Ultra-Compact Power Splitter Based on Coupled Surface Plasmons

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***Abstract*— A novel power splitter based on coupled surface plasmons (SPs) is proposed for optical frequency applications. This power divider is an ultra-compact forward or co-directional coupling device. A specific SiO_2-Ag-SiO_2 685-THz design is demonstrated by full-wave analysis, where a coupling length of only 36 nm and an overall dimension of around 500 nm is achieved. The underlying principle of coupled SPs may lead to various novel nanoscale optical devices.**

***Index Terms*— Surface plasmons, power splitter, co-directional coupler, nanoscale optical device, integrated optics.**

I. INTRODUCTION

Recently, there has been a strong regain of interest in surface plasmons (SPs) [1], [2] due to the fact that their spectacular wavelength compression capability represents unprecedented opportunities for novel nanoscale optical applications [3], [4]. In general, SPs are electron plasma density oscillations bound as a surface wave to metal/dielectric interfaces and they can couple their energy to provide miniaturized devices.

We propose here a novel ultra-compact tapered power splitter for optical frequencies based on SP coupling between the two metal-dielectric interfaces of a metal slab embedded in a dielectric material. This splitter is in fact a 3-dB quadrature forward-wave coupler. It exhibits a simpler configuration than the architecture of the contra-directional coupler proposed in [5], which requires 5 interfaces as opposed to just 2, as depicted in Fig. 1.

The proof-of-concept demonstration is provided by full-wave simulations, including both eigen-mode and driven-mode, lossless and lossy analysis.

II. MODELING OF PLASMONIC METALS IN FREQUENCY- AND TIME-DOMAIN SIMULATIONS

It is well known that noble metals, such as silver (Ag), exhibit negative permittivity below their plasma frequencies ω_p at optical frequencies, where they behave as dielectrics following the dispersive Drude-Sommerfeld permittivity function

$$\varepsilon_\mathrm{Drude}(\omega) = \varepsilon_0 \left\{ 1 - \frac{\omega_\mathrm{p}^2}{\omega\,(\omega - \mathrm{j}\Omega_\mathrm{se})} \right\}. \qquad (1)$$

This is the expression which was used for instance for Ag in [5] with the parameters $\omega_\mathrm{p} = 12.9 \times 10^{15}\mathrm{rad/s}, \Omega_\mathrm{se} = 8.0 \times 10^{13}\mathrm{rad/s}$. Here, the model of Eq. (1) is extended to the dispersive form

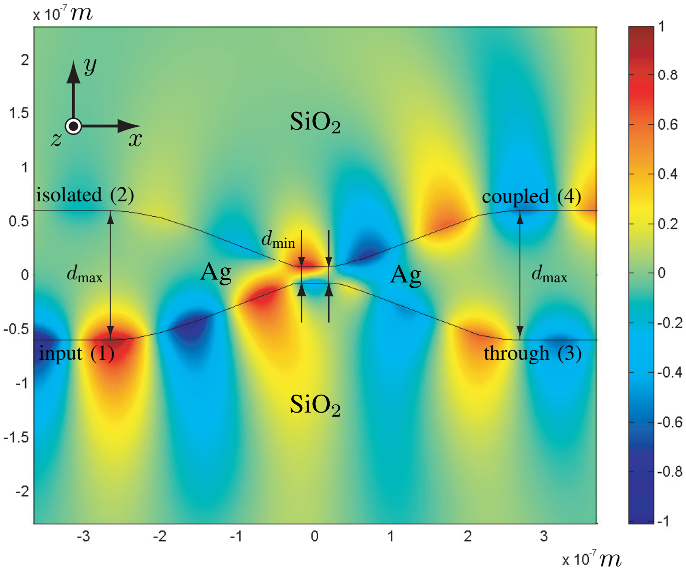

Fig. 1. Intensity plot of the driven-mode TE_z magnetic field $H_z(x, y; f = 685\ \mathrm{THz})$ in the proposed surface plasmonic power splitter, which consists of a tapered metal (Ag) film embedded in a dielectric (SiO_2) material, with the coupling region in the center and the input/output regions on either sides. The field distribution shown indicates 3-dB/quadrature splitting of the incoming guided SP. The dimensions are $d_\mathrm{min} = 15$ nm, $d_\mathrm{max} = 120$ nm, $\ell_\mathrm{narrow} = 36$ nm and $\ell_\mathrm{taper} = 250$ nm.

