}_2$  layer is sandwiched by a metal. The phase differences between the e and f waves and the g and h waves are equal. The thickness of the bottom  $\text{MgF}_2$  layer is chosen to make the phase difference equal to zero. The exact thicknesses of the two  $\text{MgF}_2$  layers and the best thickness of the central metal layer are determined by computer fitting using the estimated thicknesses as the initial values.



**Figure 1.** Important light waves for estimation of the thicknesses of the MgF<sub>2</sub> layers.

### 3. THE EFFECT OF OPTICAL CONSTANT ON POLARIZER PERFORMANCE

Three high reflecting boundaries are present in a MgF<sub>2</sub>/metal/MgF<sub>2</sub> three layer structure on top of an opaque metal. Reflection and transmission of light at a boundary are fully described by Fresnel reflection and transmission coefficients and are dependent on the optical constant of the metal layer and the incident angle of the light. The dependence of polarizer performance on these parameters is explained in terms of Fresnel reflection coefficients as

$$r_s = \frac{N_1 \cos \theta_1 - N_2 \cos \theta_2}{N_1 \cos \theta_1 + N_2 \cos \theta_2} \quad (1)$$

$$r_p = \frac{N_1 \cos \theta_2 - N_2 \cos \theta_1}{N_1 \cos \theta_2 + N_2 \cos \theta_1} \quad (2)$$

The complex optical constants  $N_j$  and the complex refractive angles  $\theta_j$  obviously follow Snell's law

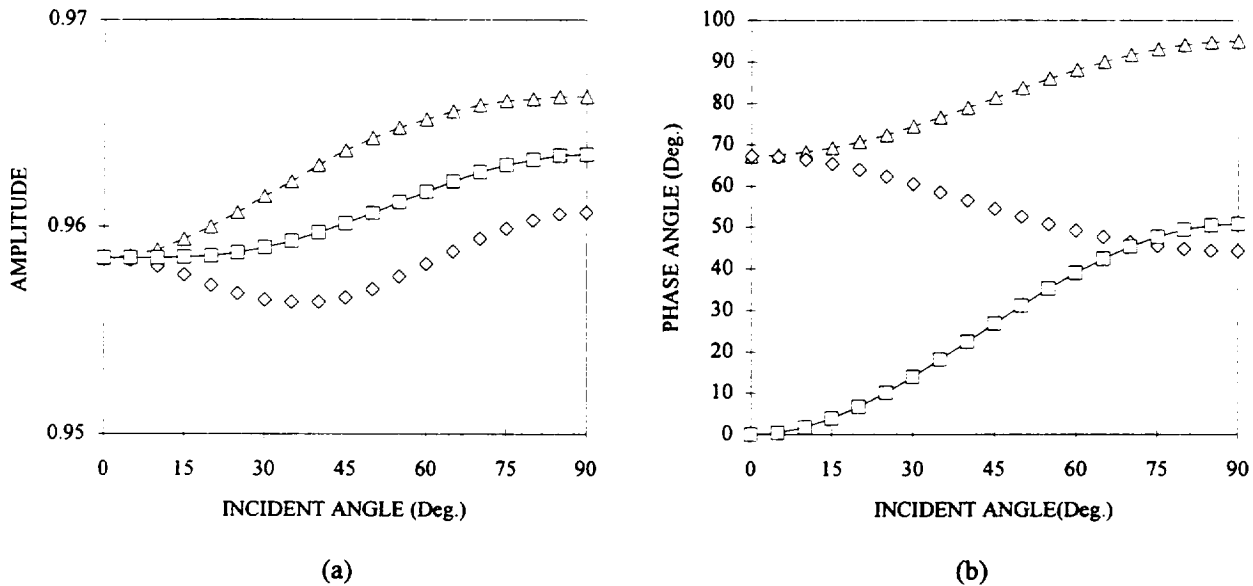
$$n_0 \sin \theta_0 = N_1 \sin \theta_1 = N_2 \sin \theta_2 \quad (3)$$

where  $n_0$  and  $\theta_0$  are refractive index and incident angle in the vacuum, respectively. The amplitudes  $|r_{s/p}|$  and phases  $\phi_{s/p}$  of Fresnel reflection coefficients are defined as following for each polarization.

