Directional coupling between dielectric and long-range plasmon waveguides

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Abstract. We have designed, fabricated and characterized integrated directional couplers capable of converting the mode of an optical dielectric waveguide into a long-range plasmon propagating along a thin metal stripe. We demonstrate that the coupling between the two types of waveguides is generally very weak unless specific conditions are met. This sensitivity could be potentially exploited in sensing applications or for developing novel active photonic components.

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1. Introduction

Over the last decade, surface plasmon polaritons (SPPs) have emerged as promising candidates to expand the functionalities of integrated optical circuits [1, 2]. SPPs are electromagnetic waves coupled to a longitudinal oscillation of free electrons at the surface of a metal [3]. Their electromagnetic distribution is evanescent in the direction perpendicular to the propagation, resulting in intense fields that decay exponentially away from the surface. Consequently SPPs are among the most sensitive of all optical modes and raise considerable hope for enhancing the performances of modulators, switches and chip-scale optical sensors. In addition, the size of certain SPP configurations can be smaller than the operation wavelength, thus providing a path to decrease the size of optical components beyond the diffraction limit [4]. However, the use of SPPs is considerably limited in practice due to the large absorption present in metals [5]. Although further miniaturization leading to reduced path lengths may eventually mitigate the losses, a more immediate answer to this problem is the pursuit of configurations that seamlessly combine SPP circuits with low-loss dielectric wave guiding elements [6]–[10]. Here, we address this issue in the context of long-range SPPs (LR-SPPs) propagating along thin metal stripes.

The LR-SPPs considered here are the fundamental modes supported by thin metal stripes embedded in a homogeneous environment [11, 12]. LR-SPPs are not as confined as other SPP modes but their large field extension outside the stripe minimizes the fraction of energy traveling in the metal [13, 14], leading to unusually low attenuation rates of the order of a few dB cm$^{-1}$ [15, 16]. In addition, their properties can be accurately predicted by standard numerical methods [17]–[19], thereby enabling the precise design of integrated components exploiting the tremendous sensitivity of LR-SPPs. Functional devices experimentally demonstrated so far include passive elements (splitters, couplers, filters and interferometers) [15], [20]–[22] as well as low-loss active integrated devices (thermo-optic and electro-optic attenuators, external cavity lasers) [23]–[26].

Experimentally, LR-SPPs are generally excited by end-fire coupling an optical fiber at the input of the metal stripe. This technique yields low insertion losses (as low as 0.1 dB [27]) because of the substantial field overlap between the optical mode guided by the fiber and the LR-SPP. Another successful coupling approach relies on exciting the metal stripes with evanescent waves generated by a prism illuminated under attenuated total reflection [28]. In this case, the coupling region is not restricted to the input of the metal stripe because the prism can be positioned anywhere above the length of the structure.

In this paper, we study the excitation of LR-SPPs waveguides placed in close proximity to integrated dielectric optical waveguides. This configuration is different from that of feeding a LR-SPP with an external fiber or a prism because of the specific constraints imposed by integrating different waveguide technologies on the same substrate. In addition, this coupling configuration effectively forms a directional coupler, which, at a system level, is an extremely important component in modern telecommunication applications [29]. In section 2, we show numerically that directional coupling between a dielectric waveguide and a metal stripe is problematic due to an intrinsic mode mismatch. We then propose an approach for minimizing this mismatch and therefore maximizing the coupling. In section 3, we describe a method for fabricating directional couplers having the parameters prescribed numerically. Section 4 reports the characterization of the structures and quantitatively corroborates our numerical predictions. Finally, we conclude this work by discussing the potential applications for these structures.
Figure 1. (a) Overview of the structures consisting of a series of SU-8 waveguides coupled to Au stripes. The radius of curvature of the SU-8 waveguides is 1 mm. (b) Cross-sectional view of a coupler. Except for the thickness \( t \) of the BCB layer, the coupler dimensions are kept constant throughout this study and the couplers are always positioned \( 3.3 \, \mu m \) above the SiO\(_2\) substrate. The Au stripe has a width of \( 4.6 \, \mu m \), a thickness of 36 nm, and is separated from the SU-8 waveguide by a gap of \( 2.5 \, \mu m \). The average width and thickness of the SU-8 waveguide are \( 2 \, \mu m \) and \( 1.5 \, \mu m \). At \( \lambda = 1.55 \, \mu m \), the permittivity of Au is \( -132 + 12.65i \) \([22]\) and the refractive indices of SiO\(_2\), BCB, and SU-8 are, respectively, \( 1.444 \) \([20]\), \( 1.535 \) \([21]\) and \( 1.57 + 8e - 5i \). Note that we have added an imaginary part to the refractive index of SU-8 so as to fit the losses of our real waveguides. These losses were determined with cut-back measurements.