$$\varepsilon_\text{ext-Drude}(\omega) = \varepsilon_0\varepsilon_{\mathrm{r},\infty} \left\{ 1 - \frac{\omega_\mathrm{p}^2}{\omega\,(\omega - \mathrm{j}\Omega_\mathrm{se})} \right\} - \mathrm{j}\frac{\sigma_\mathrm{sh}}{\omega}, \qquad (2)$$

which includes the two additional parameters $\varepsilon_{\mathrm{r},\infty}$ (asymptotic term) and σ_sh (conductive term) to better fit experimental data in the frequency range of interest [6]. The complex permittivity $\varepsilon_\mathrm{r} = \varepsilon_\mathrm{r}' - \mathrm{j}\varepsilon_\mathrm{r}''$ obtained from this model for Ag with $\varepsilon_{\mathrm{r},\infty} = 3.9, \omega_\mathrm{p} = 7.0 \times 10^{15}\mathrm{rad/s}, \Omega_\mathrm{se} = 2.3 \times 10^{13}\mathrm{rad/s}$ and $\sigma_\mathrm{sh} = 9.0 \times 10^{14}\mathrm{S/m}$, yielding the best fit to the measured values of [6] in the frequency range of 450 THz to 850 THz, is shown in Fig. 2.

One benefit of the Drude-type models of constitutive para-

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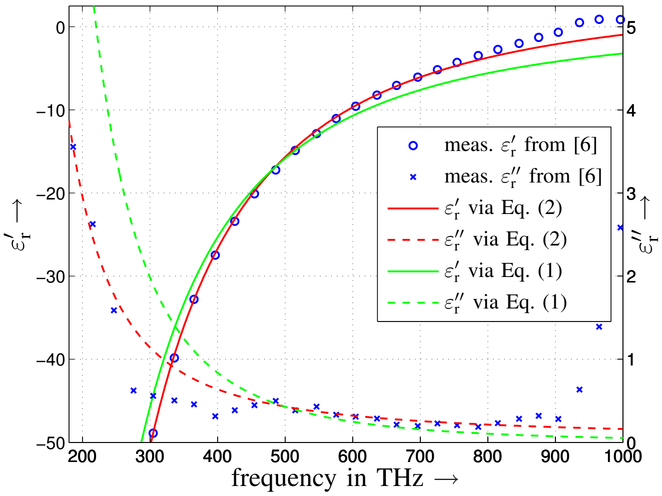

Fig. 2. Measured complex permittivity $\varepsilon_\mathrm{r} = \varepsilon'_\mathrm{r} - \mathrm{j}\varepsilon''_\mathrm{r}$ from [6] compared to the data obtained by the Drude model given in Eq. (1) and an extended Drude function given in Eq. (2).

meters [Eqs. (1) and (2)] of plasmonic media is that, as shown in Fig. 2, they may be straightforwardly fitted to experimental data for efficient *frequency-domain* (e.g. FEM) computations. In addition, they may be easily implemented in *time-domain* computational methods (e.g. FDTD) based on LC lumped element schemes [7] for the fast analysis of broadband-operation and electrically large plasmonic structures.

In this work, the insulator material in the coupler shown in Fig. 1 is SiO_2 and its permittivity is assumed to be independent of frequency:

$$\varepsilon_\text{insulator} = \varepsilon_{\mathrm{SiO}_2} = 2.09. \qquad (3)$$

III. EIGENMODE ANALYSIS OF SINGLE AND DOUBLE PLASMONIC-INSULATOR-INTERFACE WAVEGUIDES

The proposed power splitter, which is shown in Fig. 1, is effectively a coupler. Its modes of interest are the TE_z (H_z and $E_{x,y}$) even and odd [in terms of the function $H_z(y)$] SP modes coupled across the double Ag-SiO_2 interface.