$$r_{s/p} = |r_{s/p}| e^{i\phi_{s/p}} \quad (4)$$

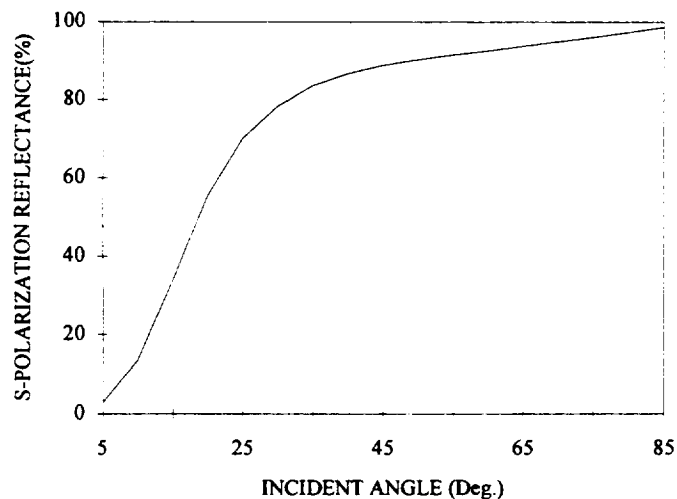
An example of the changes of the amplitudes and phases of Fresnel reflection coefficients at the boundary of a MgF<sub>2</sub>/Al layer are shown in Fig. 2 as a function of incident angle for 121.6 nm. Fig. 2-(a) shows that the amplitude of s-polarization increases monotonically as the incident angle increases. In contrast, the p-polarization amplitude has a pseudo-Brewster angle around 35°. Both polarizations have amplitude values higher than 0.95 for whole the range of incident angles. This is the

unique property for a  $\text{MgF}_2/\text{Al}$  boundary that makes Al so popular for FUV applications. The average value of the two amplitudes increases as the incident angle increases. Fig. 2-(b) shows the phase changes of reflected light for s and p-polarizations, respectively, as the incident angle changes. It also shows that the phase difference between the two polarization states increases as the incidence angle increases.



**Figure 2.** The changes of amplitude (a), and phase angle (b) of Fresnel reflection coefficients for a  $\text{MgF}_2/\text{Al}$  boundary. The triangles and diamonds are for s and p-polarizations, respectively. Squares are for average in (a) and difference in (b).

The polarizer performance obtained from a boundary with the properties shown in Fig. 2 is given in Fig. 3. Only the change in s-polarization reflectance is shown. At each angle of incidence, the p-polarization reflectance stays below 1.0%. The results in Fig. 3 show that large differences in reflectance are possible at large angles of incidence where phase angles are different and average amplitude of Fresnel coefficients are high at the  $\text{MgF}_2/\text{metal}$  boundary.



**Figure 3.** The change of s-polarization reflectance for polarizers designed with Al as a metal layer. At each angle of incidence, the p-polarization reflectance stays below 1.0%.

#### 4. POLARIZER PERFORMANCES USING OTHER METALS

Obtaining good agreement between design and actual performance of  $\text{MgF}_2/\text{Al}/\text{MgF}_2$  designs is severely limited by oxidation of the Al. Using  $\text{MgF}_2$  as the low absorbing material, other metals were investigated to replace highly oxidizing Al. The optical constants of metals that were considered are listed in Table 1. The requirements desired in the design were higher amplitudes and larger phase difference in Fresnel reflection coefficients at the metal boundary with  $\text{MgF}_2$ . Average amplitude and phase difference of Fresnel reflection coefficient for each metal at  $45^\circ$  angle of incidence are compared in Fig. 4 using optical constants for 121.6 nm. Metals with larger  $(-k/n)$  value have the higher average amplitudes in Fig. 4-(a). Obviously Al has the highest average amplitude. The next best materials are Be and Mo.