2. Design

The central problem in designing dielectric-to-plasmonic couplers is that the effective index in a dielectric waveguide is generally close to the refractive index of the guiding core, whereas the LR-SPP index approaches that of the surrounding environment. Thus, there exists an inherent momentum mismatch between the two types of modes so they do not generally interact. A recent numerical study \([30]\) has addressed this problem by considering dielectric waveguides with such a small thickness (less than 400 nm at \( 1.55 \, \mu m \)) that the mode has a considerable transverse extension outside the central core, hence lowering its index. However, this solution might be difficult to implement in practice because the quality of thin waveguides is difficult to control and hence these structures are likely to suffer from large radiative losses generated by the edge roughness. Here, we follow a different strategy for satisfying the mode matching condition. Rather than imposing tight constraints on the waveguide dimensions, we adjust the effective indices in each arm of the coupler by constraining the modes in an additional dielectric layer.

To illustrate our approach, we have designed and fabricated a series of SU-8 polymer waveguides coupled to Au stripes with incrementally longer lengths, as shown in figure 1(a). The couplers are embedded in a transparent layer of benzocyclobutene-based polymer (BCB) and supported by a Si substrate with \( 4 \, \mu m \) of thermal SiO\(_2\). In this study, we excite the structures by end-fire coupling an optical fiber to the SU-8 waveguide at a wavelength of \( \lambda = 1.55 \, \mu m \).
To avoid a direct interaction between the fiber and the coupler, the SU-8 waveguide runs over several millimeters before approaching the metal stripe. In addition, the SU-8 waveguide makes a 90° turn so as to minimize the background light generated by the transition losses between the fiber and the sample. On the output side, both the SU-8 waveguide and the metal stripe are terminated at the end face of the sample.

The dimensions and material parameters of the structures are shown in the cross-sectional view of figure 1(b). Due to their different operation principles, the two arms have very different aspect ratios, the Au stripe being 50 times thinner than the SU-8 waveguide. The SU-8 waveguide has an irregular cross section, which approximates the shape of the real samples. This geometry acts very much like a rectangular waveguide because it supports one mode with a magnetic field predominantly in the $y$–$z$ plane and one mode with a magnetic field predominantly in the $x$–$z$ plane. Only the second mode can couple to the metal stripe because the magnetic field of the LR-SPP is almost parallel to the $x$-axis [12].

We begin our study by modeling the behavior of the structure using a commercial finite element eigenmode solver (Comsol Multiphysics). Given that the couplers are invariant along the propagation direction $z$, the eigenvalue problem can be formulated in the $x$–$y$ plane as a system of equations in which the wavevector amplitude $k$ is the eigenvalue. We solved the weak form representation of these equations in Comsol and performed all the simulations at $\lambda = 1.55$ $\mu$m. Since we include the losses in our model, the eigenvalue $k$ is a complex quantity and its imaginary part is related to the attenuation rate of the mode. Our simulations do not have any fitting parameter except that we add a small imaginary part to the refractive index of SU-8 that accounts for the losses of our real waveguides.

Figure 2 shows the field distribution of the coupled eigenmodes for a BCB total thickness $t = 5.6$ $\mu$m. As expected from the geometry, there are symmetric and antisymmetric eigenmodes. Additionally, the transverse extension of the modes reaches the BCB/air and BCB/$\text{SiO}_2$ interfaces. In other words, the eigenmodes are hybridized by total internal reflection with a slab mode of the BCB cladding [31, 32] and therefore they exhibit a dispersion with the BCB total thickness $t$.

Figure 3 illustrates this point by plotting the effective indices of the two eigenmodes as a function of $t$. We consider the case where the Au stripe and the SU-8 waveguide maintain their absolute position with respect to the bottom of the BCB as $t$ is varied (the distance between the $\text{SiO}_2$/BCB interface and the waveguides is always set to 3.3 $\mu$m, see dimensions on figure 1(b)).

Figure 2. Transverse magnetic field of the two eigenmodes. The eigenmodes are almost TM-polarized, with their magnetic field predominantly oriented along the $x$-(horizontal) axis. For this reason, only this field component has been plotted here. The normalized color scale goes from $-1$ (blue) to $+1$ (red).
To interpret these results, we also plotted the energy distribution along a line parallel to the x-axis at selected points of the curves, as well as the dispersion relations of the isolated stripe and SU-8 waveguide.