The full-wave simulated (FEM COMSOL) dispersion diagram, field distributions and time-averaged power flows for these modes in the coupling region are shown in Figs. 3, 4 and 5, respectively, along with the corresponding curves for a single Ag-SiO_2 interface, which are given for comparison.

The dispersion curves in Fig. 3 show the even-odd mode splitting (from the uncoupled case, i.e. single interface) corresponding to the coupling phenomenon while the field distributions in Fig. 4 show the corresponding SP at the interface [1]. It may be noted in Fig. 4 that at the frequency considered (685 THz) the fields are relatively poorly confined to the interface. This is because this frequency is relatively far from the exact SP resonance, where in the limit $\omega \rightarrow \omega_{SP}$ infinite confinement together with maximal losses are obtained [1], [2]. Additionally the condition of weak energy confinement is necessary to ensure sufficient coupling between the two interfaces underpinning the splitter's operation.

It is interesting to note from Fig. 5 that, in the coupling process, the power flow is inverted within the Ag slab with respect to the power flow outside in SiO_2. The intensity of this inverted flow of power inside the slab is very low, especially for the odd mode, yielding an efficient power transport in the waveguiding direction (positive x-direction).

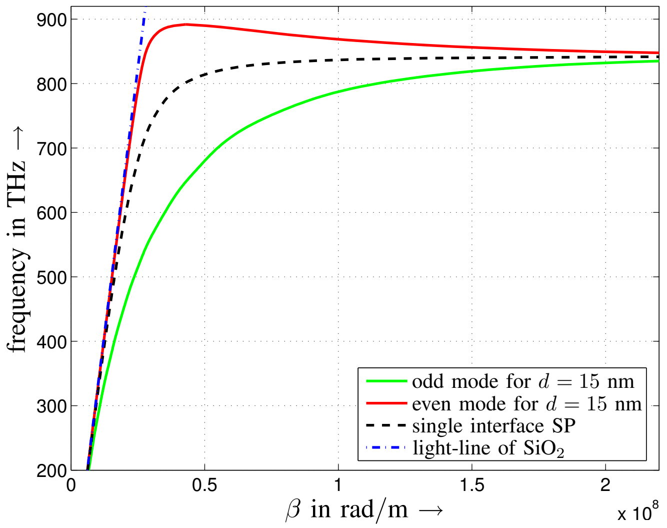

Fig. 3. Dispersion diagram (even and odd modes) for an Ag film embedded in SiO_2 with strongly coupled surface plasmons (SPs) ($d = 15$ nm, coupling region in Fig. 1). The case of a single Ag–SiO_2 interface is also shown for comparison. Only the guided modes below the light-line of the SiO_2 material are shown, since only these modes are relevant to the proposed splitter application.

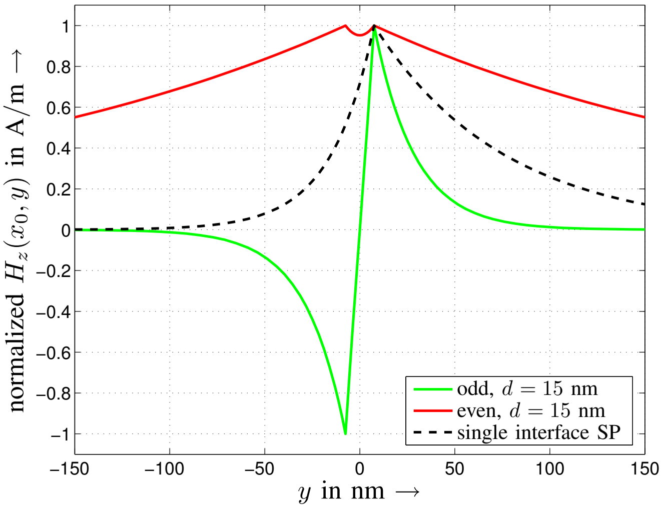

Fig. 4. Eigenmode magnetic field $H_z(x = x_0, y; f = 685$ THz) for the strongly-coupled ($d = 15$ nm) double-interface even and odd modes and for a single-interface SP.

