Reduction of bend losses in polymer waveguides by thin metallic layers

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Polymeric materials have attracted much attention in photonics due to low material costs and fabrication complexity. However, the low refractive index contrast in polymer waveguides leads to high propagation losses in sharp bends. In large-scale photonic integration, sharp bent waveguides-with radii of a few micrometers are essential to decreasing the footprint of photonic circuitry. In this work, embodying a thin metallic layer underneath the core of a sharp bent polymer waveguide is shown to considerably reduce bend losses both in TE and TM polarizations. The physical model that permits understanding these effects as well as early fabrication/characterization results will be discussed.

Introduction

In the last years, significant amount of effort has been devoted to polymeric materials for integrated optical devices due to several advantages including low cost, flexibility, ease of fabrication and processability[1][2]. However, one of the drawbacks of polymer based waveguides is the low refractive index contrast between core and cladding. This is the reason why a large radius of curvature of typically tens of micrometers is required for low-loss propagation in such waveguides. In this work, the introduction of a thin metallic layer underneath the core of a polymer bent waveguide is shown to reduce the calculated total losses (dB/90°) with respect to the equivalent pure dielectric counterpart (i.e., the architecture in which the metal layer is omitted) for a large range of bend radii. The amount of reduction is dependent on the polarization of the light in the waveguide structure. For the quasi-transverse-electric (TE) mode, the loss reduction is significant for radii below 35 µm. For this polarization, losses as low as ~0.02 dB/90° have been calculated for a wide range of radii that can be tuned by properly optimizing the structural parameters. In the case of the quasi-TM mode, the total losses of the metallic structure are smaller than those of the dielectric structure for radii ranging from 3 to 10 µm [3].

Investigated Structure

The schematic configurations of the waveguide geometries studied in this work are shown in Fig. 1. The proposed structure corresponds to a dielectric-loaded hybrid plasmonic waveguide consisting of a polymer ridge separated from the metal underneath by a thin dielectric layer. The wavelength of interest in this study is 1.55 µm. The material selected for the ridge is the negative tone epoxy resist, SU-8 ($n_{SU-8} = 1.57+i*4.93x10^{-6}$), although similar results apply to a wide range of architectures exhibiting low refractive index contrast between substrate and core. The material of the thin buffer layer is SiO_2 ($n_{SiO2} = 1.444$). Gold ($n_{Au} = 0.55+i*11.5$ [4]) was selected for the metallic layer. The substrate consists of silicon with a sufficiently thick layer of thermal SiO_2. Figure 1(b) shows the cross-section of the entirely dielectric structure used as a benchmark. The dielectric-loaded hybrid plasmonic waveguide [Fig. 1(a)] will be referred to as “metallic” in the subsequent sections, whereas the dielectric polymer waveguide [Fig. 1(b)] will be called “non-metallic”. The distance between the center of curvature and the outer rim of the waveguide defines the bend radius, R, as depicted in Fig. 1. Two-dimensional finite-difference (FD) calculations were carried out using the FieldDesigner module of PhoeniX B.V. for bend mode analysis [5]. The fields were calculated in a sufficiently large calculation window (10 µm x 10 µm) with extra mesh grids for mitigating numerical errors in the calculations. The total bend loss in a 90 degree bend of radius *R* can be calculated from the imaginary part of the effective refractive index of the mode as Total Loss (dB/90°) = 10 $\log_{10}[\mathrm{Im}(n_{eff})k_0R\pi]$, where n_{eff} is the calculated complex effective refractive index of the mode of the bent waveguide, k_0 is the wavenumber in vacuum ($k_0 = 2\pi/\lambda$) and R is the bend radius. The calculated total loss includes both the propagation loss due to scattering and absorption in the metal and SU-8 material and the radiation loss due to the waveguide curvature (i.e., bend losses).

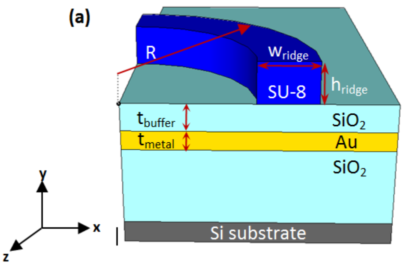

Fig. 1. Considered waveguide architectures in this study: (a) dielectric-loaded hybrid plasmonic waveguide (“metallic” structure) and (b) dielectric reference structure (“non-metallic” structure). Parameters of the structure: h_{ridge} = w_{ridge} = 2 µm, t_{buffer} = 100 nm, t_{metal} = 100 nm. The silicon substrate was not taken into account in the simulations, as the thickness of the SiO_2 undercladding was considered sufficiently thick for the mode not to be influenced by the presence of the silicon substrate.

