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Facile route of flexible wire grid polarizer fabrication by angled-evaporations of aluminum on two sidewalls of an imprinted nanograting

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Abstract

In this study, we report a new method to fabricate a wire grid polarizer (WGP) that greatly relaxes the requirement on patterning and etching, and can be easily applied to produce flexible WGP. The technique is to pattern a high aspect ratio and narrow linewidth grating by nanoimprint lithography followed by two angled aluminum depositions in opposite directions to produce the narrow spacing between the aluminum lines required for a visible band WGP. Anisotropic reactive ion etching is used to remove the aluminum deposited at the top of the grating but leave the aluminum layer on the grating sidewalls, thereby forming a metal wire grid with much smaller spacings than a lithographically defined grating. As a result, the fabricated WGP showed good performance in a wide range of visible wavelength.

(Some figures may appear in colour only in the online journal)

1. Introduction

A polarizer is an essential optical device for many optical systems and networks such as polarization-based imaging systems, free-space optical switching networks, and fiber-optic networks. Conventional polarizers are bulky optics and may not be suitable for certain applications. A metal wire grid is a potential candidate for making a high-quality, integration-capable, thin-film-type polarizer [1–8]. Wire grid polarizers (WGPs) offer a large spectral working range, small feature size and good integrability. WGPs are important for various applications such as microscopy or imaging systems, and can also be used as polarized beam splitters. The use of a WGP to replace the traditional polarizing film in an

LCD can improve the LCD brightness as little light is absorbed by a WGP and reflected light can be recycled. Generally, a WGP consists of a periodical arrangement of conductive (metallic) wires on a transparent substrate. Upon illumination, a wire grid polarizer transmits light with an electrical field vector perpendicular to the wires (transverse magnetic (TM) polarization) with high efficiency, and reflects the parallel counterpart (transverse electric (TE) polarization). In addition to the transmission of TM-polarized light, the extinction ratio, which is defined by the transmission ratio of TM- and TE-polarized light, is another characteristic optical property of a wire grid polarizer. The spectral working range and the optical properties of a wire grid polarizer (such as transmittance and extinction ratio) are determined by the grating material and the structural parameters of the metal grating such as the period, grating height, and linewidth. In the last two decades various research results on the fabrication

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of WGP using NILs have been reported [1–8]. Ekinici *et al* demonstrated the realization of a new bilayer metal WGP [9]. They fabricated the bilayer metal WGP by evaporating an aluminum film onto a poly(methyl methacrylate) resist grating fabricated using interference lithography. Hsu *et al* described the fabrication process of a flexible nano-wired polarizer by contact-transferred and mask embedded lithography using a polyurethane acrylate mold [10]. To pattern the fine pitch required for WGP, nanoimprint lithography (NIL) has been used in recent years due to its potential for high-resolution and high-throughput nanoscale patterning [11–14]. Previously we reported the fabrication of bilayer metal WGP on flexible plastic substrates by roll-to-roll UV nanoimprint lithography using an epoxysilicone resist [15] and metal evaporation technique [16]. The high-throughput UV-NIL process has the potential to enable large area metal WGP fabrication [16, 17].

Displays have progressed toward increasingly thinner, lighter weight, and more flexible devices over the last few years. This is especially true in the field of mobile devices. Polarizers made on polymer substrate could find applications in future flexible LCD displays. WGP requires the fabrication of subwavelength metal gratings, which presents a significant challenge for patterning and etching of dense structures, particularly for use in visible wavelength applications. This becomes even more challenging to process on a flexible substrate. It is known that a WGP should have a period lower than 150 nm in order to provide adequate bandwidth to cover the visible light range. In this study, a flexible WGP was fabricated on a poly(ethylene terephthalate) (PET) film by using a new method with nanoimprint lithography (NIL). Even though the imprinted high aspect ratio grating had a relatively large 220 nm period, the WGP obtained using the new method still showed very good performance in the wide visible band of the spectrum. This was made possible by using double angled aluminum deposition to cover the sidewalls of the imprinted polymer grating; therefore a much narrower spacing between the aluminum lines was obtained. Isotropic reactive ion etching was then used to selectively remove the aluminum deposited at the top of the grating, thereby forming a metal wire grid with a much smaller spacing than a lithographically defined grating. This new approach significantly relaxes the stringent requirement for the fine line patterning process used in traditional methods, and is especially desirable for future manufacture of flexible WGP using a roll-to-roll nanoimprint process.