We first focus on the dispersion of the isolated metal stripe and SU-8 waveguide (gray and black dashed curves in figure 3). For $t > 10 \mu m$, the dispersion curves approach horizontal asymptotes indicating that the BCB is thick enough to accommodate the full extension of the eigenmodes (the corresponding field distributions are not identical to those occurring in an infinite BCB thickness because the distance between the waveguides and the bottom of the BCB is equal to $3.3 \mu m$, which is smaller than the natural size of the modes). For the LR-SPP, the real part of the asymptote is close to the refractive index of BCB, as expected since the field distribution of this mode is predominantly filling the BCB region. In contrast, the TM-polarized mode of the dielectric waveguide is guided within the SU-8 core and has an exponential tail in the BCB; as a result, the real part of its effective index has an asymptote that is larger than the refractive index of BCB but smaller than that of SU-8. In other words, there is an intrinsic mode mismatch between the metal stripe and the SU-8 waveguide due to the very different field patterns of their modes. Consequently, the coupling between the metal stripe and the SU-8 waveguide is extremely weak.

However, figure 3 shows that this mode mismatch can be overcome under very specific circumstances. For $t < 10 \mu m$, the dispersion relations of the isolated metal stripe and dielectric waveguide are no longer flat because the upper air/BCB interface is close enough from the structures to perturb the distribution of the modes (again, it should be noted that the modes are always frustrated at the bottom interface). In this regime, the fields are constrained by total internal reflection [31, 32], and the proximity of the air region causes a drop in the dispersion
of the modes. The decline is sharper for the SU-8 waveguide so that the two dispersion curves cross at \( t \sim 5.6 \mu\text{m} \). For this specific BCB thickness, the modes of the dielectric waveguide and the metal stripe have the same momentum and therefore the efficiency of the directional coupler should be maximized.

The dispersion relations and intensity patterns of the coupled eigenmodes confirm this analysis (blue, red and black continuous curves in figure 3). In the region of flat dispersion \((t > 10 \mu\text{m})\), the symmetric eigenmode mode is mainly concentrated in the SU-8 region while the antisymmetric eigenmode is predominantly propagating along the Au stripe. As a result, their respective dispersion relations are close to that of the isolated waveguides. For thinner samples, the real part of the effective index decreases with \( t \) for both eigenmodes, leading to an anticrossing at the thickness for which the dispersion curves of the isolated modes are crossing \((t \sim 5.6 \mu\text{m})\). This behavior implies that the mode degeneracy of the isolated waveguides has been lifted; therefore the metal stripe and the dielectric waveguide are strongly coupled. As a corollary, the energy of the eigenmodes is equally distributed between the two arms of the coupler (see figure 3(b)). For smaller thicknesses of BCB, the interaction between the metal stripe and the SU-8 waveguide rapidly deteriorates. The anticrossing behavior results in a symmetric mode mostly propagating along the metal stripe and an antisymmetric mode mainly guided in the dielectric waveguide.

As shown in figure 3, an eigenmode analysis is very useful to understand the system and to determine the precise value of \( t \) for which the directional coupling is optimized. Moreover, the eigenmodes of a system are orthogonal so we can express the total field in the coupler as a linear combination of these solutions \([33]\):

\[
H_{\text{tot}}(x, y, z) = c_a H_a(x, y) \exp(ik_az) + c_s H_s(x, y) \exp(ik_sz),
\]

where \( H_{\text{tot}} \) is the total magnetic field vector, \( H_a \) and \( H_s \) are the magnetic field distributions of the antisymmetric and symmetric eigenmodes, respectively, \( k_a \) and \( k_s \) are their wavevectors, and \( c_a \) and \( c_s \) are the linear coefficients determining the admixture of the two eigenmodes. These coefficients correspond to the overlap integrals between the fields of the input mode (the mode in the isolated SU-8 waveguide) and those of the two eigenmodes at the coupler entrance:

\[
c_j = \frac{\int \int \Omega \left( \frac{\left| \int \int \Omega E_{\text{in}} \times H_j \cdot \hat{z} \, d\Omega \right|^2}{\int \int \Omega E_{\text{in}} \times H_{\text{in}} \cdot \hat{z} \, d\Omega \int \int \Omega E_j \times H_j \cdot \hat{z} \, d\Omega} \right)^{1/2}}{\int \int \Omega E_{\text{in}} \times H_{\text{in}} \cdot \hat{z} \, d\Omega \int \int \Omega E_j \times H_j \cdot \hat{z} \, d\Omega}
\]

