Resonant coupling in dielectric loaded plasmonic waveguides

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Light propagation in dielectric loaded surface plasmon polariton waveguide (DLSPPW) resonant coupling devices operating at visible frequencies was experimentally investigated. The transmission characteristics of these devices were studied by leakage radiation microscopy. We show that a strong coupling between DLSPPWs can be achieved with nanoscale gaps. We demonstrate the operation of compact DLSPPW linear couplers and 3 dB power splitters. The performances of micro-DLSPPW racetrack resonators and signal drop filter are also discussed. © *2010 American Institute of Physics*. [doi:10.1063/1.3525160]

Surface plasmon polaritons (SPPs) are the most effective approach to achieve light confinement and manipulation within the nanoscale.[1,2] Recently, dielectric loaded SPP waveguide (DLSPPW) was proposed as an alternative solution to achieve subwavelength optical confinement.[3] Major advantages of DLSPPWs include simple fabrication procedures, using either optical or electron-beam lithography, and relatively long optical mode propagation lengths when compared to metallic stripe waveguides. DLSPPWs can be potentially used to realize compact resonant coupling SPP devices which are key elements in any optical circuit. This has been addressed to a certain extent in a few recent reports.[4–11] However, further investigation in this research area is a necessary step toward practical realization of compact SPP based photonic integrated circuits.

In this paper, we used leakage radiation microscopy (LRM) to investigate light propagation in DLSPPW straight couplers, 3 dB power splitters, racetrack resonator, and signal drop filters, operating at visible frequencies. LRM is a far-field imaging technique that relies on the leakage of SPP into the substrate. LRM provides raster free images along with Fourier plane imaging capabilities.[12,13] Furthermore, LRM is relatively easy to implement and cost effective, particularly when compared to other sophisticated methods such as near-field scanning optical microscopy. We show that efficient coupling between two adjacent DLSPPWs can be achieved with nanoscale gaps. Using the concept of resonant coupling between closely positioned waveguides, we demonstrate compact 3 dB power splitters and linear couplers. We also demonstrate the filtering performance of a compact DLSPPW resonator and signal drop filter. Our results confirm the potential use of passive resonant coupling SPP components investigated here for optical signal processing applications.

Resonant coupling between adjacent DLSPPWs is achieved by placing the waveguides in close proximity. In order to determine the minimum gap separation between DLSPPWs, which allows resonant coupling, we used two straight waveguides (parallel line couplers), as illustrated in Fig. 1(a). The samples consist of a glass substrate covered

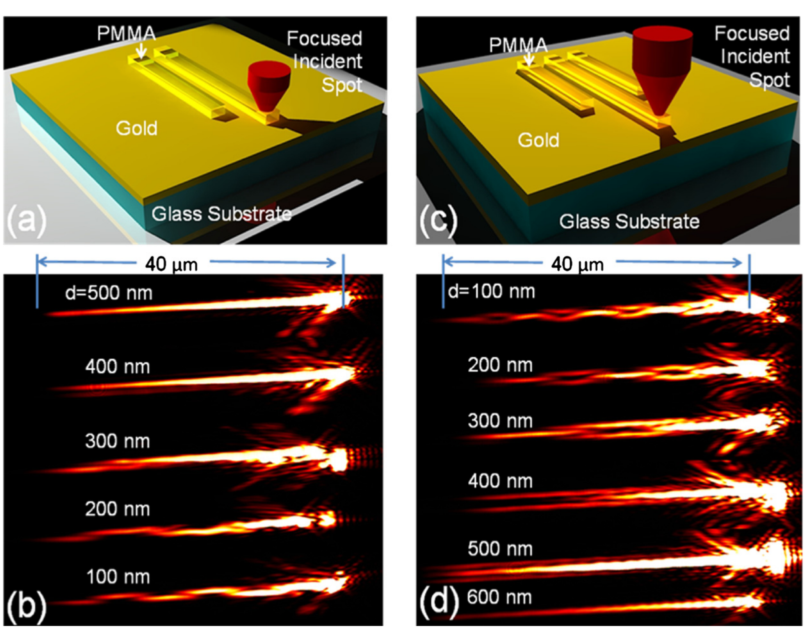

FIG. 1. (Color online) Schematics (not to the scale) of DLSPPWs: (a) line-coupler and (c) 3 dB splitter. LRM images of (b) line couplers, with gap separation ranging from 100 to 500 nm, and (d) 3 dB power splitters, with gap separation ranging from 100 to 600 nm. The width of the DLSPPWs was kept constant, w=450 nm.