2. Experimental details

NIL was performed on a flexible PET film in order to fabricate a flexible WGP. A nanograting of 220 nm period, 70 nm linewidth, and 200 nm height was imprinted into epoxy-silsesquioxane material. As compared with the material reported in [18], the epoxy-silsesquioxane used in this work was synthesized by using a larger amount of fluorinated compound to achieve higher aspect ratio structures. Then, two angled aluminum depositions were performed from both sides of the grating walls at 40° angle from a normal direction. Aluminum from the upper part of

the pattern was removed by reactive ion etching. The obtained WGP had a unique structure in which there were aluminum coatings on both sides of the wall of the nanopattern, creating a flexible WGP on PET.

2.1. Materials and synthesis of SSQ

To synthesize the SSQ material, phenyltrimethoxysilane (PTMS), (3-glycidyloxypropyl)trimethoxysilane (GTMS), (tridecafluoro-1-octyl)triethoxysilane (FTES), CsOH, and propylene glycol monomethyl ether acetate (PGMA) were purchased from Aldrich Chemical (St Louis, MO, USA). Photoacid generator (PAG) was purchased from Craig Adhesive and Coating Co. (Newark, NJ, USA) under the compound name of UV9390C. It contained about 50 wt% of bis(4-dodecylphenyl)iodonium hexafluoroantimonate as an active ingredient. Synthesis of poly(phenyl-*co*-3-glycidyloxypropyl-*co*-perfluorooctyl)silsesquioxane (epoxy-SSQ) was carried out by a modified method that has been reported in [18]. PTMS, FTES, and GTMS were used to synthesize epoxy-SSQ. The mold release agent 1H,1H,2H,2H-perfluorodecyltrichlorosilane (FDTS) was purchased from Gelest Inc. (Morrisville, PA, USA). Silquest A-187 silane (GTMS as the main ingredient) was purchased from Crompton Co. (Lisle, IL, USA). PET film was obtained from 3M Co. (St Paul, MN, USA) with a thickness of 50 μm .

2.2. Instruments

A Nanonex 2000 imprinting tool (Monmouth Junction, NJ, USA) with vacuum capability and wavelength for UV curing at 365 nm or a light curing system (ELC-430) from Electro-Lite Corporation (Bethel, Ct, USA) was used for UV-NIL. Aluminum was deposited by electron-beam evaporation. Reactive ion etching (RIE) was conducted in an LAM 9400 tool (LAM Research Corporation, Fremont, CA, USA). Scanning electron microscopy (SEM) was performed by using a Hitachi SU8000 scanning electron microscope (Tokyo, Japan). Transmission of TM and TE was measured by using an HR4000CG spectrometer (Ocean Optics Inc., Dunedin, FL, USA) and a Nikon Eclipse TE300 microscope (Tokyo, Japan), with the assistance of a high-quality polarizer.

2.3. Nanoimprint process

The formulation of the nanoimprint resist was prepared by dissolving the epoxy-SSQ resin in PGMA, followed by the addition of PAG (1 wt% of the epoxy-SSQ resin). The original silicon oxide master molds were vapor coated with FDTS in order to achieve easy mold release after the NIL processes. The epoxy-SSQ resin solution was spun on a flexible PET film substrate. The substrates were previously surface treated with O₂ plasma and then vapor coated with Silquest A-187 silane as an adhesion promoter to the SSQ resist material. The imprinting process was performed under UV light exposure for a few seconds at room temperature. A Nanonex 2000 imprinting tool with vacuum capability for UV curing at 365 nm or a light curing system (ELC-430) from Electro-Lite Corporation was used for imprinting and curing. The imprinting pressure was typically 40 psi.