Simulation Results

Figure 2 depicts the real part of the dominant electric field component for the quasi-TE (**E**$_x$) and quasi-TM (**E**$_y$) modes supported by non-metallic [Fig. 2 (a) and (b)] and metallic [Fig. 2 (c) and (d)] waveguide structures.

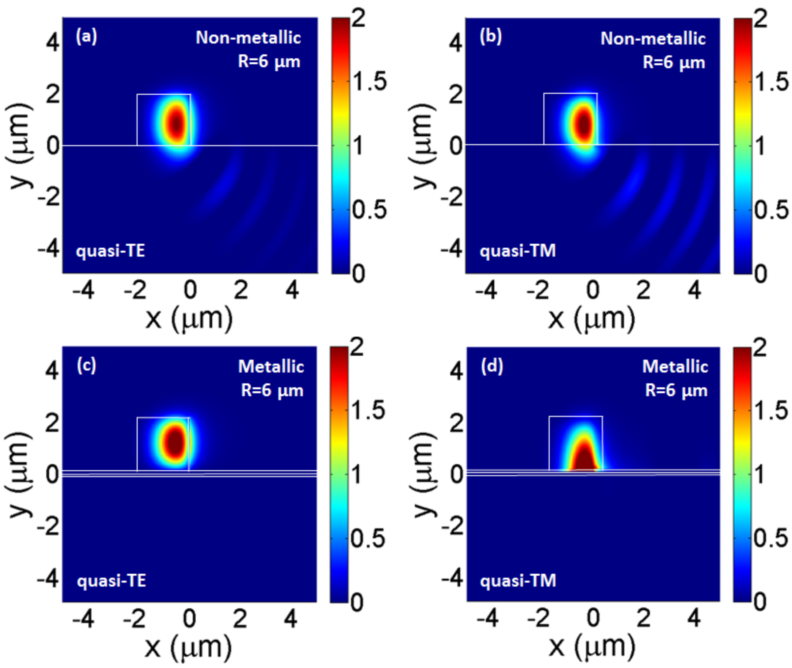

Fig. 2. Calculated 2-D mode profiles (showing the real part of the dominant electrical field component, E_x for TE and E_y for TM) at λ = 1.55 µm, R = 6 µm for the non-metallic structures (top) with the parameters of w_{ridge} = 2 µm, h_{ridge} = 2 µm for the (a) quasi-TE and (b) quasi-TM modes and for the metallic structures (bottom) with the parameters of w_{ridge} = 2 µm, h_{ridge} = 2 µm, t_{buffer} = 100 nm and t_{metal} = 100 nm for the (c) quasi-TE and (d) quasi-TM modes.

The guided mode binds to the outer rim of the ridge, since the turning is in the direction of the negative x-axis. In the non-metallic structure, the generated leaky waves can be clearly observed and are due to the sharp bending of the waveguide. As the radius of curvature is further decreased, leakage into the substrate increases with the consequent increase in bend losses. Introduction of a thin metallic layer underneath the polymer ridge blocks the radiation modes and pushes the quasi-TE mode towards the ridge in the positive y-axis direction [Fig. 2 (c) and Fig. 3(a)].

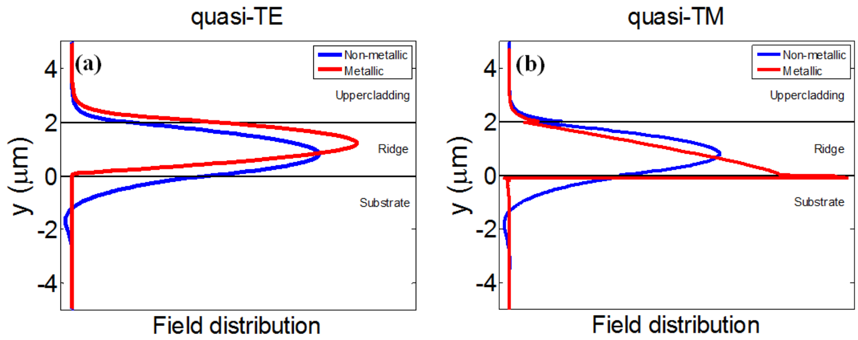

Fig. 3. Cross-sectional field distributions for both non-metallic and metallic waveguide archictures for (a) quasi-TE and (b) quasi-TM mode profile. The cross-section profiles are given at the points in x-axis where the field intesity maximized (at x = -0.55 µm for quasi-TE and x = -0.35 µm for quasi-TM). As introduced in Table 1, uppercladding and ridge correspond to air and SU-8 respectively for both metallic and non-metallic. Substrate refers to buffer/metal/undercladding layers stack for metallic and only undercladding for non-metallic.

