Directional coupling in long-range dielectric-loaded plasmonic waveguides

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Abstract: Directional couplers (DCs) based on long-range dielectric-loaded surface plasmon-polariton waveguides (LR-DLSPPWs) operating at telecom wavelengths are studied both numerically and experimentally. The investigated LR-DLSPPWs are formed by ~1.2-µm-high and 1-µm-wide polymer ridges fabricated atop of 15-nm-thick and 500-nm-wide gold stripes supported by a 288-nm-thick Ormoclear polymer deposited on a low-index (n_s ≈ 1.34) layer of Cytop. DC structures consisting of sine-shaped S-bends (having an offset of ~10 µm over a distance of ~20 µm) and ~100-µm-long parallel LR-DLSPPWs with a center-to-center separation of 2 µm are characterized using scanning near-field microscopy. The experimentally obtained values of the propagation length (~400 µm), S-bend loss (~4 dB) and coupling length (~100 µm) are found in good agreement with the numerical simulations, indicating a significant potential of LR-DLSPPWs for the realization of various plasmonic components.

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References and links
1. Introduction

Surface plasmon-polaritons (SPPs), which are surface electromagnetic waves propagating along a metal-dielectric interface [1], have been intensively studied during the last decade due to their large number of potential applications, ranging from telecommunications and signal processing to biochemistry and sensing [2–4]. Waveguiding is one of the several particularly interesting applications of plasmonics, since there is an exciting perspective to combine large operational bandwidth of photons with high-density integration feasible in plasmonics [5]. Among various types of plasmonic waveguides, a number of SPP-based configurations support strongly confined (in the lateral direction) modes, whose confinement can be deeply subwavelength. Those are, for example, metal nanowires [6], chains of nanospheres [7], as well as V-grooves cut in metal surfaces [8]. One of the challenges shared by all subwavelength SPP waveguides is considerable propagation losses, as the mode confinement is always achieved by concentrating large amount of energy in metal, thereby decreasing the spatial extent of the field in dielectric. As a result, one can realize strong field-enhancement phenomena, which can be used for sensing applications, but, on the other hand, this leads to high ohmic losses in metal and a drastic decrease of mode propagation length. In other words, an SPP waveguide configuration is subjected to the propagation length–confinement trade-off.

Considering only these two characteristics, plasmonics has a very strong competitor, viz., silicon photonics, which during the last decade has also gained a tremendous interest and progress [9] in the development of most of the critical components required for optical interconnect applications [10], leading to remarkable achievements both with respect to chip-level transceiver [11] and routing [12] circuitry applications. Having similar to plasmonic waveguides mode confinement and substantially larger propagation length [13], silicon-on-
insulator strip waveguides are often considered to be superior to plasmonic ones. However, metal stripes as an inherent part of plasmonic waveguides provides easy access to the external electrodes offering certain advantages for the implementation of electro- and thermo-optic modulation. The fact that the SPP fields reach their maximum at the metal–dielectric interface makes such modulation substantially more energetically efficient than in the case of silicon photonics, since controlling electrodes can be placed right in the center of the SPP mode. Indeed, a low-energy thermo-optical tuning and fast error-free 10-Gb/s transmission through a dielectric-loaded plasmonic waveguide (DLSPPW) has been demonstrated recently [14, 15] as a proof of principle. The DLSPPWs confine regular SPPs by use of a dielectric ridge on top of a smooth metal film [16], which introduces an effective refractive index difference. Among all plasmonic configurations, DLSPPWs are so far the only waveguides that have been exploited for the realization of complex circuit elements [17], active control [18], and partial loss compensation using optical pumping [19, 20]. Furthermore, the absorption losses in DLSPPWs can be significantly reduced by using the long-range SPP configuration [21], in which a thin metal stripe is positioned in a near-symmetric environment so that the longitudinal component of the electric field in metal (and hence the ohmic loss) is minimized. The corresponding long-range DLSPPW (LR-DLSPPW) configuration has recently been shown both theoretically [22, 23] and experimentally [24] to be able to guide an SPP mode over millimeter-long distances, while retaining relatively strong mode confinement. The usage of LR-DLSPPW-based components seems very promising for practical applications, and it is therefore important to assess the potential of LR-DLSPPW integration, which is determined by the mode coupling in adjacent waveguides. In this respect, investigations of directional couplers (DCs) should provide directly the minimum separation distance between LR-DLSPPWs and thereby set the limit on their maximum integration density.