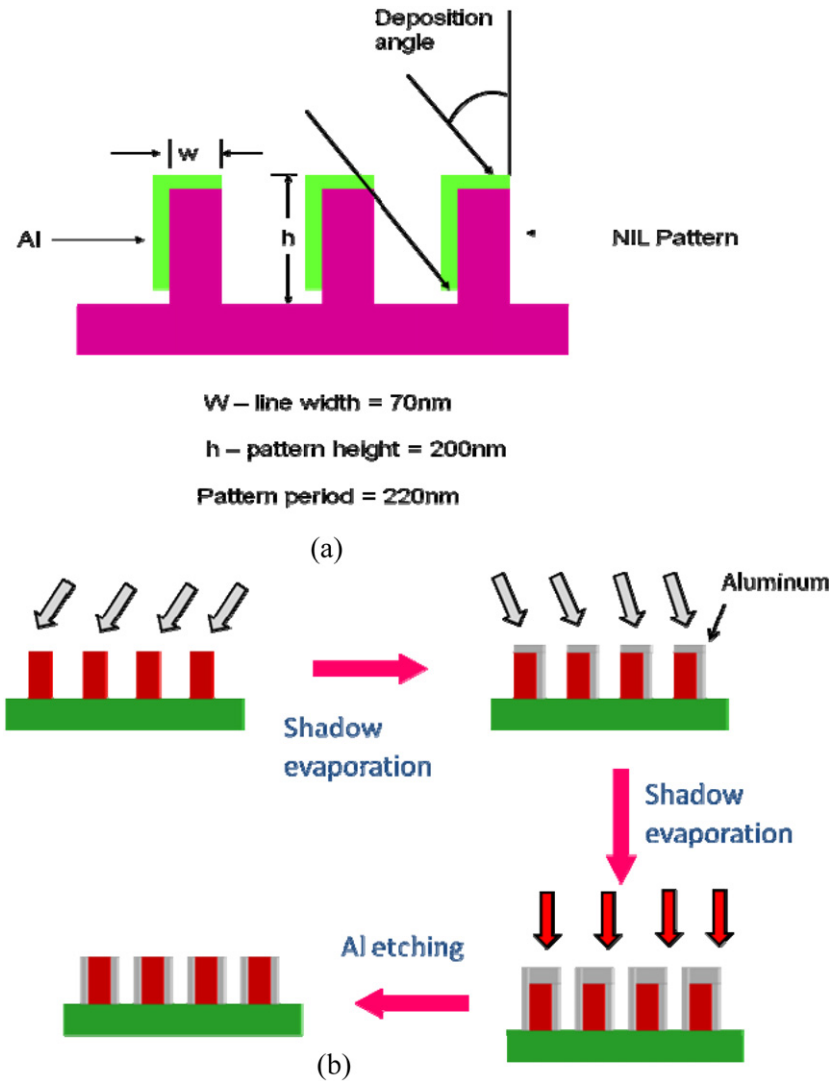


Figure 1. Tilted aluminum deposition on a nanopattern (a) and the total process involved in the fabrication of a WGP in this study (b).

2.4. Aluminum deposition

The rate of aluminum deposition in this study was 0.5 nm s^{-1} . In order to deposit aluminum on the sidewalls of the imprinted nanopattern but not on the base of the trench, the deposition mount was tilted to 40° . The deposition process was repeated in the opposite direction to achieve aluminum deposition on both sidewalls of the SSQ nanogratings. This process is explained in figure 1(a).

2.5. Plasma ion etching process

For good polarizer performance, the aluminum layer deposited on top of the SSQ grating needs to be removed. We used an anisotropic plasma etching process to selectively remove the top aluminum while leaving the aluminum on the sidewalls of the grating relatively intact. Aluminum etching was performed in the LAM 9400 tool. The aluminum etching had to be conducted in two steps under 200 W transformer coupled plasma RF power. First, any residual aluminum oxide layer (thickness $\sim 1 \text{ nm}$) was etched by using BCl_3 plasma

(40 sccm) for 5 s, followed by the aluminum layer etching by using BCl_3 (20 sccm)/ Cl_2 (6 sccm) plasma.

The overall fabrication process of the WGP is illustrated in figure 1(b).

3. Results and discussion

3.1. Design considerations for the WGP

The purpose of this study was to fabricate a WGP which showed good performance across a wide wavelength range of visible light by using NIL. It is well known that typical WGPs must have a period lower than 150 nm in order to be used in the visible light range, as was achieved in previous WGPs fabricated using NIL. However it is challenging to fabricate molds with smaller periods and imprint with high yields. To relax the fabrication challenges, a method to create efficient WGPs by using molds with larger periods is desirable.

Our new method to fabricate WGPs used angled aluminum depositions on the nanoimprinted pattern from both sides at a 40° angle from the normal direction. As shown

