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Large-area multilayer infrared nano-wire grid polarizers

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HIGHLIGHTS

- Technology of creating high quality multilayer IR wire grid polarizers was developed.
- Fabricated polarizers are large-area (170 cm^2) and flexible.
- Polarizers are broadband and have high extinction ratio (up to $3 \cdot 10^4$).
- Method for fabrication of polarizers on 3D-printed curved surfaces was developed.

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ABSTRACT

We have developed a technology for fabricating infrared polarizers based on double- and four-layer metal-dielectric nanogratings. Due to the use of nanoimprint lithography, the size of fabricated samples with 190-nm grating period could be made exceeding 170 cm^2. The fabricated polarizers are flexible, and they have high quality over the entire area of the sample. Spectrophotometric measurements and numerical simulations have showed that the polarizers exhibited a large transmission coefficient and a high extinction ratio (over $3 \cdot 10^4$). In order to expand applications of polarizers to the bio-inspired wide field-of-view systems, technology for fabricating polarizers on curved surfaces prepared by 3D printing has been developed. The obtained results offer much promise for polarimetry purposes.

1. Introduction

Polarization is a fundamental characteristic of light. In imaging with multi-element photodetector arrays, the detection of polarization offers additional opportunities in target detection and discrimination [1], including hidden objects [2], as well as in remote sensing [3], medical diagnostics [4], and astronomy [5].

Polarization may provide such information about the nature and properties of observed objects which cannot be obtained even using such advanced tools as multispectral and hyperspectral measurements. Information on polarization can be carried by object-reflected or object-emitted light. Polarization characteristics depend on the chemical composition and properties of object surface, on the viewing angle, and on the spectral range. As a rule, light coming from objects of natural origin (soil, forest, grass) has a significant contribution of depolarized component because of a high roughness of object surfaces. At the same time, very often metal surfaces insignificantly depolarize light. This allows detection and discrimination of man-made objects against natural background [6], as well as suppression of spurious signals.

In most cases, preferred tools for polarimetric measurements are nano-wire grid polarizers (NWGPs), presenting arrays of periodic conducting stripes [7–9]. Such polarizers are compact devices featuring a wide range of working wavelengths, a large transmission coefficient, and a high extinction ratio (ratio of the intensities of transmitted TM and TE waves) [10]. Flexible nanowire grid metal-polymer polarizers are compatible not only with planar photodetector devices and elements, but with three-dimensional curved structures as well. This feature enables application of such polarizers in wide field-of-view systems (up to 360°) designed by analogy with the compound eyes of insects [11,12]. Such devices are created by arranging photodetectors and a system of focusing lenses on a curved surface, e.g. cylinder or sphere; necessary shape of the surface can be created, for example, using 3D printing or other additive technology. Further step in the development of target detection devices is the creation of wide field-of-view systems capable of discriminating different polarizations [13,14].Polarizers on curved objects can be used in many optical applications, including electronic devices [15], bio-inspired optical systems [16], medical diagnostic equipment [17], etc. However, fabrication of these devices is a large challenge.

In the present study, we have developed a new technology for fabricating large-area planar and curved nanowire grid polarizers

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based on using nanoimprint lithography, compatible with 3D printing technology. The large-area polarizers prepared using IPS polymer and gold are defect-free and flexible, and they typically exhibit a high extinction ratio of 10^3–$3 \cdot 10^4$ in the infrared spectral region.

2. Grating fabrication technology

Fabrication of nanowire grid polarizers for IR and visible spectral ranges requires using nanostructuring technologies. In the majority of previous studies devoted to fabrication of nanowire grating polarizers, samples were formed using either electron or ion-beam lithography. Since both methods are rather expensive and time-consuming, the researchers are usually limited to small areas ($\approx$mm^2). Creating large-area polarizers (>100 cm^2) for practical applications has become possible due to nanoimprint lithography, which offers a cheap method for mass production of such polarizers. To date, a number of developments of NWGPs differing in quality and based on different materials have been reported [18–20].

In the present work, polymer gratings of submicron line width were fabricated using an Eitre 6 Nano Imprinter nanoimprint lithographer purchased from Obducat (Sweden) and a 15-cm diameter silicon master stamp manufactured by the same company. The stamp was a periodic array of extended nanogrooves of 110 nm width and 155 nm depth; the grating period was 190 nm. As the initial polymer for forming the gratings, thermoplastic IPS polymer was used (Obducat). An important property of this polymer is its transparence to light in the visible and IR spectral ranges: measurement of transmittance spectra on a Shimadzu spectrometer has showed that the absorption of light intensity observed on passing the light through a 180-μm thick film of the polymer did not exceed 1% for light wavelengths over 300 nm.