At the input and output of the coupler (away from the coupling section), only one interface wave is excited, and the even and odd mode dispersion curves may be shown to reduce to the single interface dispersion curve shown in Fig. 3. The corresponding uncoupled even and odd mode field distributions are shown in Fig. 6.

IV. ULTRA-COMPACT POWER SPLITTER BASED ON TWO COUPLED SURFACE PLASMONS

The proposed power splitter was shown in Fig. 1. It consists of a plasmonic metal (here Ag) film embedded in a dielectric

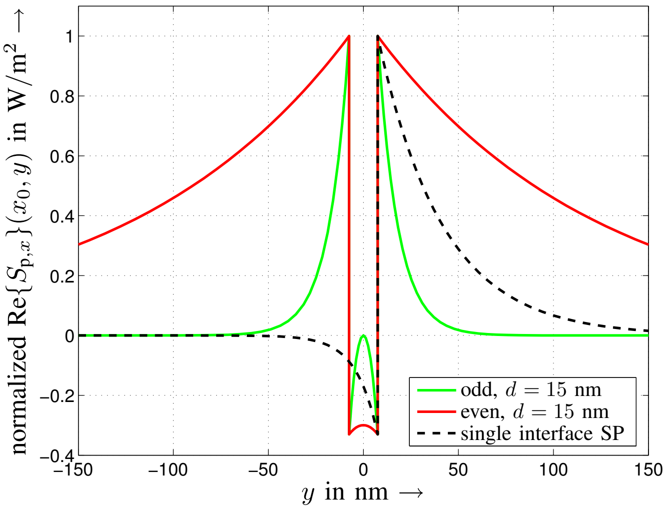

Fig. 5. Time-averaged power flow density (x-component) Re$\{S_{p,x}\}(x = x_0, y; f = 685$ THz) of eigenmode fields for the strongly-coupled ($d = 15$ nm) double-interface even and odd modes and for a single-interface SP.

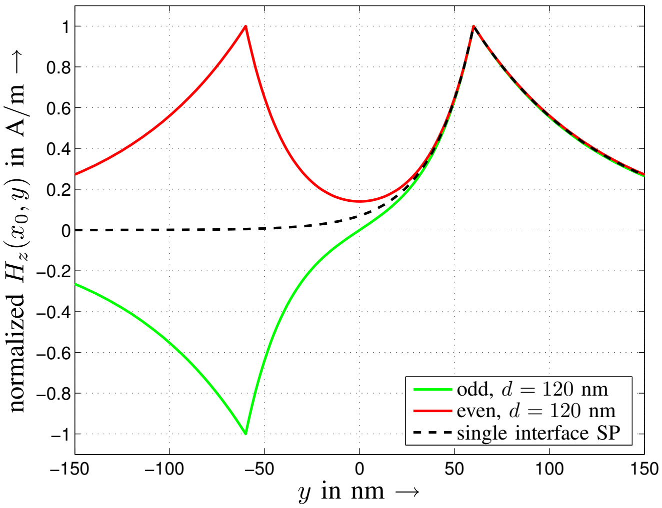

Fig. 6. Eigenmode magnetic field $H_z(x = x_0, y; f = 685$ THz) for weakly-coupled ($d = 120$ nm) double-interface even and odd modes and for a single-interface SP.

material (here SiO$_2$, $\varepsilon_{\mathrm{SiO_2}} = 2.09$). The thickness of the metal film is smaller in the center coupling region (d_{min}), which is connected to the larger-thickness (d_{max}) input and output regions by tapered sections. The structure is considered infinite in the direction z, perpendicular to the longitudinal section of the device (2D problem). The input, through, coupled and isolated ports are indicated in the figure.

In order to achieve the desired power splitting operation, the structure is excited only at one of the two SiO$_2$-Ag interfaces in the input region before the tapering section. This results in a propagating waveform which is a combination of the aforementioned perturbed odd and even modes in the coupled section. In order to provide a qualitative and quantitative information on the respective contribution of these modes, Fig. 7 shows that a fitted weighted superposition of the unperturbed even (40%) and odd modes (60%) produces a field distribution very similar to that actual coupled case. The taper is necessary to excite this single interface SP mode, which sets an upper frequency limit to the operation corresponding to the SP resonance $\omega_{\mathrm{p}}/\sqrt{1 + \varepsilon_{\mathrm{r,SiO_2}}}$.