where the vectors \( E_{\text{in}} \) and \( H_{\text{in}} \) are the field of the input mode, the vectors with the subscript \( j = \{a, s\} \) are the fields of either the antisymmetric or the symmetric eigenmode and \( \Omega \) is the \( x-y \) plane. Similar eigenmode expansions have been used for solving other long-range SPP problems \([18, 30]\). The main difference of the present formulation is that these previous calculations used the conjugated version of equation (2), which is a valid approximation for low loss waveguides having real field distributions \([33]\). We have opted for the general complex formulation leading to complex-valued \( c_j \) because we found that the imaginary part of the field distributions was too high for the low-loss approximation.

Equations (1) and (2) can be used to predict the variation of energy within each arm of the coupler along the propagation direction \( z \). Examples of such curves will be shown in figure 5 where experimental results will be compared with the simulations.

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Figure 4. (a) SEM micrograph of an SU-8 waveguide, top view of six couplers and dark field microscope image showing a section of a sample. All these images have been taken with couplers that were not covered by the upper BCB layer. (b) Output patterns for various coupling lengths (CL) when the structures are embedded in a thickness $t = 6.6 \mu m$ of BCB.

3. Fabrication

To verify the predicted behavior of the couplers, we have fabricated a series of couplers with the parameters used in section 2. In a first step, a layer of BCB (Dow Cyclotene 3022-46) is spun on a Si wafer with 4 $\mu m$ of thermal SiO$_2$ and cured in a vacuum oven at 210 $^\circ$C for 40 min. A negative photoresist (AZ-5214) is then applied on the sample and patterned with the features corresponding to the metal stripes by UV lithography (using a Cr on quartz photomask mounted on a Suss MicroTec MJB3 aligner). The sample is subsequently metalized in an electron beam evaporator (CHA Industries Solution) with a layer of Cr (nominal thickness 5 nm) followed by approximately 25 nm of Au (our AFM measurements indicate that the total metal thickness was 36 nm). The metal stripes are finally revealed by lifting-off the remaining resist. The fabrication of the dielectric waveguides (using MichroChem’s SU-8-2002 epoxy thinned to 23.5 wt.% solid) requires fewer steps because SU-8 is a negative resist that can be directly patterned by UV lithography. However, this step is the most critical part of the entire process as the dielectric waveguides must be strictly parallel to the metal stripe. After removing the unexposed SU-8 parts, the resulting structures are covered by a second layer of BCB (Dow Cyclotene 3022-46) and cured at 190 $^\circ$C for 10 h. Although the curing parameters are different than for the first BCB layer, they essentially lead to the same degree of polymerization. This change is dictated by the fact that the nominal glass transition point of SU-8 is 210 $^\circ$C and therefore a lower curing temperature is needed to avoid altering the material properties of the dielectric waveguides. As a final step, clean end facets are produced at the input and the output of the structures by cleaving the sample.

Although we used standard procedures and commercially available materials, the sensitivity of LR-SPPs imposes a very tight tolerance on the dimensions, thus considerably complicating the fabrication. For example, a variation of two nanometers in the metal thickness can compromise the coupling. Figure 4(a) shows images of samples at various fabrication stages.
4. Experimental results

The structures were characterized by exciting the TM-like mode of the curved input SU-8 waveguide and by imaging the coupler terminations at the end face of the sample. To excite the SU-8 waveguide, we used an end-fire coupling scheme involving a single-mode optical fiber connected to a 1550 nm laser source (Lightwave Measurement System HP 8164A). In this setup, the fiber was maintained on the optical table in such a way that the ratio between TM and TE polarization was kept constant and larger than ten at the entrance of the sample. To filter the remaining TE-polarized noise, we placed a linear analyzer at the output of the structures. The output images were obtained with a Mitutoyo microscope equipped with a 20× objective and an In_xGa_{1-x}As detector array (Sensors Unlimited, SU320MS-1.7RT).

We first examined a series of couplers embedded in 6.6 µm of BCB made on the model shown in figure 1, where each coupler is slightly longer than its neighbor. Figure 4(b) shows the output patterns of four couplers with lengths ranging from 0 µm–480 µm. The light emitted by the couplers evolves from a single spot centered on the SU-8 waveguide to a double spot stretching over the full section of the structure, thus demonstrating a transfer of energy from the SU-8 waveguide to the LR-SPP. We verified that no coupling occurred for the TE polarization by ensuring that the output pattern was always centered on the SU-8 waveguide.

