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Experimental cross-polarization detection of coupling far-field light to highly confined plasmonic gap modes via nanoantennas


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We experimentally demonstrate the coupling of far-field light to highly confined plasmonic gap modes via connected nanoantennas. The excitation of plasmonic gap modes is shown to depend on the polarization, position, and wavelength of the incident beam. Far-field measurements performed in crossed polarization allow for the detection of extremely weak signals re-emitted from gap waveguides and can increase the signal-to-noise ratio dramatically. © 2011 American Institute of Physics. [doi:10.1063/1.3564904]

Surface plasmon polaritons (SPPs) are highly confined electromagnetic waves on metal–dielectric interfaces which couple to collective oscillations of the electron gas. Various plasmonic waveguide modes arise from the coupling of SPPs at the interfaces of metals and dielectrics.1–6 Bozhevolnyi et al.7 reported a channel waveguide mode with a width of 1.1 μm and a propagation length of 100 μm. However, most of the experimentally realized plasmonic modes1–3 have confinements in the micrometer range and do not reach deeply subwavelength dimensions. Thus they do not have obvious advantages compared to conventional dielectric waveguides. In contrast, a true deeply subwavelength gap structure involving nanodots and slits were reported by Imre et al.8 Recently, two-dimensional, highly confined stripe wave guide modes, generators like arc-shaped nanodots and slits were reported by Nomura et al.9 and Han et al.6 They showed the integration of slot waveguides with silicon dielectric waveguides via tapered couplers. However, the aforementioned excitation schemes often lack the compactness that is required for integration into subwavelength, plasmonic circuitry. Nanoantennas are highly compact and were proposed as a kind of nanocoupler to couple far-field light to two-dimensional, highly confined gap modes.8,9 Recently, the idea of optical wireless interconnects via nanoantennas was theoretically proposed by Alù and Engheta.10 Thus the nanoantennas with plasmonic waveguides is the first step toward optical wireless communication analogous to the ubiquitous loading of radio antennas with coaxial cables in the regime of radio frequency. In this paper, we experimentally demonstrate the excitation of a gap mode enhanced by a nanoantenna and investigate its spatial and spectral dependence on the antenna by cross-polarization detection (see Fig. 1). We prove that optical antennas can potentially be used for selective excitation of highly confined, plasmonic waveguide modes in further integrated plasmonic chips.

For the experiments a 100-nm-thick silver layer with a surface roughness of around 1 nm was deposited on a glass substrate using a magnetron sputtering machine. A chromium layer with a thickness of 1–2 nm was used as a wetting layer to improve the quality of the silver layer. Afterwards 80–100-nm-wide grooves were structured into the silver layer using a focused ion beam (FIB) milling system. A scanning electron microscope (SEM) image of a cross section of the waveguide and the corresponding numerically calculated mode profile (via finite-element method, FEM) of the electric field are given in Fig. 2(a). Figure 2(b) shows an SEM image of the measured structure containing a bent-gap waveguide with a receiving antenna. Figure 2(c) shows the same structure but includes an additional transmitting antenna at the other end of the bent waveguide. The gap width is 80 nm. The optimized total length of the antenna is designed for a resonance at around $\lambda = 1.5 \text{ μm}$. The configuration of the experimental setup is shown in Fig. 1. For excitation, a linearly polarized Gaussian beam (polarization parallel to the antenna) was focused onto the

![FIG. 1. (Color online) The configuration of the experimental setup and the schematic view of the measurement.](Image)
substrate surface. Due to strong back reflection of the incident beam, it is hard to investigate the field in the waveguide unless its direction of polarization is turned so that it becomes visible in the cross-polarized direction. Since the polarization of gap modes is always perpendicular to the tangent of the waveguide, the polarization of the electric fields at the waveguide end can be turned by 90° via a waveguide bend with micrometer-sized radii. The emission intensity at the nonresonant wavelength (1 μm) is lower [yellow color in Fig. 3(a)] than the value at the resonant wavelength [red color in Fig. 3(c)]. In the same situation, the reflection does not vary much [see Figs. 3(b) and 3(d)]. This already hints that light is coupled into the waveguide for resonant excitation. We also measured the transmission and reflection spectra of the antenna for incident wavelengths ranging from 1 to 1.7 μm (see Fig. 4). The transmission drops by about 10% close to λ = 1.5 μm but the reflection stays almost constant for all measured wavelengths. A quite intuitive explanation suggests that, at resonance, energy is coupled to the waveguide mode and results in a reduced transmission but leaves the reflection almost unaffected. For comparison, we simulated the coupling efficiency using the COMSOL MULTIPHYSICS commercial FEM and at a nonresonant wavelength of 1 μm in (c) and (d). For each scan, the incident polarization was parallel to the antenna. No polarizer was situated in front of the detecting photo diode. Each scanning pixel value corresponds to the normalized transmission and reflection measured for a certain position of the focused beam relative to the sample. The sample was scanned through the beam using a defined step size. Transmission and reflection intensities were measured for every position. All presented scans were normalized to the same level. The transmission for resonant excitation of the antenna is lower [yellow color in Fig. 3(a)] than the value at the nonresonant wavelength [red color in Fig. 3(c)]. In the same situation, the reflection does not vary much [see Figs. 3(b) and 3(d)]. This already hints that light is coupled into the waveguide for resonant excitation. We also measured the transmission and reflection spectra of the antenna for incident wavelengths ranging from 1 to 1.7 μm (see Fig. 4). The transmission drops by about 10% close to λ = 1.5 μm but the reflection stays almost constant for all measured wavelengths. A quite intuitive explanation suggests that, at resonance, energy is coupled to the waveguide mode and results in a reduced transmission but leaves the reflection almost unaffected. For comparison, we simulated the coupling efficiency using the COMSOL MULTIPHYSICS commercial FEM and at a nonresonant wavelength of 1 μm in (c) and (d). 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FIG. 3. (Color online) Scanning measurements in transmission (a) and reflection (b) at resonant wavelength of 1.5 μm. Scanning measurements in transmission (c) and reflection (d) at nonresonant wavelength of 1 μm. (e) SEM image of the corresponding scanning area including the antenna and part of the straight waveguide. Polarization of the incident beam (white arrow) is parallel to the antenna axis. All scans are acquired without a detector polarizer.
In summary, the excitation and detection of plasmonic gap modes has been demonstrated. By using a crossed-polarizer detection scheme that requires bent waveguides, the SNR was dramatically improved. The excitation of gap modes was shown to be sensitive to the wavelength and position of the excitation beam. The measured sum of the coupling efficiency and antenna absorption reached up to 20% compared to the simulated optimum coupling efficiency of 15%.

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FIG. 5. (Color online) Power emitted from the end of the waveguide vs total waveguide length, which is fit exponentially (solid line). Inset: SEM image of one measured sample. The radius of the bent part (R) is 3 μm. The length of the straight part (L) varies from 1 to 4 μm.