In this paper, we present the results of our study of LR-DLSPPW-based DCs at telecom wavelengths in the range of 1425-1625 nm. The main goal of our work is to investigate the coupling strength between LR-DLSPPWs for different separation distances and excitation wavelengths. The fabrication process, as well as imaging of the propagating LR-DLSPPW modes by use of a scanning near-field optical microscope (SNOM), is described in the first section. The LR-DLSPPW-based S-bends, as an important part of DCs and many other waveguide components, are investigated separately, and the corresponding experimental and theoretical results are presented in the second part. Finally, studies of LR-DLSPPW-based DCs are reported in the last section, providing first experimental measurements of the coupling length for a DC-structure with the center-to-center separation of 2 μm between waveguides and then numerical results obtained by use of finite element method (FEM) implemented in commercial software COMSOL.

2. Experimental results and numerical simulations

2.1 Fabrication process and imaging of LR-DLSPPWs using SNOM

The LR-DLSPPW structures [Fig. 1(a)] were fabricated by spinning a 288-nm-thick layer of a high-refractive-index UV-curable organic-inorganic hybrid material Ormoclear (n_b = 1.53) [25] onto a silicon wafer pre-coated with a 4-μm-thick layer of amorphous fluoropolymer Cytop (n_s = 1.34). Straight and bent 500-nm-wide and 15-nm-thick gold stripes were patterned with electron-beam lithography, metal evaporation, and lift-off. The waveguide fabrication has been completed using a second lithography step for patterning ~1.2-μm-high and 1-μm-wide ridges of polymethyl methacrylate (PMMA, n_r = 1.49) atop of the gold stripes, ensuring the single-mode LR-DLSPPW operation. The height and width of the produced PMMA ridges was inspected with atomic force microscopy and found to be close to the designed values. The final step of the fabrication procedure was a cleavage of the sample resulting in ~150-μm-long waveguide structures.

First, we performed numerical modeling of the fabricated LR-DLSPPW configuration by use of FEM implemented in commercial software COMSOL. The calculations revealed the electric field distribution inside the waveguide, with a dominating field component $E_\perp = E_y$.
[perpendicular to the surface; see Fig. 1(b)] being almost 5 times stronger than the parallel component $E_\parallel = (E_x^2 + E_z^2)^{1/2}$ [note that a factor of 5 was also used when displaying the distributions of both components; see Fig. 1(c)]. The dielectric permittivity of gold was taken from Palik and Ghosh data set [26], and the refractive index of air was set to 1. The calculations confirmed the single-mode operation of the waveguide, and provided the following important mode characteristics: the mode effective index ($N_{\text{eff}} = 1.37$) and propagation length ($L_{\text{prop}} = 2.3 \text{ mm}$) at $\lambda = 1500 \text{ nm}$.

In the next step, we experimentally investigated the SPP mode excitation and propagation in straight waveguides [Fig. 1(d)]. We excited the LR-DLSPPW mode by use of polarization-maintaining tapered-lensed fiber placed in front of the cleaved edge of waveguide and observed from above by an IR-camera with a microscope 20 × -objective. The camera was used also for the far-field observation of the LR-DLSPPW mode excitation and propagation, when the TM-polarized light (electric field perpendicular to the sample surface) from a tunable laser (1425-1625 nm) was sent through the tapered fiber directly to the LR-DLSPPW input edge. The fabricated waveguide was terminated with an out-coupling diffraction grating, so that a bright spot was seen at the end of the waveguide, when the in-coupling fiber was adjusted well [Fig. 1(e)]. Also it was possible to see the track of the propagating LR-DLSPPW mode in the far-field, which was most probably produced by mode scattering on the imperfections of the waveguide, and its maximum intensity along with the maximum intensity of the output spot was used as an indicator of a good alignment of the in-coupling fiber [Fig. 1(e)].

