Fabrication of a new broadband waveguide polarizer with a double-layer 190 nm period metal-gratings using nanoimprint lithography

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We fabricated a new waveguide polarizer, that has a double-layer 190 nm period metal grating at the interface between the waveguide core and waveguide cladding layer. Both silicon nitride and polymethylmethancrylate were used as waveguide cores. 190 nm period gratings were patterned by nanoimprint lithography. The new type waveguide polarizer works as a broadband and highly efficient transverse magnetic-pass polarizer with transverse electric-polarized light highly attenuated. The new polarizer structure can be applied to almost any waveguide structures. The simple fabrication process, which is compatible with conventional device processing, makes it very attractive for integrated optoelectronic system.
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I. INTRODUCTION

A waveguide polarizer (WP) is a key element in photonic integrated circuits, especially in devices such as switches, modulators, and isolators. Given their importance, a number of realizations have been reported in the literature.[1–6] The most familiar WP is a metal-clad polarizer[1], which uses a metal film on the surface of a waveguide to efficiently attenuate the transverse magnetic (TM)-polarized light which has an *E* field normal to the waveguide surface.

Most existing WPs are transverse electric (TE)-pass type and only a few are TM pass. TM-pass polarizers are useful for quasiphase matched second harmonic generation, electrooptic polymers, and tunable laser diodes. Previously,[4,5] Bloemer and Haus demonstrated a TM-pass WP by depositing a silver nanocomposite film on ion-exchanged glass waveguides. The polarizer relies on the highly anisotropic optical properties of discontinuous silver film by exciting a localized surface plasmon mode in the silver nanoparticles. The absorption bands of the surface plasmon modes are strongly dependent on the shape and orientation of the nanospherical particles. Therefore, to get a certain polarizer performance the fabrication process control is critical. Other types of TM-pass polarizers use the form birefringence of multilayer films[6] or some type of polarization splitter such as a directional coupler. These TM-pass polarizers can be difficult and time consuming to fabricate.

Since the current TM-pass WPs suffer a number of shortcomings such as narrow bandwidth, complicated fabrication process, and incompatibility with conventional device fabrication processes, here, we present fabrication of a new TM-pass WP with double-layer, 190 nm period metal gratings using nanoimprint lithography. A brief discussion of the performance of the WP is also presented. The details of the optical performances will be discussed elsewhere.[7] The advantages of our new WP are the following: (1) a very broad bandwidth, (2) its design can be applied to almost any waveguide structure, (3) simple fabrication and compatibility with conventional device processing, and (4) high extinction ratio and high efficiency.

II. DOUBLE-LAYER METAL GRATING STRUCTURE

Recently,[7] we proposed a novel WP. The WP consists of a double-layer metal grating locating at the interface between the waveguide core and the cladding layer. When silicon nitride (SiN) is used as the waveguide core (type I), as shown schematically in Fig. 1, a shallow grating is etched into the core. The double-layer metal grating is formed by placing one metal grating in the trench and the other at the top of the grating ridges. When polymethylmethacrylate (PMMA) is used as the waveguide core (type II), as shown schematically in Fig. 2, a shallow grating is etched into the bottom cladding (i.e., SiO_2) of the waveguide and the double-layer metal grating is formed there.

The metal grating is only ~10 nm thick. For a TE-polarized light, i.e., the electrical field oscillates parallel to the lines of the metal grating, a large attenuation occurs during propagation. In contrast, for a TM-polarized light, since the electrical field oscillates perpendicular to the lines of the metal grating during propagation, it can propagate without attenuation. The attenuation for TE becomes much stronger if two layers of metal gratings are placed one above the other, which results in a much shorter WP length, making the WP more efficient and compact.

III. FABRICATION

Both type I and type II WPs are fabricated in this work. Type I has the double-layer metal gratings locating at the interface between waveguide core and top cladding. Type II has the metal gratings locating at the interface between waveguide core and bottom cladding. The top and bottom cladding layers are air and SiO_2, respectively.