Figure 4 (a) shows the total losses per 90 degree bend for the metallic quasi-TE mode in comparison with those of the quasi-TE mode of the non-metallic structure. For large radii of curvature, the total losses per 90 degree bend of the metallic structure rise linearly with increasing radius. In this radius range, the total losses are dominated by the propagation losses and thus, they augment as the length of the 90 degree waveguide segment increases. When the radius decreases below a critical radius, the total losses rise again, this time due to the radiative losses introduced by the bend. It can be clearly seen in Fig. 4 (a) that the introduction of the thin metal layer shifts the critical radius to a much lower value (i.e., ~7 µm) than in the non-metallic waveguide.

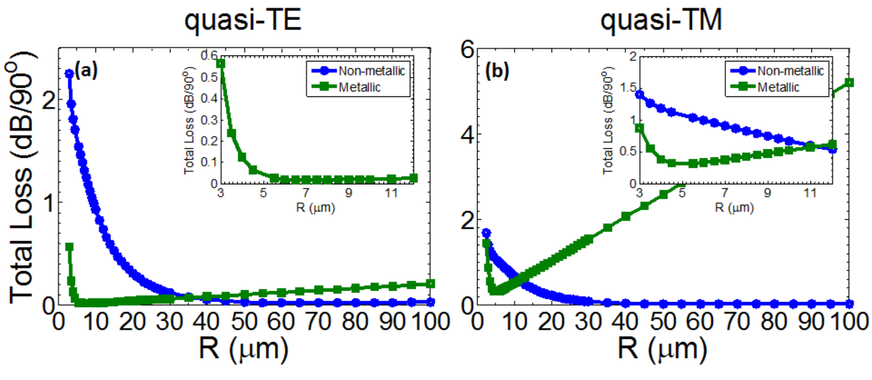

Fig. 4. Total loss (dB/90°) versus bend radius (R) for metallic and non-metallic structures for (a) quasi-TE and (b) quasi-TM modes with the parameters of w_{ridge} = 2 µm, h_{ridge} = 2 µm, t_{buffer} = 100 nm, and t_{metal} = 100 nm (only for metallic structure). The insets are a zoom of the corresponding loss plots in the region of interest.

The thin metallic layer underneath the polymer ridge transforms the quasi-TM mode of the non-metallic structure [Fig. 2 (b)] into a hybrid plasmonic-photonic mode. Such a mode is strongly coupled to the metal, thereby reducing leakage to the substrate and, therefore, the bend losses for small radii of curvature [Fig. 2 (d) and Fig. 3]. However, since the metal is highly absorptive at the wavelength of interest, high propagation losses are expected. High propagation losses are dominant for increasing radii [Fig. 4 (b)]. A shift of the critical radius, below which the bend losses become dominant, to a smaller value than in the non-metallic structure still occurs despite the large propagation losses. For a narrow range of bend radii from 3 µm to 10 µm, the metallic structure exhibits lower total losses compared to the non-metallic counterpart [inset of Fig. 4 (b)].

Fabrication

A two-step microfabrication process was followed to realize the proposed structures. Due to the elevated propagation losses of the metallic structures, a lift-off process was utilized to define the gold layer underneath the bends. The SU-8 bent waveguides are patterned in the second fabrication step. Sets of bent waveguides with increasing number of bends were fabricated in order to characterize the total losses per 90 degree bend. The results of the fabrication process for a set of non-metallic structures are depicted in Fig. 5. On the left side, Fig. 5 (a), a top view of set of SU-8 dielectric waveguides is shown. In Fig. 5 (b), a Scanning Electron Microscope of one of such bent waveguides is illustrated.

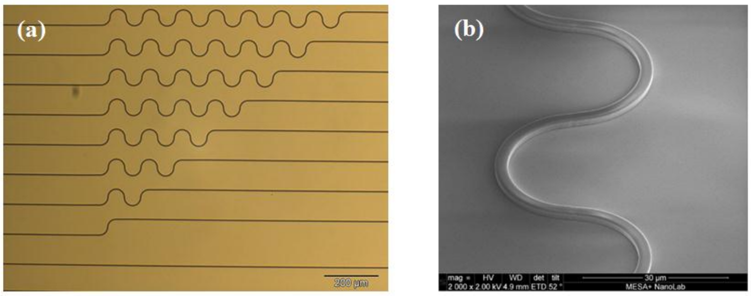

Fig. 5. Fabrication process results: (a) a set of SU-8 waveguides on SiO_2 substrate.; (b) SEM picture of a SU-8 bent waveguide.

Conclusion

In this work, we proposed and demonstrated numerically that introducing a thin metal layer underneath the core of a polymer waveguide permits the realization of sharp bends with calculated total losses (dB/90°) smaller than those of the equivalent dielectric waveguide without the metallic layer, both for quasi-TE and quasi-TM modes. The optical characterization for fabricated structures is still under way.

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