Bilayer metal wire-grid polarizer fabricated by roll-to-roll nanoimprint lithography on flexible plastic substrate

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The bilayer metal wire-grid polarizer has several advantages over single-layer wire-grid polarizer and conventional polarizer since it provides higher polarization efficiency and can be easily fabricated. In this work, the authors demonstrate the fabrication of bilayer metal wire-grid polarizer on flexible plastic substrate by a continuous roll-to-roll nanoimprint lithography (R2RNIL) process and evaluate its performance. To fabricate wire-grid polarizer, subwavelength grating structure in epoxysilicone material is first created on a flexible PET substrate by UV R2RNIL followed by aluminum deposition. In initial measurement, extinction ratio exceeding 1000 has been achieved. [DOI: 10.1116/1.2798747]

I. INTRODUCTION

The polarizer is an important optical element used in a variety of applications. Wire-grid polarizers in the form of subwavelength metallic gratings are an attractive alternative to conventional polarizers, because they provide high extinction ratio between the transmitted transverse magnetic (TM)-polarized light and the reflected transverse electric (TE)-polarized light over a wide wavelength range and incident angle with long-term stability.[1,2] In addition, they are thin and planar structures and can be easily integrated with other thin-film optical elements. Ekinci *et al.* have recently demonstrated a new bilayer metal wire-grid polarizer with superb performance.[1] The bilayer metal wire grids can be considered as two metal gratings separated by a certain distance. Not only does this type of new polarizer show very high extinction ratio between the lights of two orthogonal polarizations, but also it offers the advantage of easy fabrication and defect tolerance.

To create subwavelength grating structure required for wire-grid polarizer, several nanofabrication techniques can be used. Electron beam lithography can provide high resolution, but its throughput is very low. Liquid immersion or achromatic interference lithography can be used to fabricate 100 nm pitch grating patterns, but they have a limited field size and require a precise process control.[3] Furthermore, fabrication of nanoscale metallic wire grids on an optically transparent substrate mostly involves reactive ion etching or special sidewall deposition processes.[1] Nanoimprint lithography is an emerging technology that enables low-cost and high-throughput nanofabrication of subwavelength structures.[4,5] Chen *et al.* demonstrated high-efficiency flexible metal wire-grid polarizer using nanoimprint lithography and shadow metal evaporation technique.[6] For many practical applications of metal wire-grid polarizers, it is essential to have a high-speed fabrication process. We note that the wire-grid polarizers demonstrated in Refs. 1 and 6 do not require a reactive ion etching step, and can potentially be scaled up to a roll-to-roll process. We would like to investigate such a possibility in this work. Specifically, we apply the recently developed roll-to-roll nanoimprint lithography (R2RNIL) technique[7] to the fabrication of bilayer metal wire-grid polarizer on plastic substrate and evaluate its performance. The details of the roll-to-roll nanoimprint process are described in a separate paper,[8] but we will outline the main steps of the process and emphasize the critical issues in the application for making the flexible wire-grid polarizers.

In our work, we demonstrate fabrication of metal wire-grid polarizer on flexible plastic substrate by a continuous roll-to-roll nanoimprint lithography process and evaluate its performance. First, a 70 nm linewidth grating structures is imprinted in an UV curable resist by using a flexible fluoropolymer mold fixed on a motor-actuated roller. Next, aluminum metal of various thicknesses is deposited on the imprinted polymer gratings to form bilayer metal wire grids. In our initial test, extinction ratio exceeding 1000 has been achieved. This approach has the potential to become a commercially viable technology for low-cost production of high-performance wire-grid polarizers from UV to near-infrared (NIR) wavelength range.

II. EXPERIMENTAL SETUP

A. R2RNIL setup

Figure 1 illustrates the overall configuration of a continuous R2RNIL process targeting metal wire-grid polarizer fabrication on flexible substrate. R2RNIL consists of three separate processing steps: (1) coating process; (2) imprinting and separating process; (3) metal deposition over the imprinted