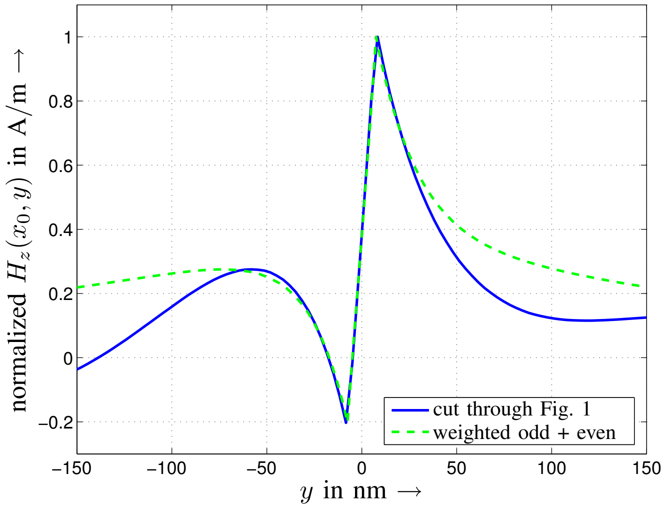

Fig. 7. Magnetic field component in the power splitter of Fig. 1 along $x = 0$ compared to a weighted sum of the normalized even (40% weight) and odd (60% weight) eigenmodes of the film waveguide (Fig. 4), indicating the relative contributions of the odd and even modes to the coupling mechanism.

Fig. 1 shows by full-wave analysis (FEM COMSOL, FDTD EMPIRE XCcell used for co-simulation) that, for the parameters selected, the device splits power evenly (3 dB or hybrid coupler) and in phase quadrature between its through and coupled ports at $f_{\mathrm{o}} = 685$ THz (corresponding to the free space wavelength of 438 nm). Other coupling levels may be achieved by adjusting the length or thickness of the coupling section. The corresponding time-averaged power distribution is shown in Fig. 8.

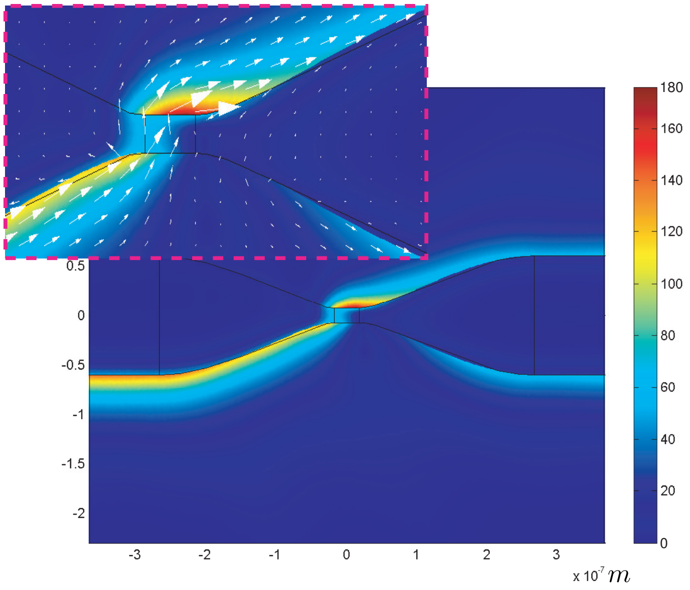

Fig. 8. Time-averaged power flow density showing the equal power splitting and guiding towards the two coupled ports on the right-hand side. In the upper left inset a zoomed view of the coupling area with vectorial (indicating the direction) and scalar (indicating the intensity) power flow plot is depicted.

Fig. 9 plots the main scattering parameters of the power splitter for both a lossless and a lossy Ag film, showing coupling levels of around 3.75 dB and 5.0 dB, respectively, at 685 THz. The extra 0.75 dB loss in the lossless Ag case is due to leakage at the imperfect excitation of the single interface SP and at the tapered surface. The splitter, with its coupling region of 36 nm, is extremely short. In contrast to the contra-directional coupler proposed in [5], it is a forward-coupling (and not contradirectional) power splitter.

