

Polymer-based surface-plasmon-polariton stripe waveguides at telecommunication wavelengths

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Long-range surface-plasmon-polariton (LR-SPP) waveguiding along thin gold stripes embedded in polymer is investigated in the wavelength range of 1510–1620 nm. LR-SPP intensity distributions at the output are measured for different stripe widths and thicknesses. Coupling loss of ~ 0.5 dB is achieved when exciting the fundamental LR-SPP mode along 10-nm-thick stripes of 6–10 μm width with a polarization maintaining fiber. LR-SPP propagation loss of 6–8 dB/cm is estimated (at 1550 nm) and attributed to scattering from inhomogeneities of the metal stripe and polymer cladding. © 2003 American Institute of Physics. [DOI: 10.1063/1.1542944]

Surface-plasmon polaritons (SPPs) represent a quasi-two-dimensional wave that can propagate along an interface between two media with real parts of permittivity of opposite signs, e.g., a dielectric and a metal.¹ The SPP fields decay exponentially into both media and reach a maximum at the interface, a condition that makes SPPs extremely sensitive to interface properties. Many fundamental properties of SPPs have been studied, and a number of applications (mostly for surface sensing) have already been suggested. Recent investigations suggested the usage of SPPs for guiding^{2,3} and routing⁴ of radiation in highly integrated optical devices. One of the main problems in this context is the SPP propagation loss due to internal damping (ohmic loss) of radiation in metal. SPPs propagating along a metal-dielectric interface are typically limited to propagation lengths of the order of tens (in the visible range) or hundreds (in the near-infrared) micrometers. However, for sufficiently thin metal film embedded in dielectric, the SPPs associated with the upper and lower of the metal-dielectric interfaces couple and form an asymmetric mode tightly bound to the metal film and a symmetric mode which extends several micrometers into the upper and lower dielectric via two identical evanescent tails. As thickness of the metal decreases, less energy of the symmetric mode so called long-range SPP (LR-SPP), is dissipated into the metal leading to an increase of propagation length.⁵ It was recently demonstrated⁶ that the LR-SPP can be used to transmit polarized light at a wavelength of 1.55 μm through long (3.5 mm) and narrow (8 μm) gold stripes embedded in silica glass and excited in an end-fire experiment (the latter was proposed by Burke *et al.*)⁷ The next steps to be taken in this direction would naturally be measurements of the LR-SPP propagation loss and the coupling loss when using a single-mode fiber.

In this letter, we report design, fabrication, and characterization of polymer based LR-SPP stripe waveguides at telecom wavelengths. The samples were fabricated by spin coating a silicon substrate with a 15- μm -thick layer of benzocyclobutene (BCB) and coating with a layer of UV resist.

Stripes of different width (3, 5, 8, 10, and 12 μm) were patterned using UV exposure, gold deposition (10, 15, and 20 nm in thickness) and lift-off. The top cladding consisted of a second 15- μm -thick layer of BCB. We would like to stress that the cladding layers should have the same dielectric constant and be thick enough to accommodate the electromagnetic field of the LR-SPP. In turn, their thickness can be used to control the LR-SPP mode depth profile, however, simultaneously influencing the propagation loss. These features are illustrated in Fig. 1 showing the LR-SPP propagation loss (for infinitely wide stripes) and the Gaussian mode field diameter (MFD) calculated at the wavelength of 1.55 μm for different BCB cladding thickness. The LR-SPP characteristics were found by solving (in the complex plane) a dispersion relation obtained from boundary conditions for the tangential field components.⁷ Note that the transverse distribution of the LR-SPP is by nature not Gaussian, but consists primarily of two exponentially decaying tails extending from the metal film into the dielectric cladding layers. It turns out, however, that the overlap integral of symmetric exponents with a Gaussian distribution can be even better than 97%. In the following we use the Gaussian MFD found by fitting a Gaussian distribution to the actual mode profile for the mode field characterization. Note (Fig. 1) that, for ~ 10 -nm-thick films, the propagation loss is already acceptable (~ 1 dB/cm) and, at the same time, the MFD can be close to that of a standard single mode fiber (~ 10.5 μm).

The LR-SPP stripe mode was excited via end-fire coupling of laser light (in the wavelength range of 1510–1620 nm) polarized perpendicular to the sample surface, by aligning a cleaved fiber facet with the end of a stripe. The output from the other end of the guide was either imaged with 200 \times magnification onto a vidicon camera for mode analysis or captured by a photodiode for loss measurements. Since light coupled from the input fiber to the cladding of the LR-SPP guide is not confined in any way to the vicinity of the guide, this light is quickly stripped away and practically only the light confined in the LR-SPP mode is observed.