After the far-field adjustments, we moved the whole fiber-sample arrangement under the SNOM head and mapped the intensity distributions near the investigated waveguide structure.
by the uncoated sharp fiber tip used as a SNOM probe. The tip was scanning along the sample surface at a constant distance of a few nanometers maintained by shear-force feedback, and the radiation collected by the fiber was detected with a femtowatt InGaAs photoreceiver. The recorded near-field images showed the mode propagation with the propagation length estimated to be ~400 µm at excitation wavelength of 1500 nm. It was, however, interesting albeit somewhat unexpected to observe that the imaged mode shape strongly depended on the SNOM probe used. For some probes, the detected optical signal reached a maximum in the middle of the topographical image of waveguide [see left insets in Fig. 1(f) and corresponding cross-sections, plotted with hollow circles], whereas, for other probes, two pronounced local maxima were found at the sides of the waveguide [see right insets in Fig. 1(f)]. We relate this behavior to a strong influence of the fiber tip shape on its transfer function [27, 28]. Indeed, an axially symmetrical (and sharp) fiber tip collects only the field components perpendicular to the tip axis ($E_x$ and $E_z$), but, with even a small probe asymmetry being present, the dominant component of the LR-DLSPPW mode field, $E_y$, can be collected as well, producing the main signal contribution for a sufficiently large asymmetry. From the above numerical simulations [Figs. 1(b) and 1(c)] it is clearly seen, that, for the field in the air, where it is collected by the SNOM probe, the parallel component $E_x$ is mostly pronounced in the middle above the waveguide [which corresponds to the left inset in Fig. 1(f)], while the perpendicular component $E_z$ has two maxima at the sides of the waveguide [which corresponds to the right inset in Fig. 1(f)]. Overall, as observed experimentally and conjectured from the simulations, the SNOM images of the LR-DLSPPW mode depend strongly on the shape and symmetry of the fiber tip, and, in general case, do not represent the actual LR-DLSPPW mode distribution. Importantly, the average strength of the SNOM signal can still be used to evaluate the dependence of the LR-DLSPPW mode power along the propagation direction.

2.2 LR-DLSPPW-based sine-shaped S-bends

Our next step was an investigation of LR-DLSPPW-based S-bends, as an important part of DCs and many other waveguide components. We fabricated our S-bends in a half-period sine shape, providing an offset of ~10 µm over a distance of ~20 µm [Fig. 2(a)]. Far-field images showed, along with a track of propagating mode and a bright output spot, relatively bright track along the S-bend, which can be ascribed to the increased scattering losses on the imperfections of rough bend [Fig. 2(b)]. Near-field measurements revealed mode propagation through the S-bend [Figs. 2(c) and 2(d)], with a total transmission decreasing from $-3.5$ to $-4.2$ dB with the increase of wavelength from 1425 nm to 1525 nm.

Fig. 2. (a) Optical microscope top-view image of sample (S-bend) and (b) coupling arrangement superimposed with the far-field image taken at the wavelength $\lambda = 1450$ nm. (c) Pseudocolor topographical and (d) near-field optical images taken at $\lambda = 1450$ nm.

In order to study theoretically our S-bend structures, we used a method of conformal transformation [29]. The idea is to apply a conformal transformation \( \{x,y,z\} \rightarrow \{u,v\} \) such that two new coordinates are defined by the following equation:

\[
(u + iv) = r_{\text{bend}} \ln \left( \frac{x + iz}{r_{\text{bend}}} \right).
\]

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where $r_{\text{end}}$ is bending radius, $i$ is an imaginary unit, and origin is at a center of the bending arc [top-view schematic layout of bend is shown on inset of Fig. 3(a)]. As a result, a bent waveguide (with a constant bending radius $r_{\text{end}}$) is transformed into a straight waveguide with approximately the same cross-section (the coordinates of the sides of the ridge, $r_{\text{end}} \pm w_r / 2$, are transformed into $r_{\text{end}} \ln[(r_{\text{end}} \pm w_r / 2) / r_{\text{end}}]$, but the total width of the waveguide approaches the original value of $w_r$ for relatively large bending radii, $r_{\text{end}} \gg w_r$). Such transformation leads to the following change in Laplacian: $\nabla^2 \rightarrow \nabla^2 - (2u / r_{\text{end}})$, so, for bent 2D-waveguides (waveguides, confined in one dimension – along $u$-axis), this conformal transformation is equivalent to the propagation in straight waveguide (with corresponding transformed cross-section) with refractive indexes of media changing as $n^* = n_e \exp(u / r_{\text{end}})$, where $n_e$ is the original refractive index of corresponding medium. It should be noted that our LR-DLSPPW is 3-dimensional (2-dimensionally confined), so this theory cannot be applied strictly. However, as in the effective index method (EIM), one can replace LR-DLSPPW with equivalent set of layers along $x$-axis, each having its effective refractive index, and then apply conformal transformation for this equivalent 2D-waveguide.

