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# Phase Engineering of Subwavelength Unidirectional Plasmon Launchers

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Plasmonics is an eminent candidate to meet the requirements for taking the next step in increased communication bandwidths in conventional data processing by using carrier frequencies of several hundreds of terahertz.[1] In contrast to photonic modes, binding to plasmonic waveguides confines the light to deep subwavelength regions and allows for small circuit elements and high integration density.[2] Absorption losses are a challenging drawback, which limit plasmonic devices—compared to dielectric components—to relatively short distance applications like on-chip communication or novel quantum plasmonic effects.[3–6] Recently, advances have also been made with waveguides based on structured plasmonic elements.[7,8] Such elements are usually difficult to excite directly by photonic fields due to mismatched wavevectors of photons and plasmons. In the language of electrical engineering, plasmonic and photonic modes suffer from considerable impedance mismatch.[9–14] Efficient matching may be achieved by optimizing the complete structure geometry with a specific figure of merit, employing full-field simulations.[15–18] Alternatively, the illumination of a given structure can be optimized by coherent control methods in time and space.[19–22] Here we employ an approach that introduces intermediate coupling points, borrowing from all of the above concepts. These coupling points are point-like resonators that excite the target structure via near-field coupling. The coupling points act as antennas, converting far-field photonic modes into plasmonic modes.[23–26] Multiple couplers, which may be designed and placed individually, thus allow for flexible construction rules and the excitation of nearly any desired eigenmode (**Scheme 1**).

Phase matching is the primary guiding principle for placing an individual coupling point. The response phase lag of the coupler has to compensate the difference between the phase of the incident light field and the phase of the desired mode. The optimal coupler position is found where the phases match

$$\varphi_{\mathrm{inc}} + \Delta\varphi_{\mathrm{c}} = \varphi_{\mathrm{s}} \tag{1}$$

In general, the response of any resonant particle needs to be adjusted by tuning suitable structure parameters. For a linear wire antenna, for instance, this can be its length or width. Both the plasmonic excitation amplitude and phase of the coupler can be optimized by these two parameters, as illustrated for thin antennas (**Figure 1**).

By combining several coupling points, generally a configuration can be found where all couplers constructively excite the desired mode and suppress undesired ones. This is achieved by varying the coupling strength via changing the gap size, the coupler position, or the intrinsic phase delay of the coupler. A practical limitation to the total number of couplers is imposed by geometric consideration of the limited surface area. Also, too closely spaced couplers are generally detrimental as this leads to hybridization of their resonances, affecting the matching rule Equation (1). However, as we show below, hybridized aggregated subunits may be employed beneficially as a different kind of compound coupling point.

For our experiments, we use gold structures patterned by electron beam lithography on a silicon dioxide substrate. The measurements are carried out using an apertureless scanning nearfield optical microscope (aSNOM) in cross-polarization mode, measuring the z-component of the sample nearfield nearly without any perturbation by the probe.[27–30]

The proof-of-concept structures we fabricate fulfill one of the basic functions for passive plasmonic elements. They are designed as efficient couplers of s-polarized light to a plasmonic waveguide. We focus on directional couplers that can selectively excite modes traveling from the coupler in the direction of a device. Directional coupling has previously been achieved, for example, in end-fire configuration by illuminating the end of a waveguide or by using the direction-selective properties of asymmetric grating coupler configurations.[31,32] The spatially dispersive behavior also implies the advantage of such devices to be used as multiplexers. Whereas efficient gratings are typically several wavelengths long, here we demonstrate that subwavelength couplers can be achieved with the concept of coupling points constructed from plasmonic antennas.

We consider long, thin gold wires as plasmonic waveguides (**Scheme 2**). In order to facilitate excitation of waveguided modes by plane wave excitation, we place dipolar wire antennas as couplers next to the waveguide. Upon successful launching, plasmons travel in the waveguide in both directions away from

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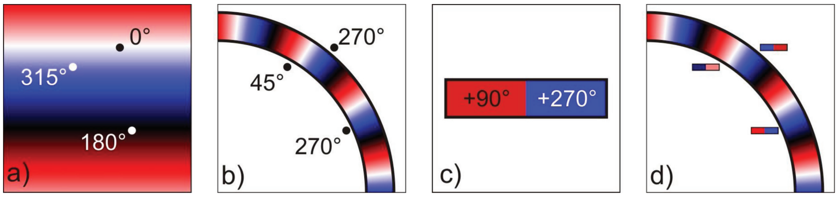



**Scheme 1.** The phase engineering principle. (a) Phase pattern of an incident mode, e.g. a plane wave. Three points are marked as guide to the eye with the local phase of the incident field indicated. (b) Phase of the desired mode on a structure. (c) Individual coupling points, here a resonant dipolar antenna, have a characteristic, tunable resonance phase delay compared to the incident field. (d) Couplers are placed where the intrinsic delay matches the difference of incident and desired mode.

the coupling points. Similar to an optical grating, placement of several coupling points can result in directional plasmon launching.[33] The structures presented here are one of the smallest realizations of a grating coupler.