Most measurements were performed at 1550 nm and the fiber used was a polarization-maintaining (PM) fiber with the

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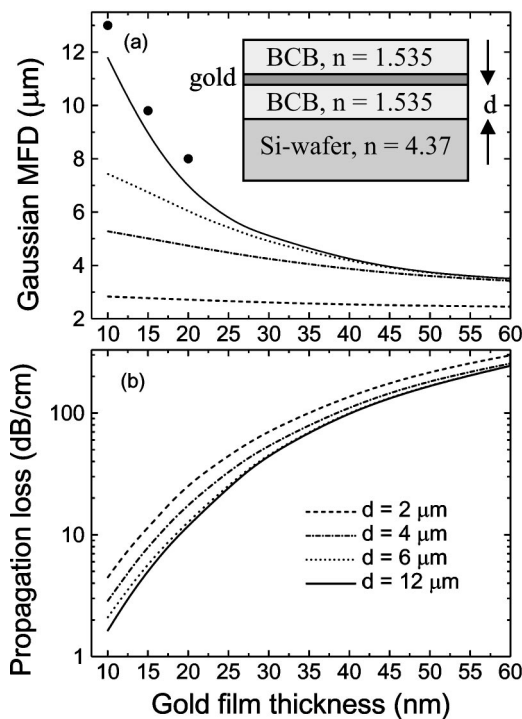


FIG. 1. Dependencies of (a) the Gaussian mode field diameter and (b) the LR-SPP propagation loss on the gold film thickness at the wavelength of 1550 nm for different thickness of polymer cladding layers. The considered configuration is shown in the inset. Dots represent the values measured with 8 μm wide stripes sandwiched between 15-μm-thick polymer (BCB) cladding layers.

MFD of 10.8 μm. Angular adjustment of the PM fiber⁶ ensured that the polarization of light coupled into the LR-SPP guide was orthogonal to the metal layer. In addition, the PM fiber was also used for the calibration of the software developed for measuring the mode field intensity distributions.

The LR-SPP mode profiles measured in depth (perpendicular to the sample surface) are shown in Fig. 2 for samples having 10-, 15-, and 20-nm-thick gold stripes (8 μm in width). It is seen that, the LR-SPP modes consist of two exponentially decaying fields, whose penetration length increases with the decrease of the metal thickness. These mode profiles were fitted to Gaussian distributions, and the resulting MFDs are plotted as points in Fig. 1. The correspondence to the simulation results is quite good, especially when one

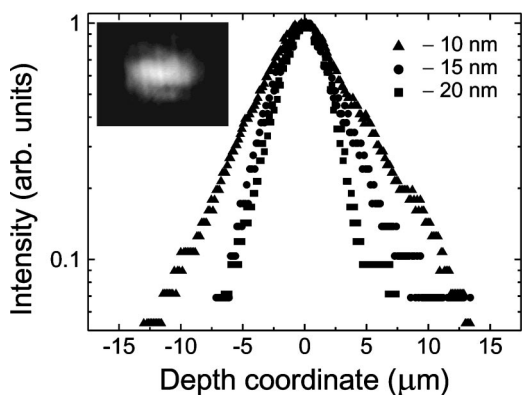


FIG. 2. LR-SPP intensity distributions in depth measured with 8 μm wide stripes of different thickness (10, 15, and 20 nm) sandwiched between 15-μm-thick polymer layers. The inset shows a photo of the intensity distribution (20×15 μm²) at the output facet of the 20-nm-thick stripe.

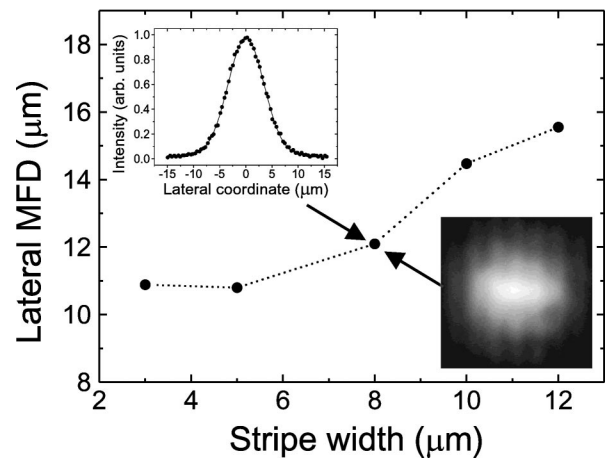


FIG. 3. Lateral mode field diameter as a function of the 10-nm-thick stripe width. The dotted line is added as a guide to the eye. Two insets show a photo of the intensity distribution (20×20 μm²) at the output of the 10-nm-thick stripe and the corresponding intensity lateral profile fitted to a Gaussian distribution.

takes into account the fact that, for thin and narrow stripes, the field confinement is expected to be weaker than for infinitely wide ones.⁸ It is interesting to note that the MFD in depth can be varied within a relatively large range without seriously influencing the propagation loss.