To gain more quantitative insight, we have extracted from these images the intensity carried by the SU-8 waveguide and the Au stripe and plotted the results as a function of the coupling length (CL). The results are summarized in figure 5(a) together with the numerical predictions based on equations (1) and (2). In these calculations, the energy carried in each arm of the coupler has been obtained by integrating \( \mathbf{H}_{\text{tot}}^2 \) over the left and right sides of the computational domain, respectively. The measured and simulated points are in good agreement, except for small deviations which we attribute to losses that are not accounted for in the simulations (radiative defects and the use of Cr as an adhesion layer for the Au stripes). Figure 5(a) shows that a periodic exchange of energy occurs between the SU-8 waveguide and the metal stripe, which is the distinct signature of directional coupling. However, the coupling is incomplete (less than 50%), as expected since the BCB thickness \( t \) considered here is far from the anticrossing point of figure 3.

We then thinned the sample in a reactive ion etcher (RIE, Trion Technology Phantom II) to approach the optimum \( t \sim 5.6 \) µm predicted by figure 3. The characterization of the modified sample is reported in figure 5(b). Both measurements and simulations consistently indicate that the coupling has significantly improved though it is still not perfect—in fact, we have etched 0.2 µm too deep in the BCB due to the poor tolerance of our RIE. Nevertheless, both measurements and calculations clearly demonstrate that the coupling can be optimized by constraining the fields in a controlled thickness of BCB, hence validating our approach.

As a comparison, the inset of figure 5(b) shows the predicted coupling at the optimum thickness \( t \sim 5.6 \) µm. In contrast with pure dielectric couplers, the coupling efficiency never reaches 100% due to the absorption in the metal. Consequently, the degree of coupling cannot be directly evaluated from the intensity carried by the metal stripe but rather by the extinction in the SU-8 waveguide, which only approaches zero when the two arms of the coupler are perfectly matched, as illustrated with the different graphs of figure 5. Another important consequence of the losses is that the energy oscillations between the SU-8 waveguide and the metal stripe are not synchronized. However, these limitations could be substantially mitigated in principle by minimizing the length required to convert the incoming mode into the LR-SPP, for example...
Figure 5. Experimental evidence of directional coupling. (a) Intensity transmitted by the SU-8 waveguide (black squares for the experiments and black line for the simulations) and the Au stripe (red diamonds for the experiments and red line for the simulations) as a function of the CL for a BCB thickness of $t = 6.6 \, \mu m$. The experimental error can be mainly attributed to fluctuations in the gain of the detector, as well as variations in the coupling efficiency between the fiber and the different dielectric waveguides. (b) Experiments and simulations when the BCB thickness of the sample has been reduced to $t = 5.4 \, \mu m$. Inset: numerical predictions for the optimum thickness of $t = 5.6 \, \mu m$.

by narrowing the separation gap between the two arms of the coupler. As an example, we have found numerically that the coupling could reach 95% after 350 $\mu m$ of propagation when the gap is reduced to 1.5 $\mu m$—an efficiency comparable to what can be achieved by exciting LR-SPP waveguides with an external optical fiber [27].

5. Conclusion

We have integrated dielectric optical and metal LR-SPP waveguides on the same chip using directional couplers. Our simulations and measurements are in quantitative agreement and show that the coupling is made possible by frustrating the modes within the polymer surrounding the structures—an approach which is also highly beneficial for other LR-SPP configurations such as bends [31, 32]. The purpose of this study was to elucidate the coupling mechanism and we did not try to optimize the energy transfer between one arm of the coupler to the other. The insertion loss of our best experimental samples is lower than 2.5 dB and can be attributed to fabrication tolerances and absorption in the metal. However, coupling efficiencies being as high as those achieved with end-fire coupling configurations are theoretically possible.

Since the coupling only occurs for the TM polarization, the directional couplers considered in this work effectively act as integrated polarization splitters. Another important aspect of these structures is that they are effective only under very specific conditions. This property may find applications in optical sensing; for example, directional couplers operating in an
aqueous environment should be very sensitive to small changes in the refractive index of the solution. Alternatively, it should be easy to degrade the coupling using electro-optic or nonlinear materials, which could be of potential interest for developing low-loss plasmonic switches and modulators.

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