Polarization-Selective Coupling to Long-Range Surface Plasmon Polariton Waveguides

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Supporting Information

ABSTRACT: We demonstrate polarization-selective coupling from an optical fiber to long-range surface plasmon polariton waveguide modes using plasmonic antenna arrays. The arrays allow the sorting of two distinct (not necessarily orthogonal) polarizations to counter-propagating waveguide modes. The polarization-selective behavior of the devices is described by a compact graphical representation based on Stokes vectors that offers a clear illustration of the response. We experimentally observe polarization-controlled switching and unidirectional coupling with extinction ratios greater than 30 dB and coupling efficiencies comparable to those of a conventional grating coupler.

KEYWORDS: Long-range surface plasmon polaritons, plasmonic antenna arrays, metasurfaces, couplers, beam splitters, polarization-selective devices

Grating couplers are a prevalent design choice for coupling light to optical waveguides, yet they offer limited control over both the direction of propagation of the coupled optical power in the waveguide as well as over the polarization state that is coupled. Recently, novel coupling schemes were used to couple light to bound electromagnetic waves at a metal–dielectric interface called surface plasmon polaritons (SPPs), which were launched unidirectionally in different directions depending on the circular polarization state of the incident light.1,2 These couplers, which we may refer to as “meta-gratings,” rely on arrays of polarization-selective aperture antennas milled into the metal film, which are spaced and rotated to obtain polarization-sorting properties. As a particular case of a meta-grating, the “Fishbone” (FB) coupler demonstrated by our group1 has the additional advantage of principle allowing the coupling of any polarization state on the Poincaré Sphere with equal overall efficiency, thus removing the limitation on the coupled polarization states commonly encountered with previous plasmonic couplers. We demonstrate here for the first time a realization of a Fishbone coupler in a waveguide system and describe deviations in the polarization response that occur with the respect to the “ideal” case that is described in ref 1. The fishbone coupler is furthermore implemented with metal rod antennas rather than apertures in a metal film, which is a configuration that is more readily adaptable to a wide variety of waveguide systems such as dielectric waveguides. To succinctly describe the polarization-sorting properties of the array we introduce a simple formalism based on Stokes vectors that allows for a geometrical representation of the effective response of polarization-selective optical elements. This intuitive picture is useful in the presence of distortions to the response that arise due to defects and reflections when a polarization-selective coupler is integrated in a real-world optical circuit.

As a model system, we employ long-range surface plasmon polariton (LRSP) waveguides, which consist of nanometer-thin metal strips embedded in a homogeneous dielectric environment. The guided mode of such waveguides corresponds to the symmetric hybrid mode that arises from the coupling of the SPP modes at the top and bottom surfaces of the metal film as the film thickness is decreased, and is always transverse-magnetic (TM) polarized. In contrast to conventional surface plasmon polaritons, LRSPs can achieve centimeter-scale propagation lengths and enable near-perfect mode-matching to optical fibers, as well as simultaneous guiding of electrical and optical signals. Their simple geometry enables straightforward and highly reproducible fabrication using standard methods, which in combination with the possibility of thermo-optic fine-tuning, absence of polarization noise and lower pump noise renders LRSPs an excellent platform for specialized applications in high-precision optics.

Our waveguides consist of 10 μm wide Au stripes with a thickness of 15 nm that are embedded in benzocyclobutene (BCB) polymer (Figure 1a), which has a refractive index of n_{BCB} = 1.535 at 1550 nm. This geometry supports a single TM-polarized mode at C and L band frequencies (λ_0 = 1530 to 1625 nm), covering the “erbium window” commonly used in optical communications. Waveguides were patterned with UV-
The previously demonstrated Fishbone coupler\(^1\) was characterized using direct imaging of the launched SPPs using near-field scanning optical microscopy, which did not yield quantitative information about the intensity of the launched SPPs. In the present case, we wish to describe the device response in terms of the optical power routed to the left and the right propagating SPP channel as a function of the incident polarization. To do so, we consider that the action of any polarization selective device may be described in terms of projective measurements of a vector describing the polarization of the incident light, such as a Stokes vector, which offers the advantage of a description of light in terms of directly measurable quantities.\(^8\) The Stokes vector describing a fully polarized beam is given by \(\vec{S} = I_0[1,\hat{s}]^T\), where superscript \(\dagger\) denotes the matrix transpose, \(I_0\) is the intensity of the beam, and \(\hat{s} = [S_0/S_0/S_0/S_0]^T\) is a three-dimensional unit vector describing the state of polarization (SOP), where \(S_0\) are the four Stokes parameters of the incident light.\(^8\) The SOP of light corresponds to the coherent superposition of two orthogonal polarization states, so that the possible values of \(\hat{s}\) can be conveniently graphically represented as points on the surface of a sphere. This type of geometric representation of a two-level system is known as Bloch sphere in solid state physics and as the Poincaré sphere in optics.

The response of any real device will be subject to deviations from the ideal case, for example due to fabrication defects and internal reflections. To account for this, we separately consider the response of the left and right waveguide outputs as independent channels. They each couple to some polarization that is described by Stokes vectors ("device vectors") \(D_R = c_R[1,d_R]\) and \(D_L = c_L[1,d_L]\), where \(c_{RL}\) in this case are coupling efficiencies and \(d_{RL}\) describe the coupled SOP on the Poincaré Sphere.\(^7\) The left and right output intensities \(I_L\) and \(I_R\) are then given by the respective projections of the Stokes vector describing the incident light \(\hat{s}\) along the device vectors, that is, \(I_R = S D_R\) and \(I_L = S D_L\).