Figure 3 shows the variation in the lateral MFD parallel with the surface, with the width of the stripe in the lateral direction parallel to the surface. The insert shows a measured mode profile for an 8 μm wide stripe. The profile is fitted to a Gaussian distribution with excellent agreement. As stripes become narrower than 6 μm, the lateral MFD seems to stabilize around 11 μm. Further decrease in the stripe width is expected to result in the increase of the lateral as well as the transverse MFD.⁸ Making the stripe wider increases the MFD toward the onset of multimode (in width) behavior, which was observed for stripes wider than 12 μm. The minimum MFD of 11 μm is determined partly by the thickness of the stripe. We expect this value to decrease as the thickness of the stripe increases. In principle the aforementioned features allow a proper shaping of the LR-SPP mode dimensions so as to match its profile with that of the mode of a fiber used for coupling.

The fabricated samples were cut to different length for performing the measurements of propagation and coupling losses with a standard cutback technique. The results obtained for 10-nm-thick stripes are shown in Fig. 4 along with a typical optical image recorded with a collection near-field optical microscope.⁹ It is seen that the total insertion loss (sum of the total propagation and coupling losses) for stripes different in width exhibits close to exponential dependencies on the sample length. Fitting each curve to the exponential length dependence, coupling and propagation losses can be estimated. It should be noted, that coupling losses varied from sample to sample (and from stripe to stripe) due to the edge quality of the sample. From the data obtained we estimate that the propagation loss is in the range of 6–8 dB/cm and the coupling loss for the best case is of the order of 0.5 dB. Similar measurements were performed for 15- and 20-nm-thick 10 μm wide stripes resulting in similar values of the propagation and coupling loss. This suggests that the

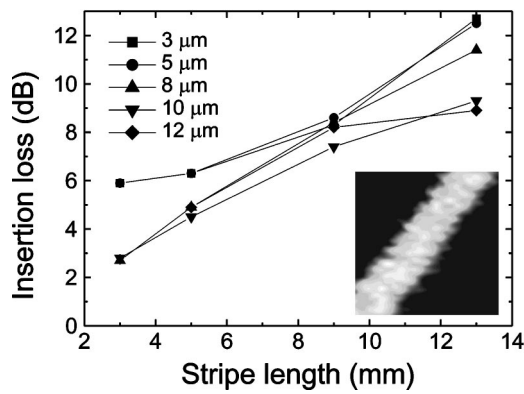


FIG. 4. Insertion loss for 10-nm-thick stripes of different width as a function of the stripe length. The inset shows a typical near-field optical image ($69 \times 69 \mu\text{m}^2$) obtained with the $5 \mu\text{m}$ wide 10-nm-thick gold stripe.

main propagation loss is not related to ohmic loss in the stripes but rather to the scattering by inhomogeneities of the metal stripe and the polymer cladding. One can suggest that the first contribution decreases with the increase of the stripe thickness balancing the expected increase in the ohmic loss. Comparing with Fig. 1 the measured loss for 20 nm thick guides lower loss is actually observed to be below what is expected from simulations on infinitely wide films. Considerable reduction in the propagation loss, below 1 dB/cm should therefore be possible to achieve through material and processing optimization.

In conclusion we have demonstrated LR-SPP stripe waveguides as a promising planar technology for integrated

optical devices. Features of the guides include efficient coupling with single-mode fibers and low propagation loss. The mode of the guide can be designed easily through varying the thickness of the metal and/or cladding layers as well as the width of the guide. Good correspondence of experiments with theory were found for the vertical mode profiles. Propagation loss on the other hand was found to be independent of film thickness suggesting that the fundamental loss of a LR-SPP channel guide is even smaller than predicted by simulation for a continuous film. LR-SPP channel guides provide a true planar waveguiding technology, which simplifies development and fabrication of integrated optical devices. Excellent mode match with optical fiber, low propagation loss, and ease of fabrication make LR-SPP guides worth considering as an alternative to traditional technologies for integrated optics.

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