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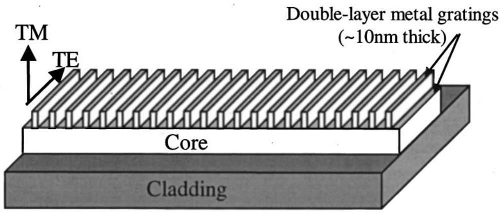

FIG. 1. Schematic of a novel TM-pass WP with double-layer metal gratings. For a TE-polarized light (i.e., the electrical field oscillates parallel to the lines of the metal grating), an efficient attenuation occurs during propagation. In contrast, for a TM-polarized light, since the electrical field oscillates perpendicular to the lines of the metal grating, it can transmit with minimal attenuation.

A. Fabrication of type I WP

To fabricate the type I WP (Fig. 1), we start from a silicon wafer with a thick silicon oxide layer ($\sim 2.0\ \mu m$) deposited by low-pressure chemical vapor deposition. A SiN layer with a thickness of $\sim 1\ \mu m$ is deposited on the silicon oxide layer by plasma enhanced chemical vapor deposition. The SiN layer has a refractive index of ~ 1.95 at the wavelength of 633 nm measured by an ellipsometer.

A grating with a period of 190 nm is formed in the top layer of the SiN using nanoimprint lithography, Cr deposition, lift-off, and reactive ion etching (RIE). The 190 nm period mold used in nanoimprint lithography is prepared by interference lithography, which produces a large and uniform grating area (5 cm$\times$5 cm).[8] The molds are made in silicon dioxide (180 nm thick) grown on silicon substrates. The detailed description of the nanoimprint lithography process can be found elsewhere.[9,10] The processing temperature and pressure for imprinting is 175 °C and 600 psi, respectively. Oxygen RIE is used to remove the polymer residues at the recessed parts on the substrate after nanoimprint. Then a thin layer of Cr is deposited by e-beam evaporation followed by a lift-off process.

We used a RIE process with CHF_3 and O_2 mixture (5:1) to transfer the pattern into silicon nitride. The etching depth is about 200 nm. After removing Cr on the sample surface, a thin aluminum layer (8–20 nm) was deposited vertically on the SiN grating surface by *e*-beam evaporation. It forms the double-layer metal gratings: one in the trench and one on the top of the SiN grating ridges. Finally, the waveguide strips with different widths from 2 to 20 μm were patterned by photolithography and RIE etching. Figure 3 is a scanning electron microscopy (SEM) micrograph of a finished type I waveguide polarizer. The width of the waveguide strip is about 3 μm.

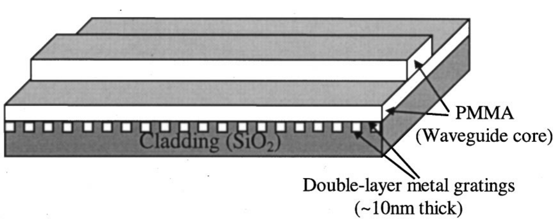

FIG. 2. WP with a type II structure. Polymer (PMMA) is used as the waveguide core. The doublelayer metal grating is positioned at the interface between the waveguide core and bottom cladding (SiO_2).

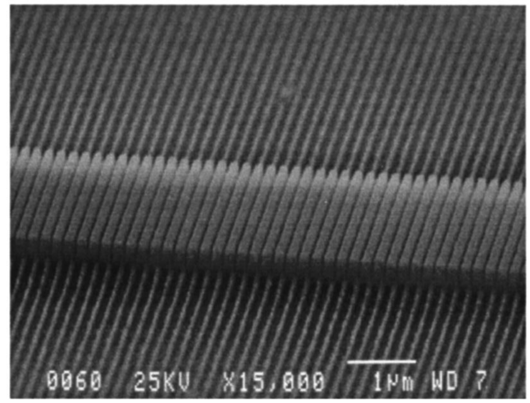

FIG. 3. WP with silicon nitride as the core layer and silicon dioxide and air as bottom and top cladding layers, respectively. The grating has a period of 190 nm, which is patterned by nanoimprint lithography, lift-off, and RIE. A 12-nm-thick aluminum layer is deposited vertically on the silicon nitride grating surface to form the double-layer metal gratings. Finally, a ridge structure is patterned by photolithography and etching.