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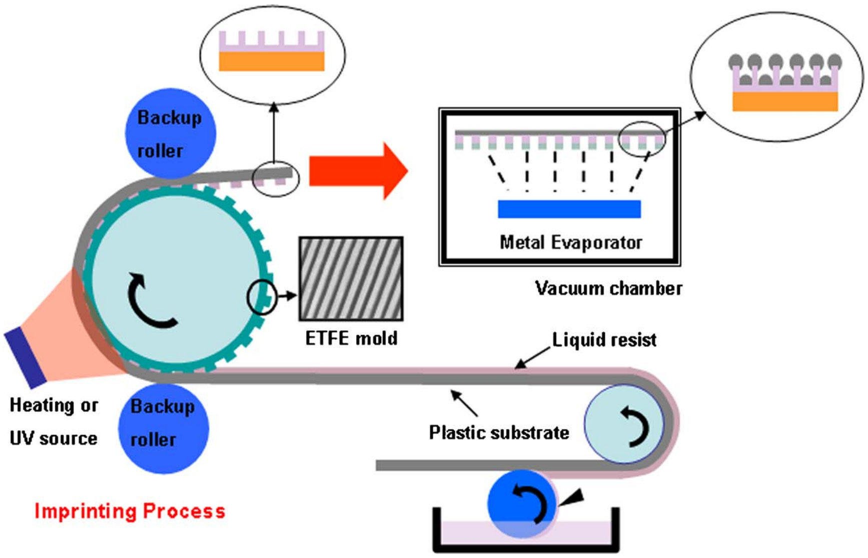

FIG. 1. Schematics of R2RNIL process targeting bilayer metal wire-grid polarizer.

nanostructures for wire-grid polarizer. In our experiment, metal deposition is carried out in a separate electron beam evaporator. In the R2RNIL process, resist material is continuously coated on flexible PET substrate first and then moves to the imprinting section. With backup roller pressure and web tension as shown in the schematic, resist material quickly fills into the mold cavity on the imprint roller and is cured by focused UV light source. The solidified pattern is separated from the roller mold as the PET moves away from the roller surface. Finally, metal such as aluminum is evaporated on the imprinted nanograting structures. In our prototype, all imprinting process from coating to demolding steps are done continuously and synchronized by an ac motor. Details on the R2RNIL process and structure characterization are described in a separate publication.[8]

B. Flexible mold and imprint resist material

Hard molds used in conventional nanoimprint lithography are generally not applicable for R2RNIL.[9] In this study, flexible fluoro-polymer, ethylene-tetrafluoroethylene (ETFE),[8] is used as mold material. ETFE is flexible but has high enough modulus at room temperature to imprint other materials. Moreover, its exceptional antisticking property makes it easy to demold after the imprinting process, without the need of any mold surface treatment and without deterioration in surface properties over many imprinting cycles. Using conventional thermal NIL, we replicate ETFE mold from original SiO_2 mold that has been fabricated by laser interference lithography. Then, ETFE molds of proper size are attached onto a 60 mm diameter stainless-steel roller surface.

For fast roll-to-roll NIL process, we use liquid phase, UV curable epoxysilicone that has low viscosity as imprint resist material.[10] Due to its low viscosity, the resist precursor quickly imprinted even at low pressure (~0.1 Mpa), and cured in a second by focused UV exposure. Furthermore, its very low shrinkage after curing (only a fraction of the acrylate system) allows a reliable patterning.[8]

III. RESULTS

A. Continuous nanopatterning by R2RNIL

A continuous 700 nm period grating pattern on the flexible PET web was created by the R2RNIL process. The bright color in the photograph of the sample [Fig. 2(a)] is due to strong light diffraction of visible wavelength from the well-replicated grating structure. Web speed is about 3.5 ft/min but can be adjusted depending on the period of grating pattern and its aspect ratio. Figure 2(b) shows the scanning electron microscopy (SEM) picture of the replicated epoxysilicone pattern. The residual layer thickness in this result is about 1 μm, but can be adjusted by changing web tension and backup roller pressure. Since residual thickness does not affect the extinction ratio of the wire-grid polarizer, we used sufficiently thick residual layer to ensure better pattern quality.