![Fig. 3](image_url)

Fig. 3. (a) Transmission through 90-degrees bend as functions of the bending radius at $\lambda = 1450$ and 1500 nm. The inset shows schematic layout of 90-degrees bend. (b), (c) Distribution of the dominating electric field $E_y$ for bending radius of 20 and 100 µm, respectively, showing strong leaky radiation for smaller bending radius. The size of panels: $9 \times 4.5$ µm².

So we made numerical simulations in such transformed LR-DLSPPW with exponentially changing refractive index of media for different bending radii by using FEM implemented in COMSOL, and calculated total transmission through the 90-degrees-bend [Fig. 3(a)]. The leaking radiation to the substrate due to the bending was clearly seen for small bending radii, and the smaller the radius, the stronger this radiation [see comparison of instant field distributions $E_y$ in Figs. 3(b) and 3(c)]. In order to evaluate the transmission through our original sine-shaped S-bend, one should calculate the radius of curvature as a function of the length along the waveguide and then properly integrate propagation losses over the whole S-bend. Overall, the total transmission through the investigated S-bend was found to be $-4.0$ dB at $\lambda = 1425$ nm and decreases uniformly with the increase of wavelength up to $-4.8$ dB at $\lambda = 1525$ nm, which matches the experimental results within the accuracy of measurements.

### 2.3 LR-DLSPPW-based DCs

Finally, we proceeded to the investigation of directional coupling of LR-DLSPPW modes by use of direction couplers. In our sample coupling occurred between two straight LR-DLSPPWs, separated by center-to-center separation distance $d = 2$ µm over the distance of $\sim 100$ µm [Fig. 4(a)]. Each waveguide had the same cross-section as shown in Fig. 1(a). The mode was excited in one of the waveguides (called here as main and shown with a red arrow), which was completely straight; while the other waveguide (called here as adjacent) had S-bends in order to limit the coupling region. The far-field observations showed, along with the track of propagating modes, the distributed output between main and adjacent waveguides,
with the distribution depending strongly on the wavelength [Figs. 4(b) and 4(c)]. For the used range of wavelengths, 1425 – 1625 nm, we noticed almost complete switch for \( \lambda = 1450 \) nm. Then we proceeded to the near-field investigation of DC, which revealed the intensity variation of modes in each waveguide along the propagation direction [Figs. 4(d) and 4(e)], where the intensity in the main channel was going down while the intensity in adjacent channel was going up. By the proper fitting of near-field data, we estimated the coupling length, which decreased uniformly from \(~115 \, \mu m\) to \(~75 \, \mu m\) with the increase of the wavelength from 1425 nm to 1625 nm.

The directional coupling of LR-DLSPPW modes was then investigated numerically by use of the FEM implemented in COMSOL [Figs. 5(a) and 5(b)]. The first set of simulations was made for the varying center-to-center separation distance \( d \) (from 1.2 to 5 \( \mu m\)) at a fixed excitation wavelength \( \lambda = 1500 \) nm [Fig. 5(c)]. The other set of simulations was made for the varying free-space excitation wavelength \( \lambda \) (from 1400 to 1650 nm) for DC with fixed center-to-center waveguides separation distance \( d = 2 \, \mu m\) [Fig. 5(d)]. The results were plotted in terms of effective mode index (of even and odd modes and compared with the one of a single LR-DLSPPW mode and the refractive index of the substrate) and coupling length (compared with the propagation length of single LR-DLSPPW mode and experimental results).
One can see that, by varying the separation between waveguides, one can vary coupling strength in the wide range, so one can achieve coupling length as low as 20 μm, which is approximately 100 times smaller than the propagation length. This is an important feature for realizing a number of compact passive waveguide components – such as switches, add-drop multiplexers, etc. However, by decreasing the separation distance, the effective mode index of odd mode goes down closer and closer to the refractive index of substrate. That means the increase of the scattering losses on imperfections for this mode, and eventually, for separation distance smaller than 1.2 μm, odd mode starts to leak to the substrate and therefore it is not supported by the waveguide (so only even mode will survive, resulting in equal output in both waveguides). On the other hand, by increasing the separation between waveguides, one can decrease coupling strength to avoid cross-talk (for example, for the separation of 5 μm the coupling length is almost 10 times larger than the propagation length). Hence, the dependence of the coupling strength on the separation distance can be used to set a limit on maximum integration density of LR-DLSPPW-based components.