B. Fabrication of type II WP

For the type II WP (Fig. 2), polymer (PMMA) is used as the core material. Previously, PMMA is demonstrated to be a very low loss waveguide material. Furthermore, the low refractive index of polymer matches that of typical fiber, which results in a very low insertion loss.

We start from the same substrate with thick silicon oxide on silicon wafer. The subwavelength grating with a period of 190 nm and a depth of ~ 200 nm is patterned in SiO_2 using nanoimprint lithography, Cr deposition, lift-off and RIE. SiO_2 was etched by RIE with CHF_3 and O_2 mixture (10:1) which produced an optimal etching profile. Figure 4 shows the SEM micrograph of the fabricated 190 nm period grating in silicon oxide. Then, a thin aluminum layer (8–20 nm) was deposited vertically on the SiO_2 grating surface by *e*-beam evaporation, which forms the required double-layer metal gratings. Then, a thick layer (~ 900 nm) of PMMA was spun

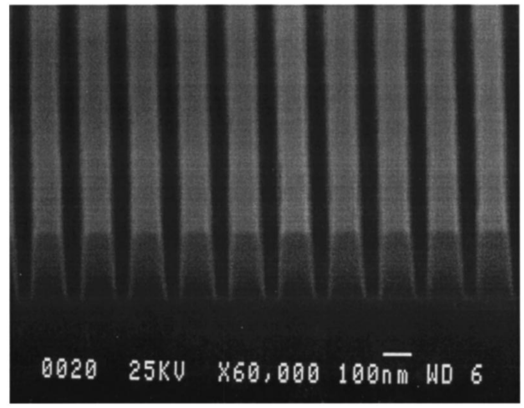

FIG. 4. SEM cross-sectional view of the silicon oxide grating with a period of 190 nm fabricated by nanoimprint lithography, lift-off, and RIE.

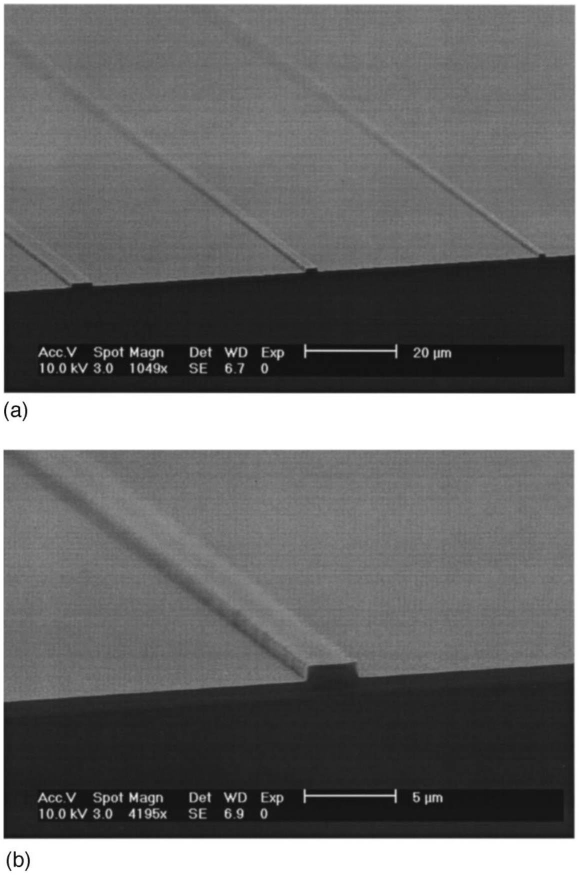

FIG. 5. (a) SEM picture of the imprinted PMMA waveguides with widths of 10, 5, and 2 μm, respectively. The waveguide ridges are directly patterned by the imprinting process. The double-layer metal gratings are located at the interface between the PMMA (waveguide core) and the silicon oxide (cladding). (b) Micrograph of a single polymer waveguide.