The grating fabrication technology included the following steps: heating IPS stacks with a stamp to a temperature of 180 °C, followed by applying pressure to the stamp. In our experiments, pressure of 60 atm was produced for a time interval of 10 min. Then, the stack was cooled down to room temperature in 5 min, the pressure was relieved, and the replica was detached from the stamp. The obtained polymer molds were subsequently used as a basis for forming hybrid metal-polymer gratings.

The relief on the formed surfaces of polymer prints was studied using a Solver Pro 47 atomic-force microscope (AFM) obtained from NT-MDT (Russia). Measurements were performed in semicontact scanning mode using ultra-thin (aspect ratio 12:1) SSS-NCHR-20 probes manufactured by NanoAndMore GmbH (Germany). Due to the use of such probes, the depth of stamped grooves could be measured. The grating period was 190 nm, the relief depth was 155 nm, and the groove width, 80 nm (Fig. 1a). Several dozen measurements were made over the entire area of the sample; measured data proved high reproducibility and uniformity of grating-topology parameters on an area greater than 170 cm^2. Scanning electron microscopy measurements have confirmed uniformity of reproduced geometric dimensions.

The formed polymer gratings were coated with a 5-nm thick adhesive layer of titanium deposited using electron-beam sputtering and a 50-nm thick gold layer deposited by thermal spraying. Flexibility of polarizers was checked by bending with curvature radius of several mm. This allows such polarizers to be attached to curved surfaces, for example cylindrical optical systems.

The fabricated polarizer had two metal-stripe layers (Fig. 2a). Polarizers of such geometry usually have a high extinction ratio whose value normally reaches 10^2–10^3 in the visible and near-infrared spectral regions. However, solving some problems such as, for instance, detection of distant/small objects, requires reaching even higher extinction ratios. This goal can be achieved by increasing the number of metal-stripe layers. To this end, a cheap technology for forming four-layered structures by bonding together a pair of double-layer polarizers has been developed (Fig. 2b).

The developed technology includes the following steps. The first step is the deposition of an additional adhesive layer of titanium about 5 nm thick onto grating. The second step is the application

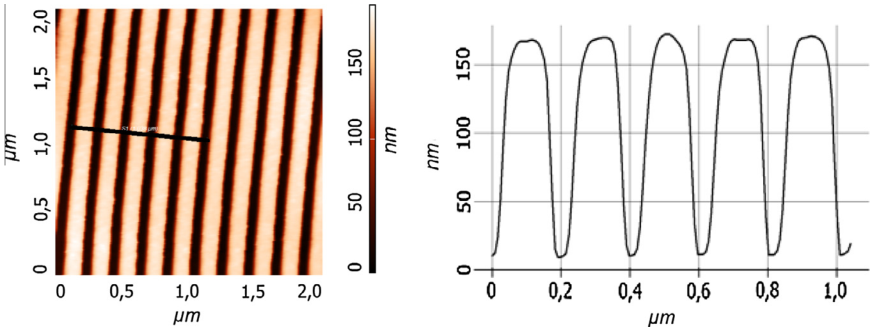

Fig. 1. AFM image of the surface of a fabricated polymer grating (left). Cross section of the grating along the line indicated on the AFM image (right).

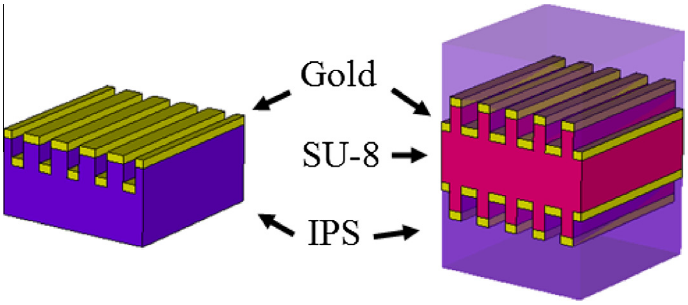

Fig. 2. A sketch of double- (left) and four-layer (right) polarizer structures.