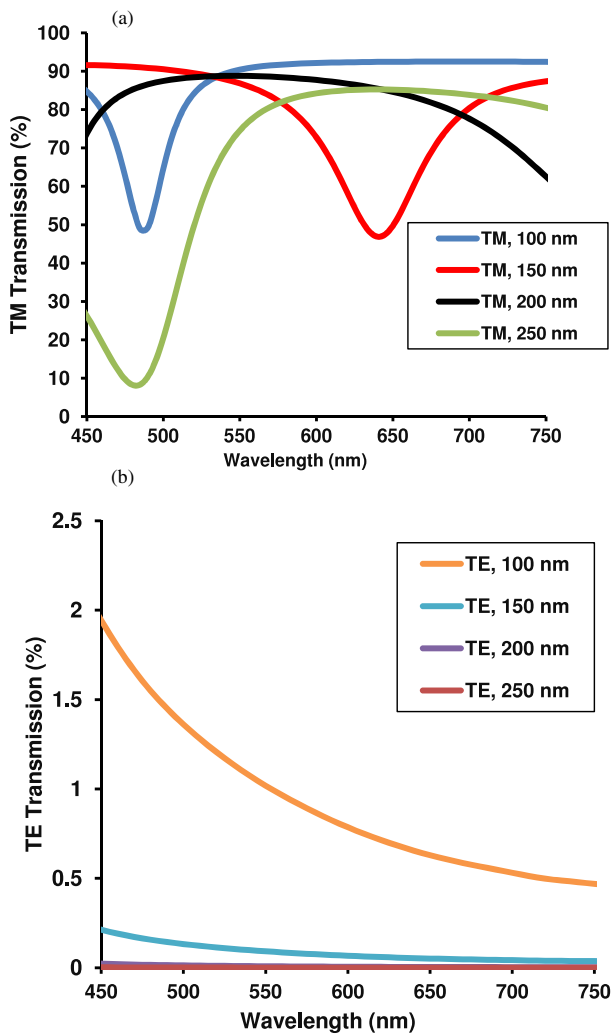


Figure 2. Simulation results of TM (a) and TE (b) for WGP that contain different heights of the nanopattern (220 nm period, 70 nm linewidth, 30 nm thickness of aluminum).

in figure 1(b), aluminum from the upper part of the pattern was removed by reactive ion etching. The final structure of the WGP had aluminum coating on both sides of the nanoimprinted grating walls. A nanoimprinted pattern with a 220 nm period and a 70 nm linewidth was prepared by using NIL in this study to leave room for the aluminum coating.

We carried out a simulation of the performance of the WGP by using the COMSOL program to design the structure and optimize its polarization performance. The performance of the WGP was characterized by the TM transmittance and extinction ratio, defined as the ratio of transmittance of the TM-polarized light to that of the TE-polarized light. Fixing the period at 220 nm, the linewidth at 70 nm, and the sidewall Al coating at 30 nm, TM/TE transmission simulation results for heights varying from 100 to 250 nm are shown in figure 2. The dips in the transmission curve are the result of Fabry–Perot resonances formed within the metallic nanoslits [19]. The WGP with a 200 nm height showed relatively flat TM transmission over the visible region as compared with the others.

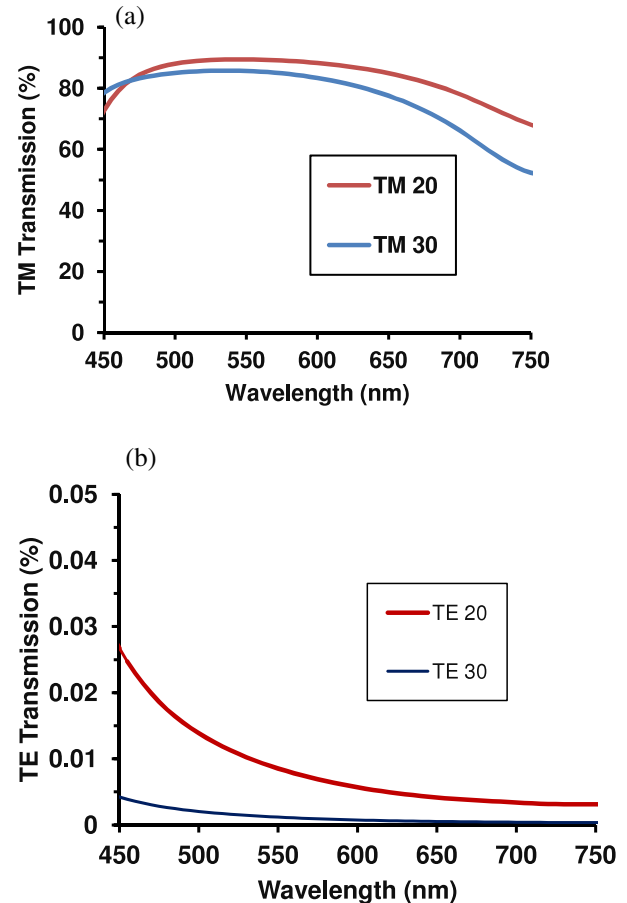


Figure 3. Simulation results of TM (a) and TE (b) for WGP that contain epoxy-SSQ nanopatterns with 20 or 30 nm aluminum deposition on both the sidewalls (220 nm period, 70 nm linewidth, 200 nm grating height).