The device vectors \(D_L\) and \(D_R\) can be measured by adjusting the incident SOP \(\vec{I}\) to three different polarizations \(\hat{m}_i\) (for example left circularly, horizontally linearly, and diagonally linearly polarized) while recording the output power. For each polarization \(m_i\), the output intensity \(I_{R/L}^i\) on the right or the left channel is given by

\[
I_{R/L}^i = I_0 c_{RL} [1 + \hat{m}_i \hat{d}_{RL}] \tag{1}
\]

This enables us to write a linear system for the SOP of the device vectors \(\hat{d}_{RL}\)

\[
\vec{I} = I_0 [\vec{I} + M \hat{d}] \tag{2}
\]

where \(\vec{I} = [I_1 I_2 I_3]^T\), \(\vec{I} = [1,1,1]^T\) and

\[
M = \begin{bmatrix}
\cdots & m_1 & \cdots \\
\cdots & m_2 & \cdots \\
\cdots & m_3 & \cdots
\end{bmatrix} \tag{3}
\]

is a matrix containing the three incident polarizations \(m_i\) used in the measurement as rows. The subscripts indicating the left- or right channels \(R/L\) were omitted for clarity. The SOP of the device vectors \(\hat{d}\) is found by solving

\[
\hat{d} = M^{-1} \left( \frac{\vec{I}}{I_0} - I_0 \hat{d} \right) \tag{4}
\]
where superscript $^{-1}$ denotes the matrix inverse. The maximum coupling efficiency that is obtained when the input polarization is directly aligned with the device vectors, $c$, can be found by recognizing that $\hat{d} \cdot \hat{d} = 1$ and choosing the positive root of the resulting quadratic equation, that is

$$c = \frac{1}{I_0} \left[ -\beta + \sqrt{\beta^2 - 4\alpha\gamma} \right]$$

where $\alpha = (M^{-1}\hat{T})^T M^{-1}\hat{T}$, $\beta = (M^{-1}\hat{T})^T M^{-1}\hat{T} + (M^{-1}\hat{T})^T - 1$. It is worth emphasizing that the device vectors capture the effective source-to-detector coupling efficiency and polarization response of the entire system, which are the relevant quantities for an actual integration of the device. As such, they are subject not only to the response of the coupler by itself, but also to the alignment of the optical fibers at the input and output of the devices, fiber losses, reflections, and other factors. This is in particular true for the effective coupling efficiency $c$, which is extremely sensitive to alignment.

Figure 2a shows the device vectors of the left and right output channels of a Fishbone coupler and a conventional grating coupler designed for operation around 1550 nm determined using this approach. The device vectors of the structure exhibit only weak wavelength dependence over the entire C and L bands, consistent with simulations indicating a large bandwidth for conventional LRSPP grating couplers based on metal films with a modulated thickness. Figure 2b displays the normalized left and right outputs of the devices as the input polarization was traced along a great circle around the Poincaré Sphere corresponding to the intersection of the sphere with the $S_1S_3$-plane (Figure 2b inset). As expected, the output undergoes a sinusoidal variation corresponding to the projection of the input Stokes vector $S$ on the device vectors. Notably, channels can be switched off by choosing the input polarization to be orthogonal to the corresponding device vector while the output on the opposite channel remains finite. This allows signals to be unidirectionally coupled to only one of the output channels with the unidirectionally coupled polarization states $\tilde{u}_{RL}$ satisfying $\tilde{u}_{RL} ; \tilde{d}_L = -1$ and $\tilde{u}_{RL} ; \tilde{d}_R = -1$. Any other incident polarization state results in a division of the total coupled intensity between the left and right output channel according to $I_R = S \cdot D_R$ and $I_L = S \cdot D_L$. We observed unidirectional coupling with extinction ratios of at least 30 dB, limited by the noise threshold of our measurement (Figure 3).

Consistent with the weak wavelength-dependence of the device vectors, we did not observe any significant shifts in the wavelength-dependent coupling efficiency for antenna arrays that had row spacings designed for operation at wavelengths between 1550 and 1610 nm. This indicates that the response of the gratings themselves is relatively flat and grating effects do
not play a dominant role over the measured wavelength range. The measured wavelength response is however significantly modulated in a manner consistent with interference in the BCB layer that is caused by internal reflections at the Au–BCB and BCB–Si interfaces, which results in a rapid fluctuation of the coupling efficiency as a function of wavelength (see the Supporting Information). The details of the wavelength response over a wider range of wavelengths will be reported elsewhere. The maximum efficiency of our polarization-selective couplers was observed to be close to that of a conventional grating coupler on the same type of waveguide, using ridges with the same width (80 nm) and height (15 nm) as for the individual rod antennas and the same grating period. This is indicates that the Fishbone couplers should in principle be able to perform with similar efficiency as grating couplers, which have been extensively studied in the literature. While the very shallow antennas were designed to provide weak coupling (<1%) to the plasmonic mode, we expect that the efficiency of the Fishbone couplers can be significantly optimized in particular the resonant properties of individual antennas.

In conclusion, we have demonstrated polarization-selective coupling to LRSPPP waveguide modes by implementing a recently developed coupling scheme for the first time in an integrated waveguide system. The system is capable of polarization-sorting to two counter-propagating output channels, enabling in particular polarization-controlled unidirectional coupling. The effective polarization response of the device can be accurately described and graphically represented with vectors analogous to Stokes vectors describing the state of a light beam. The enhanced control over the coupling to waveguide systems may pave the way towards a new class of optical switches and polarization splitters for integrated optical networks, as well as for novel experiments in quantum optics.

**REFERENCES**