on. Finally, the PMMA waveguide ridges were directly formed by imprinting. The mold used for patterning PMMA waveguide ridges has deep ($\sim$1 μm) strip trenches with various widths from 2 to 20 μm prepared by photolithography and RIE. The process for fabricating polymer waveguide is quite simple and meanwhile avoids exposing the polymer to chemicals during the fabrication by using nanoimprint. Furthermore, it can make waveguide having a smooth surface and therefore low propagating loss. Figure 5(a) shows the imprinted polymer waveguides with a width of 10, 5, and 2 μm, respectively. An enlarged picture of the waveguide is shown in Fig. 5(b).

IV. POLARIZER CHARACTERIZATION

The transmission property of the fabricated WPs was characterized. The WPs were cleaved into bars with different lengths and mounted on a three-dimensional adjustable stage. Both a He–Ne laser (633 nm) and an argon-ion pumped Ti:sapphire laser, with a wavelength tunable from 710 to 820 nm, were used for characterization. The laser beam is butt coupled into one end of the WP by a microscope lens [25×, 0.50 numerical aperature]. Figure 6 shows a typical result of the WP with a TE- and TM-polarized input light, respectively. For a TM-polarized input, a bright strip is seen from the top of the waveguide. It shows that the light is coupled into the waveguide strip and propagates in the waveguide with a low loss. In contrast, for the TE-polarized input, the light is highly attenuated during propagating. At the wavelength range from 710 to 820 nm, the extinction ratio of TM to TE polarization is determined to be $>$50 dB/mm with 2 dB/mm loss for the TM polarization. In principle, the WP should work in a wavelength range from ultraviolet (350 nm) to infrared ($>$2 μm) as long as the applied waveguide materials are transparent in this region.

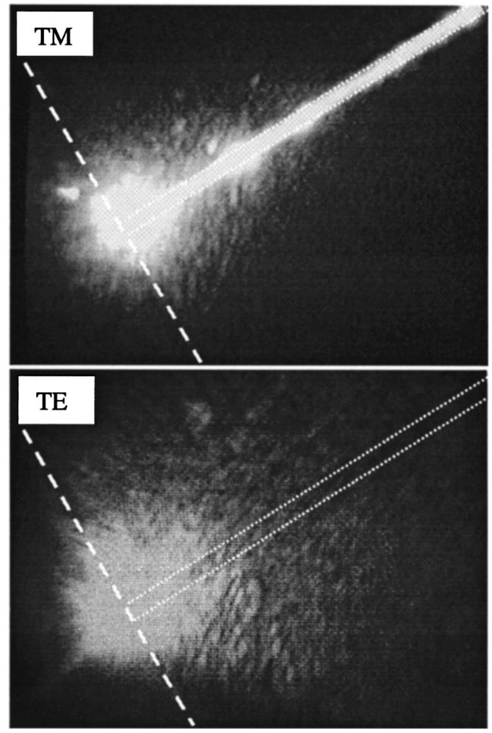

FIG. 6. Typical result of the WP by butt coupling of a TE- and TM-polarized light, respectively. It is seen that the TE-polarized light is highly attenuated and the TM-polarized light can propagate with a relatively low loss. The pictures are taken from the top of the waveguide with a microscope and an infrared charge coupled device camera. The white lines are drawn to show the sample edge (dash line) and the waveguide strip (dot line).

V. CONCLUSION

We fabricated a new type of WP which incorporates a double-layer 190 nm period metal gratings at either the interface between waveguide core and top cladding or the interface between the waveguide core and bottom cladding. Nanoimprint lithography is used to pattern the 190 nm period gratings as well as imprint directly the waveguide ridge for the polymer waveguide. The new type waveguide polarizer works as a broadband and highly efficient TM-pass polarizer with TE-polarized light highly attenuated. The WP structure we present here can be applied to almost any waveguide structure or material. The simple fabrication process, which is compatible with conventional device processing, makes it very attractive for integrated optoelectronic systems.

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