Three different realizations of waveguide couplers constructed with the coupling point principle are displayed in **Figure 2**. While the waveguide is only weakly excitable without couplers (see Figure 2a), the coupling points in Figure 2b–d clearly launch plasmons on the waveguide with reasonable directionality. With all coupling points on the same side of the waveguide, the grating can be tuned to match plasmons travelling in the forward (Figure 2c) or backward (Figure 2d) direction relative to the incident light (see also supporting information). Placing coupling points on either side of the waveguide affords an additional 180° phase shift, reducing coupler size in the horizontal direction (compare Figure 2b and d). A comparison of the structure performance with finite difference time domain (FDTD) simulations shows good agreement with experiment and verifies the design approach.

To increase unidirectionality, more grating elements could be used. However, in addition to the larger footprint, losses limit the achieveable forward/backward ratio. Rather, we use the intrinsically tunable phase delay of near-resonant couplers to form asymmetric coupling points for directional excitation of the waveguide. A structure with compound couplers, consisting of two antennas of different length, is shown in **Figure 3**. Each compound is reminiscent of Yagi-Uda type antennas.[34–37] To find the best performing structure, we employ a combinatorial approach, studying many individual devices, with systematically varyied distances and lengths. We find that the optimal structure has similar dimensions as that of Figure 2b. However, the single resonant antenna elements are replaced by composite antennas. These are formed by adding longer, off-resonant elements to the backward side. Both experiment and simulation indicate, however, a phase lag of only 20° in the response of these two antenna elements. Evidently, the antenna elements interact with each other strongly and a hybridized mode is excited by the incident radiation. The resulting hybrid antenna thus performs differently from Yagi-Uda type antennas; it can be seen as one composite coupling point, which has a larger surface area than a single wire element exposed to the wire waveguide, and a correspondingly increased coupling strength. This structure allows for more efficient coupling, keeping the footprint on the order of the scale of single antenna coupling points (see **Table 1**).

Hybridization between sub-elements opens new opportunities for flexible construction of composite couplers: For example, Fano resonances can lead to spectrally very sharp in- and outcoupling of certain frequencies, internal phase optimization of a coupler can lead to improved directionality, or as in our case, the active surface area of the coupler is enhanced.

In summary, we have shown a general approach for elastic plasmon excitation processes. Antennas act as coupling points converting photonic modes to localized or propagating plasmonic modes. Selective excitation of a desired mode is achieved by tuning structure, position, and phase retardation

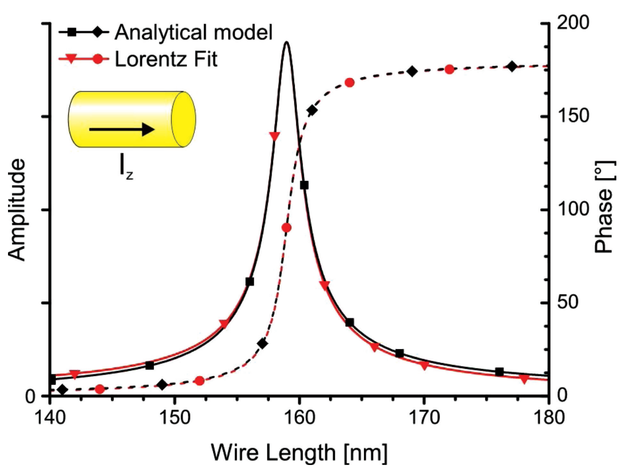
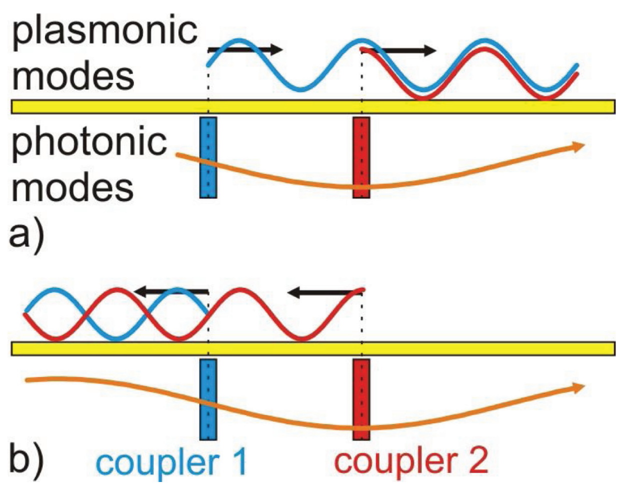



**Figure 1.** Current in a thin gold wire antenna under plane wave illumination. Amplitude (solid line) and phase (dotted) are shown using an analytic model. The antenna excitation is well approximated by a Lorentz curve (red).