We also simulated the performance of the WGP by changing the thickness of the aluminum deposition from 15 to 35 nm. The simulation results of TM values and TE values at the different wavelengths for the WGP are shown in table 1. Simulation results in the whole wavelength range of visible light for WGP with 30 or 20 nm aluminum deposition on the sidewalls are shown in figure 3.

3.2. Synthesis of epoxy-SSQ and NIL

Epoxy-SSQ was synthesized from PTMS, FTES, and GTMS. The PTMS component helps to increase the hardness of the synthesized SSQ polymer and the FTES helps to improve the releasing property of the imprinted SSQ patterns from the mold. GTMS contains the epoxy functional group which can polymerize during NIL via cationic polymerization, and make it immune to the oxygen environment. Epoxy-SSQ was synthesized by using a method that was modified from a previously reported method [18] used by our group. The epoxy functional group shows good mechanical properties after the completion of curing, and simultaneously shows good adhesion. This property plays an important role in an NIL process to help the adhesion of the imprinted material with the substrate. Better mold releasing is also very important

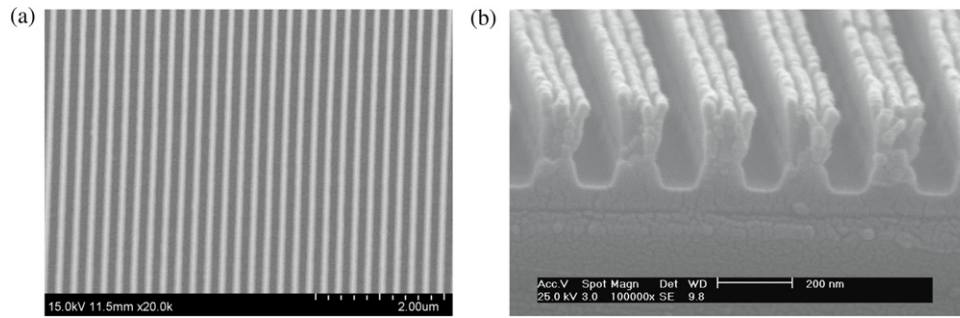


Figure 4. SEM photograph of the SSQ nanopattern on a flexible PET film (a) and the cross section of a nanopattern after aluminum deposition and ion etching (b).

Table 1. Simulation results of transmission (%) of TM/TE-polarized light at the different wavelengths for WGP with different thicknesses of aluminum deposition.

Thickness (nm)	450 nm	550 nm	650 nm	750 nm
15	47.4/0.789	91.8/0.268	91.9/0.131	83.6/0.087 5
20	72.6/0.026 7	89.5/0.008 53	84.9/0.004 14	68.1/0.003 11
25	69.9/0.067 8	90.0/0.244	87.2/0.012 3	69.5/0.008 35
30	78.6/0.004 23	85.7/0.001 18	79.5/0.000 507	62.3/0.000 354
35	74.3/0.008 69	87.1/0.002 99	81.7/0.001 49	56.4/0.001 03

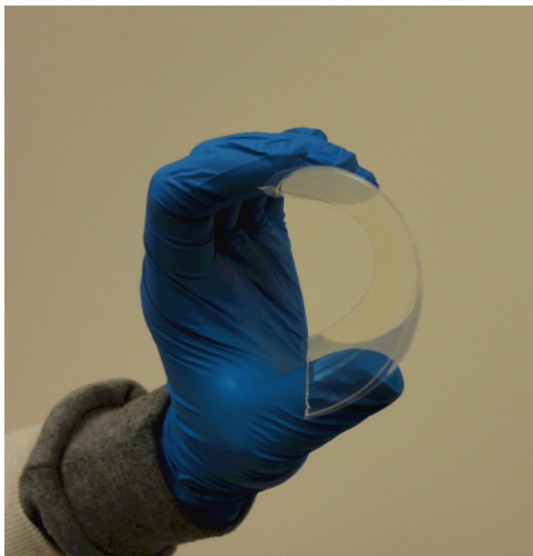


Figure 5. Flexibility of a PET film containing the WGP structure.

to ensure defect-free patterning over a large area. This was achieved by increasing the amount of FTES in the resist formulation. The SEM of the formed SSQ nanograting pattern is shown in figure 4(a), showing a well defined high aspect ratio and uniform nanopattern. Most notably a very regular and uniform pattern without any defects was obtained in a large area, due to the increase in the amount of FTES in the resist formulation for ease of demolding.

