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Integrated power monitor for long-range surface plasmon polaritons

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Abstract

We propose a method for monitoring the power carried by long-range surface plasmon polaritons (LRSPPs) propagating along a metal stripe embedded in dielectric. The method utilizes the fact that the stripe is heated by LRSPPs (due to ohmic loss), and is based on stripe resistance measurements using a Wheatstone bridge configuration. 1-mm long power monitors integrated with LRSPP guides, consisting of 15-nm thin and 8-μm wide gold stripes embedded in polymer, are fabricated and characterized at telecom wavelengths, featuring linear responses for up to 50 mW of input power, responsivities of up to 0.15 mV/mW (for a bias voltage of 2 V), weak wavelength dependence and total (fibre-to-fibre) insertion losses down to 2 dB when using single-mode and polarization-maintaining fibres.

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Surface plasmon polaritons (SPPs) are electromagnetic excitations comprising optical fields in a dielectric, that are coupled to oscillations of free electrons in a conductor (usually a metal), and propagating along the metal–dielectric interface [1,2]. The SPP fields are tightly bound to the interface, where their fields reach a maximum, and decay exponentially into both media. The interest in SPPs has dramatically risen in recent years partially due to the possibility of their usage for guiding [3,4] and routing [5,6] of radiation in highly integrated optical devices. Furthermore, SPP-based guiding components are potentially able to carry optical signals and electric control currents through the same thin metal circuitry, a remarkable feature that opens perspectives of

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unprecedented technical configurations, e.g., of merging electrical and optical integrated circuits. One of the main problems in this context is the SPP propagation loss due to internal damping (ohmic loss) of radiation in metal, a circumstance that limits the SPP propagation to lengths of the order of tens (in the visible range) or hundreds (in the near-infrared) micrometers [2].

The latter issue can be resolved by employing a symmetric configuration, in which a sufficiently thin metal film is embedded in dielectric. In such a case, the SPPs associated with the upper and lower interfaces couple and form a symmetric mode (Fig. 1(a)), a long-range SPP (LRSPP), whose propagation loss decreases drastically with the decrease of the film thickness [7,8]. Furthermore, a thin metal stripe surrounded by dielectric (Fig. 1(b)) supports the propagation of an LRSPP stripe mode, whose field distribution can be adjusted close to that of a single-mode fibre [9–11]. The LRSPP-based guides having propagation loss down to a few dB/cm [11] are promising, at least in a longer perspective, as elements of integrated photonic components, e.g., due to the aforementioned possibility of guiding optical radiation and transmitting electrical signals along the *same* metal stripes. Very recently, we have demonstrated the *first* electrically controlled (plasmonic) components utilizing this principle, in which the dielectric refractive index and, thereby, the LR-SPP propagation constant were controlled via the thermo-optic effect by simply heating the appropriate metal stripe with the transmitted current [12,13]. LRSPP-based Mach-Zender modulators, directional coupler switches [12] and in-line extinction modulators [13] were fabricated and characterized at the light wavelength of 1.55 μm, featuring low driving powers (<100 mW), high extinction ratios (∼30 dB) and moderate response times (∼1 ms).

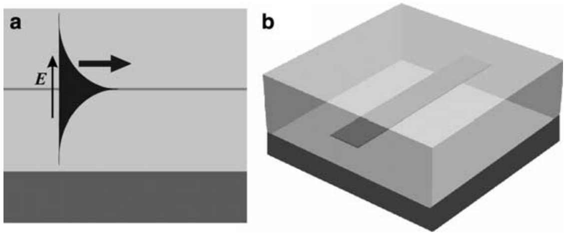

Fig. 1. Schematic representation: (a) of the LRSPP field distribution near a thin metal film embedded in dielectric along with the orientation of the dominant electric field component and (b) schematic layout of an LRSPP stripe waveguide.

Here, we demonstrate that essentially the *same* metal stripes, which constitute the heart of LRSPP-based modulators and switches, can also be used to monitor the *transmitted* LRSPP power by means of measuring variations in the stripe resistance caused by heating (due to the LRSPP absorption). We report the design, fabrication and characterization of power monitors for LRSPPs (excited at telecom wavelengths) that can be used in LRSPP-based integrated photonic circuits and also, due to relatively low insertion losses, as stand-alone infrared optical power monitors that can be integrated with other fibre-optic components and devices.

Let us consider a thin metal stripe (of thickness t and width w) embedded in dielectric (polymer) with the same thickness d of upper and lower cladding layers (Fig. 1(b)) that transmits an LRSPP stripe mode having the power $P(x)$, with x being the coordinate along the stripe. In the steady-state regime, the optical power absorbed by the stripe is dissipated into the cladding. Evaluating the power dissipated per unit length as $Q \sim 2\kappa\Delta Tw/d$, where κ is the dielectric thermal conductivity and ΔT is the temperature increase of the metal stripe due to absorption of the LRSPP power, one can estimate the latter as follows:

$$\Delta T(x) = \frac{d\alpha_{\mathrm{abs}}}{2\kappa w} P_{\mathrm{in}} \exp(-\alpha_{\mathrm{pr}} x). \tag{1}$$

Here, α_{abs} is the coefficient of LRSPP absorption by the metal stripe, P_{in} is the power coupled in the LRSPP stripe mode and α_{pr} is the LRSPP attenuation coefficient that determines the LRSPP propagation loss. The temperature increase causes an increase in the metal resistivity and, consequently, in the stripe resistance that can be written down

$$R(P_{\mathrm{in}}) \cong R(P_{\mathrm{in}} = 0) \times \left\{ 1 + \left[1 - \exp(-\alpha_{\mathrm{pr}} L)\right] \frac{\alpha_{\mathrm{th}} d\alpha_{\mathrm{abs}}}{2\alpha_{\mathrm{pr}}\kappa w L} P_{\mathrm{in}} \right\}, \tag{2}$$