Table 1. Optical constants of metals considered in this study at 121.6 nm.

metal	n	-k
Al	0.042	1.139
Be	0.362	1.409
Pd	1.290	0.660
Pt	1.345	1.178
Cr	0.994	0.723
Ag	1.248	0.565
Au	1.268	0.972
Mo	0.812	0.930
Cu	1.045	0.804
Ir	1.450	1.040
Rh	1.160	0.649
Ni	0.948	0.833
Os	1.190	1.080

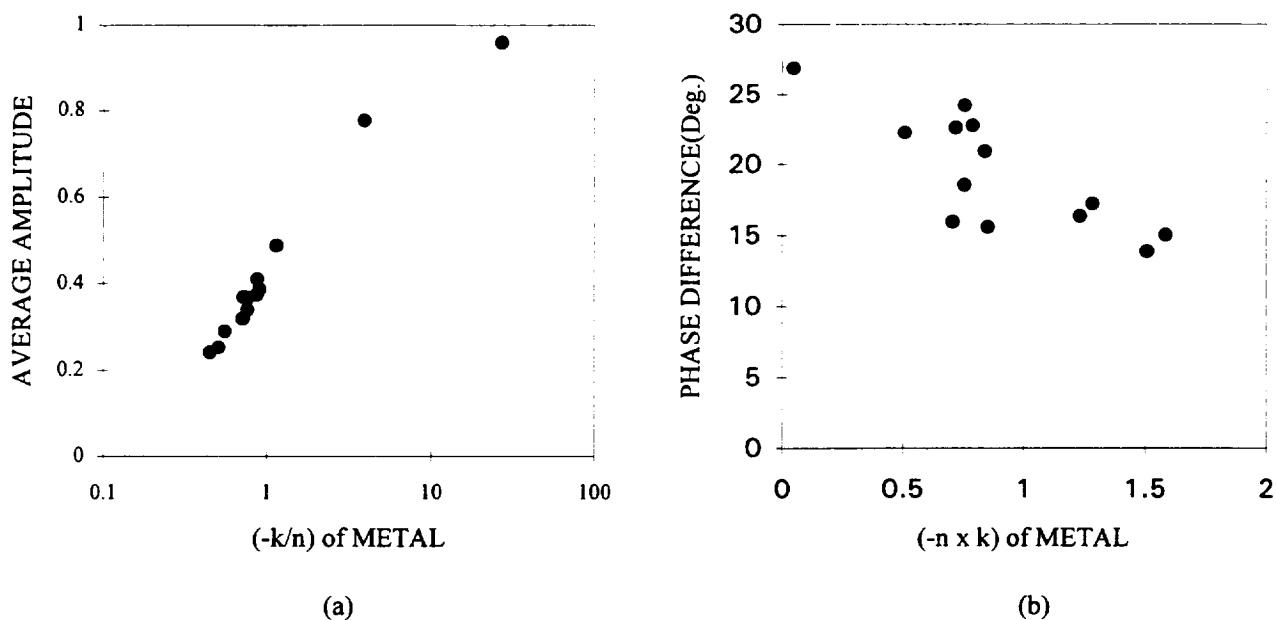
Fig. 4-(b) shows the phase difference of reflected light between two polarizations for each  $\text{MgF}_2/\text{metal}$  boundary. The figure is drawn as a function of  $(-n \times k)$  to show the trends. The results show that a lower value of  $(-n \times k)$  causes a larger phase difference. From Fig. 4-(b), Mo is seen to be the second to best material, and Be, Cr, and Ni are the next materials. The conclusion drawn from Fig. 4 is that a metal with a smaller n value brings larger  $(-k/n)$  and smaller  $(-n \times k)$  values and thereby leads to better polarizer performance.

Based on the above discussions, Be and Mo were selected as candidate metals. The s-polarization reflectances of  $\text{Be}/\text{MgF}_2$  and  $\text{Mo}/\text{MgF}_2$  polarizers designed to have p-polarization reflectance less than 1% are shown in Fig. 5 as functions of the angle of incidence. The results show that larger angles of incidence from the surface normal are needed to achieve high s-polarization reflectance compare to Al. For example, s-polarization reflectance obtained at  $45^\circ$  angle of incidence using Al is obtained at  $75^\circ$  for Be and at  $80^\circ$  for Mo.