3.3. Aluminum deposition and etching

In figure 1(b), the structure of the obtained WGP was shown with the aluminum coating on both sides of the 70 nm nanopattern line. The SEM photograph of the fabricated WGP after aluminum deposition and etching is shown in

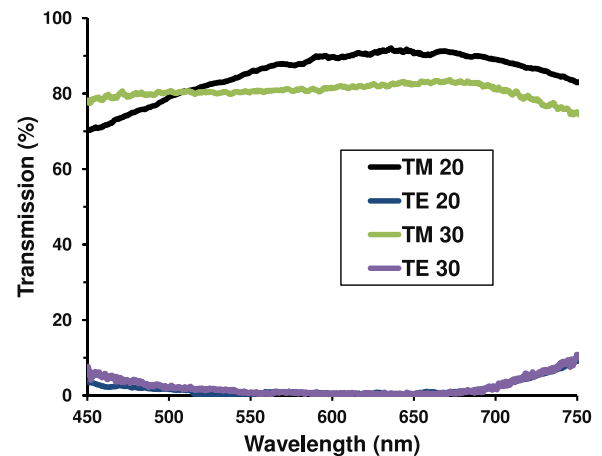


Figure 6. The TE and TM curves of a nanopatterned epoxy-SSQ WGP with 20 or 30 nm aluminum deposition on both the sidewalls (220 nm period, 70 nm linewidth, 200 nm grating height).

figure 4(b), where the aluminum layers on both sidewalls of the nanopatterns can be clearly seen. Note that this structure was damaged slightly by the reactive ion etching process.

As the WGP structure was fabricated on a PET film, the final WGP sheet was very flexible as shown in figure 5.

3.4. Measurement of TM and TE transmission and extinction ratio

The optical properties of the obtained WGP were estimated by measuring the transmittance of both the TM and the TE polarized light. The results of the measurements of TM and TE transmission for the fabricated WGP are shown in table 2. The results in the whole wavelength range of visible light for WGP with 30 or 20 nm aluminum deposition on the sidewalls are shown in figure 6.

Table 2. Measured optical transmission (%) of TM/TE-polarized light through nanopatterned epoxy-SSQ/aluminum WGP at different wavelengths for WGP with different thicknesses of aluminum deposition on the SSQ grating sidewalls.

Thickness (nm)	450 nm	550 nm	650 nm	750 nm
15	50.6/6.53	90.3/0.670	89.7/0.179	82.1/9.43
20	70.5/4.65	85.8/0.082	90.6/0.031	82.9/9.09
25	71.1/5.09	89.5/0.097	81.7/0.104	75.9/11.3
30	77.7/5.02	80.3/0.100	82.4/0.039	74.7/10.4
35	70.8/5.12	78.9/0.377	80.1/0.235	68.2/11.2

The case of the WGP with 30 nm aluminum sidewall coating is shown in figure 6. 75–85% of the TM polarized-light was transmitted in the wide wavelength range of visible light. On the other hand, below 5% of the TE polarized-light was transmitted in the same wavelength range. The case of the WGP with 20 nm aluminum coating is also shown in figure 6. 70–90% of the TM polarized-light was transmitted in the wide wavelength range of visible light.

The extinction ratio (ratio of TM to TE) for the 30 nm coated WGP showed values of 803 at 550 nm, and 2117 at 650 nm, while the 20 nm coated WGP showed ratios of 1046 at 550 nm, and 2900 at 650 nm. The TM transmission in figure 6 showed a flatter curve in the wide wavelength range of visible light.

4. Conclusion

Nanopatterns of 220 nm period, 70 nm linewidth, and 200 nm height were formed using synthesized epoxy-SSQ on a flexible PET film. Angled aluminum depositions were performed at a 40° angle from the perpendicular plane and aluminum was removed from the top of the pattern by reactive ion etching. The obtained WGP had a unique structure in which the aluminum coating was on both sides of the walls of the nanopattern. Despite using a larger period than previously reported WGP, high extinction ratios were achieved over the visible spectrum with a simple fabrication process. If these results can be migrated to roll-to-roll processing methods [16, 17], it will be possible to easily manufacture efficient WGP over large areas.

Acknowledgments

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