A dependence of the coupling strength on the excitation wavelength is an important parameter for the wavelength selective components. Calculations shows that the coupling length is ~170 μm at λ = 1400 nm, that is more than twice as long as the coupling length at λ = 1650 nm (which is around 80 μm). However, with the increase of the wavelength the mode effective index of each mode is also going down, so there is a certain cut-off wavelength (approx. at 1740 nm), for which the effective mode index of odd mode reaches the value of the refractive index of the substrate and consequently the mode is no longer coupled to the waveguides. As for the experimental results, a small mismatch with numerical calculations can be explained by a different real geometry of the waveguide (for example, the thickness of metal might be slightly different, and ridge edges might be rounded), as well as by the imperfections of the real waveguide. Overall, a strong dependence on wavelength and separation distance makes LR-DLSPPW very promising for realization of passive and active plasmonic components.
3. Conclusion

Overall, we have studied LR-DLSPPW-based DC and its components: single straight waveguides and sine-shaped S-bends, over the wavelength range 1425-1625 nm. It was shown that the near-field optical images depend strongly on the shape and symmetry of the SNOM probe and do not always reflect the actual LR-DLSPPW mode distribution. The experimental observations were explained by the transfer function of the fiber tip [27, 28] and specific LR-DLSPPW mode electric field distribution. However, the average strength of the SNOM signal can still be used to track the propagation of the LR-DLSPPW mode.

Sine-shaped S-bends (having an offset of ~10 µm over a distance of ~20 µm) have also been investigated experimentally by use of SNOM. Based on experimental data, the total transmission was evaluated to be −3.5 dB at \( \lambda = 1425 \) nm, decreasing gradually with the increase of wavelength up to −4.2 dB at \( \lambda = 1525 \) nm. Bent waveguides were studied further by applying conformal transformation [29], which allows replacing bent waveguide with an equivalent straight waveguide with exponentially changing refractive index of each medium. By use of FEM we calculated numerically bending losses as a function of bending radius and, eventually, a total transmission through our sine-shaped S-bend, which matched experimental results within the accuracy of measured data.

Finally, we studied LR-DLSPPW-based DCs with a center-to-center waveguides separation of 2 µm over the distance of ~100 µm. The far-field observations showed a strong dependence of DC output on the wavelength and almost complete switch at the wavelength of 1450 nm. The near-field experimental measurements showed a strong coupling between waveguides, resulting in coupling length which decreases uniformly from ~115 µm to ~75 µm with the increase of the wavelength from 1425 nm to 1625 nm.

In addition to experimental study, we performed numerical simulations based on FEM implemented in COMSOL. Calculations showed that, for center-to-center waveguides separation \( d = 2 \) µm and for the excitation wavelength varying from 1400 to 1650 nm, the coupling length decreases gradually from ~150 µm to ~80 µm. A small mismatch between numerical and experimental results can be explained by a different real geometry of the waveguides (for example, the thickness of metal might be slightly different, and edges might be rounded), as well as by the imperfections of the real waveguides. On the other hand, simulations of DCs at \( \lambda = 1500 \) nm for varying separation distance from 1.2 µm to 5 µm showed that the coupling strength can be adjusted vastly: the coupling length increases from ~20 µm (at separation of 1.2 µm) to ~20 mm (at separation of 5 µm). Combining these features with a relatively large propagation length (~2 mm) and relatively strong mode confinement, one can conclude that LR-DLSPPWs have a high potential for realization of passive and active plasmonic components.

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