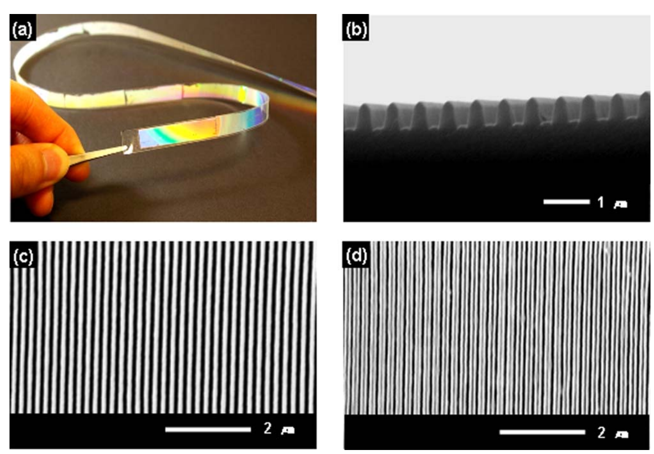

FIG. 2. (a) R2RNIL result of 700 nm period grating pattern on flexible PET substrate showing strong light diffraction (total length is 2 ft, width is 10 mm) and (b) its SEM picture; (c) 200 nm period and (d) 100 nm period epoxysilicone pattern on PET substrate fabricated by UV R2RNIL process.

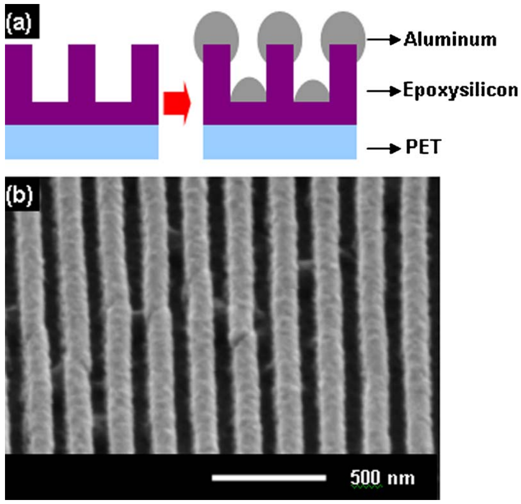

FIG. 3. (a) Schematics of fabrication process of metal wire-grid polarizer and (b) SEM picture of wire-grid polarizer (200 nm period grating and 50 nm Al film).

Continuous roll-to-roll imprinting of thinner and denser grating structure required for the visible band wire-grid polarizer is more challenging because the strong friction force during demolding tends to break or collapse the grating if the trench is very small. To achieve successful pattern definition of 100 and 200 nm period grating structures, we performed oxygen plasma treatment followed by thermal deposition of Silquest A187 adhesion promoter (GE Advance Materials) on PET substrate before imprinting, which improves adhesion of the imprinted pattern to the substrate. Furthermore, a few drops of fluorosurfactant were added to the epoxysilicone resist to further reduce adhesion between the imprinted pattern and the ETFE mold surface. Figure 2(c) shows a 200 nm period, 70 nm linewidth grating pattern in epoxysilicone fabricated by UV R2RNIL. SEM photograph of 100 nm period grating structures is shown in Fig. 2(d). The aspect ratio is about 4 for the 100 nm period grating and 3 for the 200 nm period grating structures.

B. Fabrication of bilayer metal wire-grid polarizer

A high-efficiency polarizer can be achieved by depositing thin metal (Al) layer on subwavelength grating structures.[1] In our initial experiment, 200 and 100 nm period grating patterns on 200 μm PET film were prepared by R2RNIL process [Figs. 2(c) and 2(d)] and aluminum was deposited on top and bottom of the trench pattern by vacuum evaporation, as depicted in Fig. 3(a). Figure 3(b) shows SEM picture of 200 nm period pattern with 50 nm Al deposition.

To verify the polarization effect quantitatively, spectral transmittance was measured using an UV/visible spectrometer. Figure 4 represents the TM (transverse magnetic) and TE (transverse electric) mode transmittance through the metal wire-grid polarizer fabricated by R2RNIL. The 200 μm thick bare PET shows 85–90% of optical transmittance in our measurement range (400–800 nm) [Fig. 4(a)]. In this measurement, we referenced transmittance of the sample to that through the air. For the 200 nm period polarizer with a 50 nm Al layer, transmittance is about 60% at the wave-