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with 50 nm thick gold. The waveguides are defined on a 100 nm thick polymethylmethacrylate layer using electron-beam lithography. In order to ensure high coupling efficiencies, the waveguide widths (w) were fixed at w=550 nm, corresponding to single mode operation for the 632.8 nm wavelength, which was used as the laser excitation source in all experiments described in this work. Several patterns were fabricated with gap spacing (d) between adjacent waveguides ranging from 100 to 500 nm. The length of one of the two waveguides was intentionally designed to be 10 μm longer than the other one in order to ensure that the focused incident beam excites only one of the waveguides. The laser was focused on the top of the longer waveguide using a 40X microscope objective lens, and the SPPs were excited by scattering at the waveguide edge. The propagation of SPP guided modes in these waveguides was imaged by collecting the leaked radiation from the substrate using a 100X immersion objective with a numerical aperture of 1.4. LRM images of light propagation through the line couplers with different gaps are shown in Fig. 1(b). When d=500 nm, no coupling between the adjacent waveguides occurs over 40 μm long propagation of SPPs. As the gap is reduced to d=400 nm, a small fraction of the SPPs is coupled to the adjacent waveguide; however, the coupling efficiency is small since the longer waveguide still carries most of the power. As can be clearly observed in Fig. 1(b), strong mode coupling between the parallel waveguides occurs for d<300 nm. Similar to optical fibers and planar waveguides, the coupling length in DLSPPWs can be estimated as the distance between the maximum light intensity in one waveguide and the intensity maximum in the adjacent one. It is evident from Fig. 1(b) that the efficient light coupling between adjacent parallel DLSPPWs can be achieved with small gaps of reduced coupling lengths. This analysis is essential to realize complex and compact photonic circuits involving resonant coupling between adjacent DLSPPWs.

One of the key functions in integrated photonic circuits concerns power splitting. Equal power splitting between waveguides is important for signal distribution, routing, and monitoring. Conventional fiber and planar optical splitters are typically based on adiabatic Y-junctions or multimode couplers. Although several power splitters are commercially available, the sizes of these devices are of the order of few cm^2. Realization of compact power splitters can be achieved using DLSPPWs and this was discussed in Refs. 4 and 6–8. Here, we propose and implement an alternative 3 dB plasmonic power splitter design based on the resonant coupling involving three parallel straight DLSPPWs. Figure 1(c) shows the schematic of the proposed plasmonic 3 dB power splitter. The structure, fabrication parameters, and characterization procedures are similar to those used in Figs. 1(a) and 1(b). The gap between adjacent waveguides of the 3 dB power splitter was symmetrically varied from 100 to 600 nm. The central waveguide of the 3 dB splitter was intentionally designed to be 10 μm longer than the lateral waveguides and it was used as the excitation input waveguide. Figure 1(d) shows the LRM images of SPP propagation in 3 dB power splitters with different waveguide gaps. Similar to the linear coupler shown in Fig. 1(b) when d≥500 nm, almost no light coupling is observed between adjacent waveguides. When d=400 nm, clear coupling between adjacent waveguides with ~50/50 splitting ratio was observed over the 40 μm length of the fabricated waveguides. Similar to the LRM images obtained for the line couplers shown in Fig. 1(b), further reduction in the gap distance between adjacent waveguides of the 3 dB splitter resulted in shorter coupling lengths. The LRM images shown in Fig. 1(d) reveal splitting power ratios of ~50/50 for all 3 dB DLSPPW based splitters with d≤400 nm. This confirms the effectiveness of the proposed 3 dB splitter and its potential for on-chip scale applications. However, it should be pointed out here that at the telecommunication wavelengths, further size reduction with the possibility of high density of integration can be achieved with silicon-based DLSPPWs.[11]

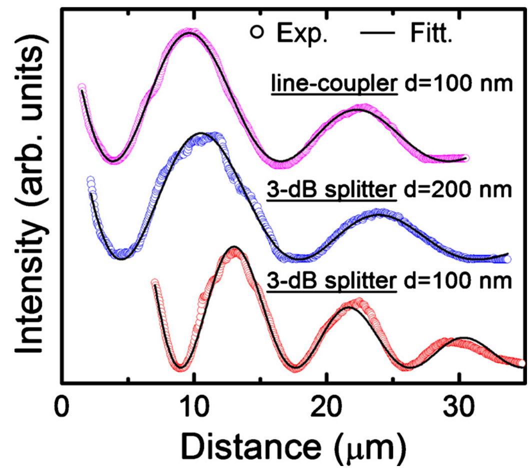

FIG. 2. (Color online) Line profiles and fittings to the data using Eq. (1) of the line-coupler (d=100 nm) and 3 dB splitters (d=100 nm and d=200 nm) shown in Figs. 1(b) and 1(d), respectively.

In order to provide a quantitative analysis of the coupling length (L_c) and propagation length (L_p) of the resonant structures studied here, we performed line profiles in some of the images shown in Figs. 1(b) and 1(d). Figure 2 shows the line profiles of the line-coupler (d=100 nm) and 3 dB power splitters (d=100 nm and d=200 nm). L_c and L_p can be determined by fitting the intensity profile (I) as a function of distance (x) with the expression[8]

$$I(x) = I_o\left\{1 - \cos\left[\frac{\pi(x - x_o)}{L_c}\right]\right\} \cdot \exp\left(-\frac{x}{L_P}\right), \quad (1)$$

where I_o and x_o are constants. The least squares fittings of the three profiles are also shown in Fig. 2 where a good agreement between data and Eq. (1) is evident. From the fittings we determined a propagation length L_p=12.6 μm and coupling lengths of 6.3, 4.5, and 6.4 μm for the line-coupler with d=100 nm and 3 dB couplers with d=100 nm and d=200 nm, respectively. The obtained coupling lengths are comparable to those reported in Ref. 8 for similar DLSPPWs operating at the telecommunication wavelengths.