**Scheme 2.** Unidirectional couplers. Dipolar antennas act as couplers of photonic far-field modes (orange) to a waveguide (yellow). Each coupler launches plasmons on the waveguide traveling in both forward (a) and backward direction (b). Interference between the plasmons launched by both antennas introduces directionality.

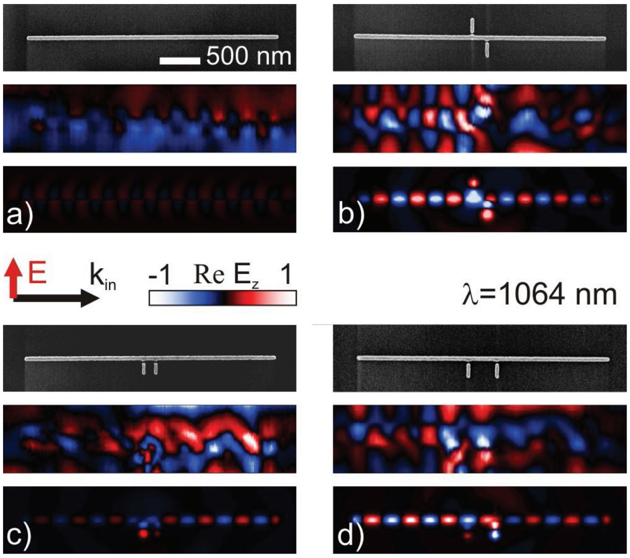



**Figure 2.** Nearfield optical images of unidirectional plasmon launchers. The top image of each subfigure shows a scanning electron micrograph of the gold structures on silicon dioxide. The center image shows the measured electric near-field, compared to FDTD calculations at the bottom. Simulations are normalized with a common scale.

of the couplers. As a demonstration of the concept, we show launchers of unidirectional waveguided modes. The approach allows for extremely compact assemblies, where the footprint of the coupler assembly is less than 1/10 of a square wavelength. As an outlook, we draw attention to the recent demonstration of self-assembled growth of plasmonic logic gates.[38] The concepts presented in this report are well suited for performing improved addressing and read-out tasks with such circuitry. In

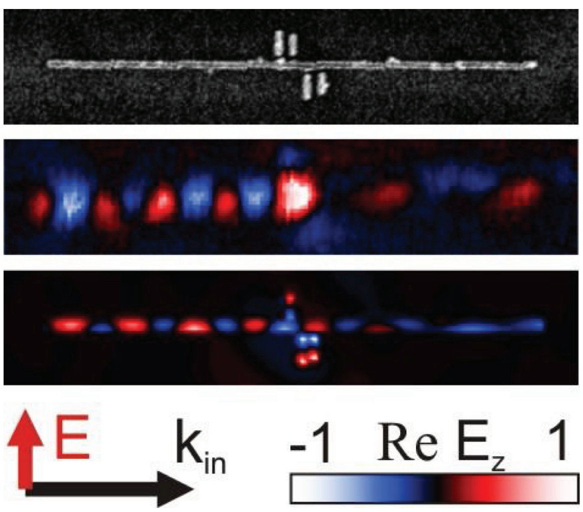



**Figure 3.** Unidirectional plasmon launcher with composite couplers. The upper panel shows a SEM micrograph. The middle panel shows a near-field optical image, compared to a FDTD simulation on the lower panel. Color scales are normalized individually. No background subtraction has been applied to the measurement data.

**Table 1.** Relative coupling efficiencies of the structures presented, calculated by FDTD simulation. Compared to the case without antennas (see Figure 2a), all couplers increase the total energy transferred from the farfield to the waveguide.

| Structure | Figure 2a | Figure 2b | Figure 2c | Figure 2d | Figure 3 |
|---|---|---|---|---|---|
| Relative waveguided energy | 1 | 7.4 | 4.2 | 7.8 | 12.1 |

combination with active elements, such as high speed modulators, they might also prove useful in amplifier plasmonics.[39]

## Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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