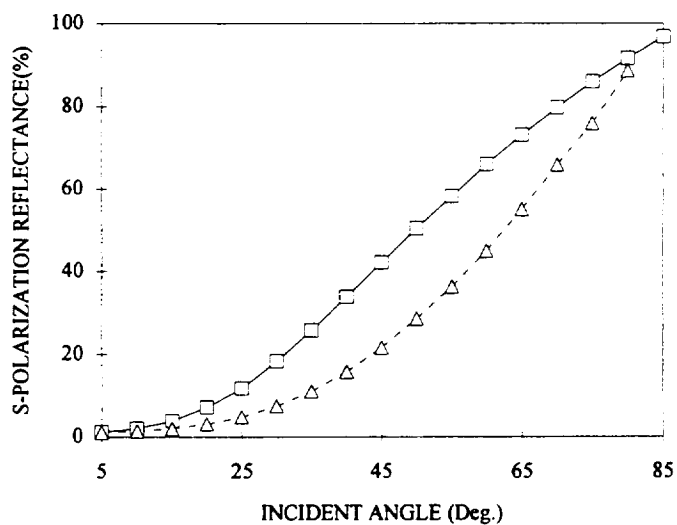
A larger angle of incidence brings better polarization performance. However, it may cause difficulty in experimental set up and aberration problems. If sacrificing s-polarization reflectance is acceptable, smaller angle of incidence can be selected from Fig. 5. Spectral performances of polarizers designed with Be at  $60^\circ$  and with Mo at  $70^\circ$  for 121.6 nm are shown in Fig. 6 as examples. There is no drastic change in the optical constants of these metals or  $\text{MgF}_2$  in the FUV region, so a similar approach can be applied for other wavelengths.

The two candidate replacement metals have not been studied as much as Al. According to Ref. 10, only a few studies have been made on Be. They have produced widely different results, particularly in the visible region of the spectrum where the methodology and instrumentation are best developed and the results are therefore normally most consistent. The variability of results may be traced to the difficulty of sample preparation. Bulk samples are usually produced by high-pressure sintering of microcrystalline powder, and this results in incorporation of significant amounts of  $\text{BeO}$  in the sample. The FUV optical properties of Mo has also not been studied much, and truly clean surfaces have not been measured<sup>9</sup>. In the

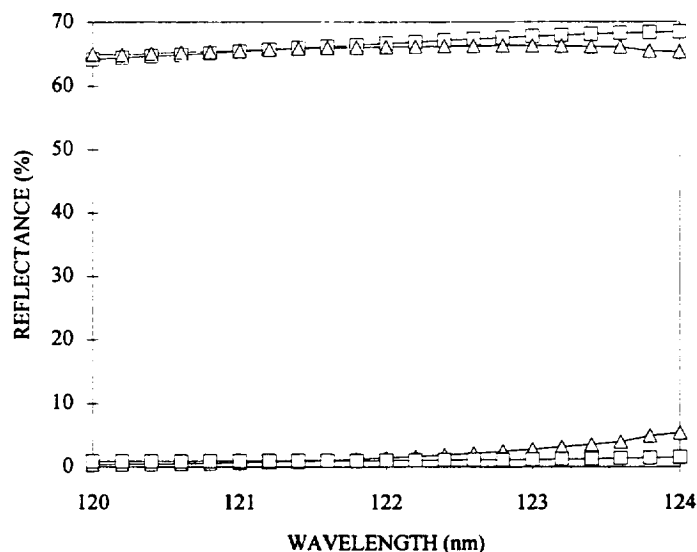
visible region, the optical properties of Mo have been measured many times and the results generally agree rather well. In order to fabricate these polarizers precise optical constants measurement is a prerequisite.



**Figure 4.** Average amplitude (a) and phase difference (b) of Fresnel reflection coefficient at a boundary of  $\text{MgF}_2/\text{metal}$ .



**Figure 5.** The changes of s-polarization reflectance for polarizers designed with Be (square) and Mo (triangle) as the angle of incidence changes. At each angle of incidence, the p-polarization reflectance stays below 1.0%.



**Figure 6.** Spectral performances of polarizers designed with Be at  $60^\circ$  (square) and with Mo at  $70^\circ$  (triangle) for 121.6 nm

## 5. CONCLUSIONS

The requirements on the optical constants of a metal needed to obtain good induced transmission and absorption performance have been examined. Large values of amplitudes and phase differences of Fresnel reflection coefficients at the  $\text{MgF}_2$ /metal boundary are the necessary conditions. A metal of smaller refractive index,  $n$ , brings better polarizer performance. At larger angles of incidence from the surface normal, higher s-polarization reflectances are possible while maintaining p-polarization reflectance less than 1%. Be and Mo are good candidate metals to replace highly oxidizing Al.

## 6. ACKNOWLEDGMENTS

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