Another important function in photonic circuits concerns filtering and routing at specific wavelengths. Add/drop filters, multiplexers, and ring resonators are examples of wavelength selective devices with great significance for optical communications. Although a large number of these devices have been demonstrated over the last few years, and some are also commercially available, they still lack compactness. Among the wavelength selective devices, resonators are of particular importance. Compact resonators can be also realized using plasmonic waveguides. Recently, DLSPPW based ring resonators operating at the telecom wavelength have

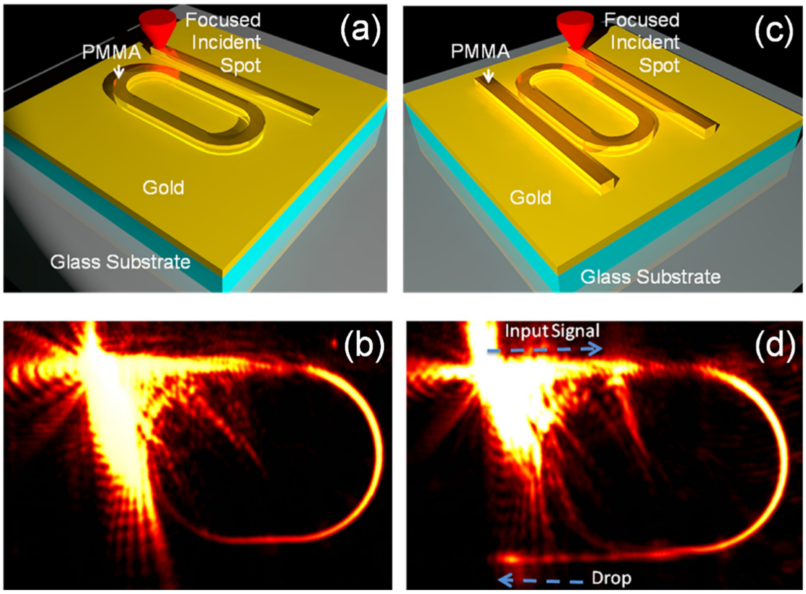

FIG. 3. (Color online) Schematics (not to the scale) of DLSPPWs: (a) racetrack resonator and (c) signal drop filter. LRM images of (b) racetrack resonator and (d) signal drop filter. On both devices, the gap separations between straight waveguides and racetrack resonators were kept fixed at d=100 nm.

been demonstrated.[5] In order to investigate the use of DLSPPW structures in more advanced optical signal processing, drop filters operating at visible frequencies with compact dimensions are discussed. Figures 3(a) and 3(c) show the schematics of a DLSPPW racetrack resonator and a drop filter, respectively. The devices were patterned using parameters and fabrication procedures similar to those used to obtain the linear couplers and 3 dB power splitters shown in Fig. 1. The resonators consist of a straight waveguide for light coupling and a racetrack waveguide. From the results shown in Fig. 1, we determined that a coupling length of ~6–7 μm, corresponding to a gap d~100 nm, is required for complete energy transfer between two DLSPPWs at visible frequency. In order to reduce device footprint, the straight portions of the racetracks were patterned with 7 μm length. A conservative radius of curvature of 10 μm was chosen for the two curved waveguide segments of the racetracks in order to minimize radiation losses. Figure 3(b) shows the LRM image of the DLSPPW racetrack resonator. Light is coupled to the top of the straight waveguide of the resonator by scattering. Clear SPP propagation across the entire device can be observed from this image, indicating strong coupling between the straight waveguides to the racetrack resonator. However, it is evident from Fig. 3(b) the inherent propagation attenuation effects as light traverses the device. Figure 3(d) shows the LRM image of the drop filter. Similar to the racetrack resonator, light is coupled to the top straight waveguide by scattering. In this case, most of the signal is dropped to the bottom straight waveguide, hence confirming the drop filter capabilities of the fabricated device. As shown in Fig. 3, propagation attenuation is a limiting factor for practical utilization of these devices in optical systems. A prospective solution to overcome this issue is to incorporate an active gain medium into the waveguides.[14,15]

In summary, we have investigated experimentally the propagation of SPPs in DLSPPW based line couplers, 3 dB power splitters, racetrack resonator, and signal drop filters at the visible frequency using leakage radiation microscopy. We showed that efficient coupling between two straight DLSPPWs can be achieved by closely positioning them within nanoscale gaps. Similar to fiber and planar optical waveguides, the coupling length in DLSPPWs scales with the gap increase between the two waveguides. Using the concept of resonant coupling between closely positioned waveguides, we demonstrated compact DLSPPW 3 dB splitters. We also verified the operation of a DLSPPW racetrack and signal drop filter. Our results revealed the great potential of compact resonant DLSPPW passive components for realistic photonic signal processing applications.

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