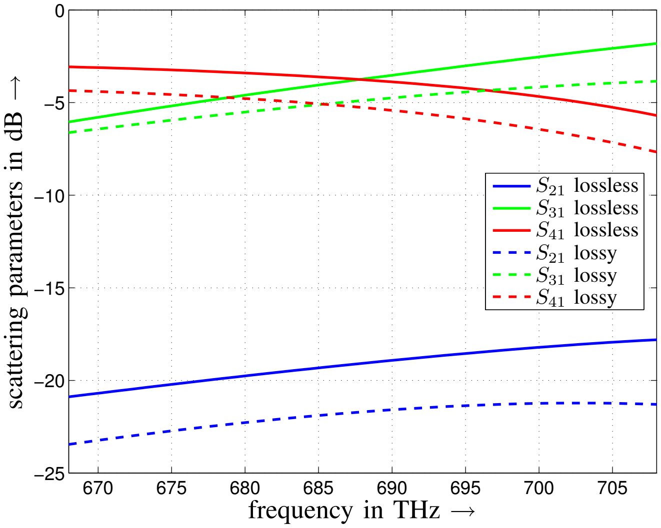

Fig. 9. Scattering parameters of the proposed power divider for the lossless case (solid lines) and for the case with lossy silver (dashed lines) resulted from fullwave simulation with the measured frequency-dependant permittivity given in [6].

In order to assess the accuracy of the extended-Drude model of Eq. (2) for Ag, Fig. 10 plots the difference (in dB, i.e. the ratio on a linear scale) between the scattering parameters obtained by full-wave simulations with curved-fitted measured results for Ag and obtained from the extended-Drude model. The higher insertion loss for the Drude material response compared to the measured data (Fig. 10) is due to the higher ε_r'' at the frequency of operation $f_o = 685$ THz (Fig. 2). The difference between the two sets of curves never exceeds 1 dB, which indicate that the proposed extended-Drude model may be safely used in equivalent circuit based time-domain computational schemes for broadband analyzes [7].

CONCLUSION

A novel ultra-compact quadrature power splitter based on coupled surface plasmons has been proposed. Both eigenmode and drivenmode full-wave simulations have been carried out to analyze it. In the proposed 685 THz (438 nm) design, the splitter exhibits a coupling length of only 36 nm and an overall dimension, including the tapering sections of around 500 nm. This device can be fabricated using standard processes (e.g. e-beam lithography). Its principle of coupled SPs may lead to various novel nanoscale optical devices. An accurate extended-Drude model was used to model the metal Ag film, and may be exploited in lumped-element based time-domain computational schemes for efficient analysis of broadband-operation and large-scale plasmonic structures.

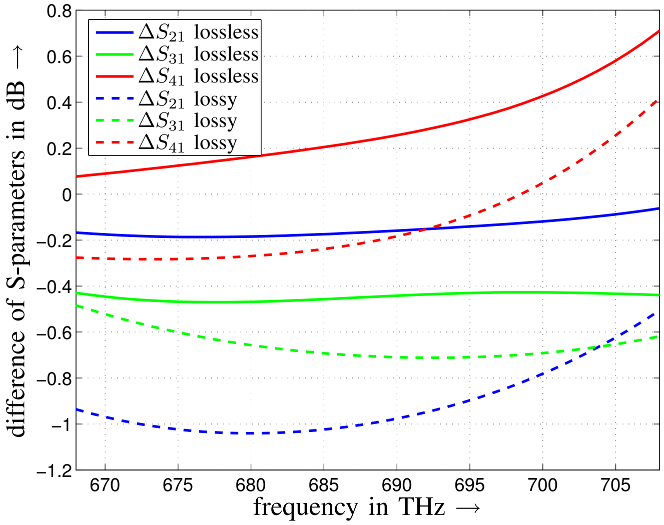

Fig. 10. Difference in terms of scattering parameters between fullwave simulation with the permittivity predicted by the extended Drude model given in Eq. (2) compared to the results obtained with the measured material values of [6].

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