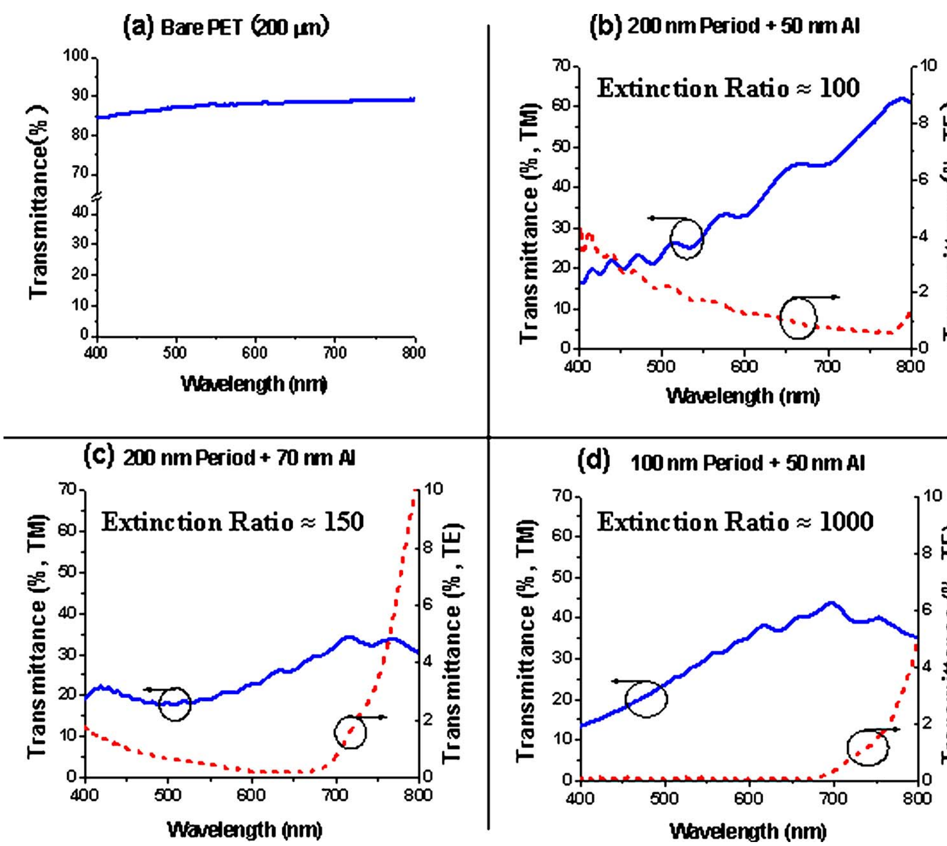

FIG. 4. Spectral transmittance and extinction ratio (transmittance of TM mode/transmittance of TE mode) of metal wire-grid polarizer: (a) Bare PET (200 μm); (b) 200 nm period gratings and 50 nm Al deposition; (c) 200 nm period gratings and 70 nm Al deposition; (d) 100 nm period gratings and 50 nm Al deposition.

length of 800 nm and the maximum extinction ratio (transmittance of TM/transmittance of TE) is about 100 at the wavelength of 776 nm [Fig. 4(b)]. When a thicker Al film of 70 nm is deposited on 200 nm period structures, transmittance drops to 35% but shows a higher maximum extinction ratio of 150 [Fig. 4(c)]. Polarizers with smaller periodic gratings show much higher extinction ratio. For a polarizer with 100 nm period and a 50 nm thick Al film, we achieved one order of magnitude higher extinction ratio, about 1000 at the wavelengths from 580 to 660 nm [Fig. 4(d)].

Since these are preliminary results to fabricate polarizers by R2RNIL, many parameters such as geometry of the grating and the metal thickness need to be optimized.

IV. CONCLUSION

In this work, we demonstrate fabrication of flexible metal wire-grid polarizer by a continuous R2RNIL process followed by metal deposition. In our preliminary experiments, we achieved a high extinction ratio, over 1000, for a 100 nm period grating structure with a 50 nm Al layer. A bilayer polarizer fabricated by R2RNIL process provides high extinction ratio, and could find attractive applications in LCD displays to double the brightness by utilizing the reflected light. Furthermore, from the manufacturing point of view, it has great advantages such as simple fabrication process and defect tolerance. The high-throughput R2RNIL process may enable high-efficiency wire-grid polarizers for practical applications. Since the performance of wire-grid polarizer is determined by the geometry of the gratings, the metal thickness, and the optical properties of the material, we are certain that the efficiency of wire-grid polarizer can be significantly improved by optimizing the structural parameters and materials.

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