Nonlinear couplers with tapered plasmonic waveguides

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Abstract: We suggest and demonstrate numerically that, by employing tapered waveguides in the geometry of a directional coupler, we can enhance dramatically the performance for optical switching of nonlinear plasmonic couplers operating at the nanoscale, overcoming the detrimental losses but preserving the subwavelength confinement. We demonstrate that, by an appropriate choice of the taper angle of the coupled metal-dielectric slot waveguides, we can compensate for the amplitude decrease and enhance the sharpness of the response for the switching operation.

OCIS codes: (190.4390) Nonlinear optics, integrated optics; (130.4815) Optical switching devices.

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#162626 - $15.00 USD Received 7 Feb 2012; revised 21 Mar 2012; accepted 2 Apr 2012; published 9 Apr 2012

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1. Introduction

Recent advances in the study of light propagation in nanophotonic structures suggest many potential applications of subwavelength photonics for light manipulation at the nanoscale, with perspectives for creating functional optical devices [1,2]. When the size of conventional optical devices is reduced to the nanoscale, the spatial confinement of light becomes inherently limited by diffraction. However, metal-dielectric structures allow to achieve subwavelength light confinement with surface plasmon polaritons, or *plasmons* [3]. Using plasmons we can spatially confine and manipulate optical energy over distances much smaller than the wavelength.

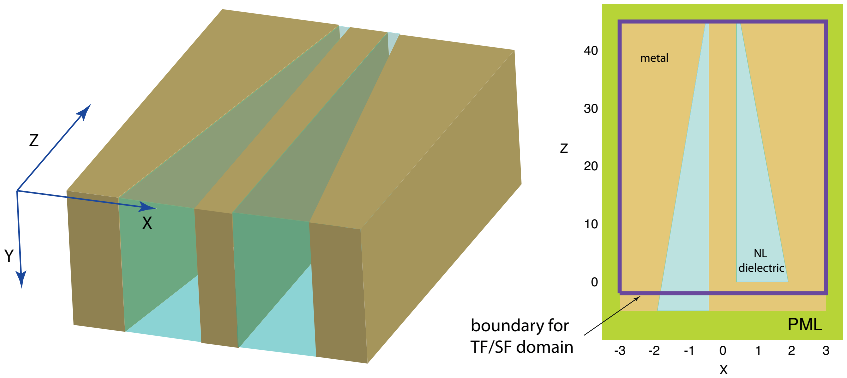
Because of the strong enhancement of the field induced by the excitation of plasmons and increased nonlinearity, surface plasmons can be employed for the realization of a variety of nonlinear optical effects. In particular, several nonlinear optical processes have been demonstrated in plasmonic nanostructures, e.g. optical limiting and self-phase modulation in arrays of structured nanoparticles [4] or second-harmonic generation in nanostructured metal films [5,6].

The simplest plasmonic waveguide is an interface between metal and dielectric that supports surface plasmon polaritons. However, more complex systems as metal-dielectric-metal waveguides became attractive for more efficient excitation of plasmonic modes and for the loss reduction. In such guiding structures, light is tightly confined between two metal slabs, and it can be used for efficient nanofocusing [7].

A directional coupler is composed of two coupled waveguides, and for plasmonic waves it was studied theoretically and demonstrated experimentally for different geometries [8–10]. Such couplers were suggested also for converting the modes of a dielectric waveguide into plasmonic modes propagating along a thin metal stripe [11].

Nonlinear effects may provide novel functionalities for the light control in plasmonic structures. Nonlinear plasmonic waveguides were studied for a number of years (see, e.g., Refs. [12–14]), and it was recently shown that nonlinear slot waveguides created by a nonlinear dielectric slab sandwiched between two metals may support subwavelength nonlinear guided modes of different symmetries [15], including a novel type of asymmetric modes which is important for nonlinear switching, which is the application we are considering for the directional coupler in this paper. If the length of the coupler is adjusted to a beat length the device has two different output states depending whether the input signal is over or below certain power threshold, and this means that the signal can be optically switched from one channel to the other just controlling its power. It was already shown that couplers formed by a pair of plasmonic slot waveguides may demonstrate all-optical switching at the distances of few tenths of nanometers [16].

Received 7 Feb 2012; revised 21 Mar 2012; accepted 2 Apr 2012; published 9 Apr 2012



(a) (b)

Fig. 1. Tapered plasmonic waveguide coupler. (a) Sketch of the coupled tapered metal-dielectric-metal slot waveguides. (b) View of the XZ-plane showing the different domains used in numerical FDTD simulations of the plasmonic coupler. Notations are: PML, perfectly marched layer; TF/SF, total field-scattered field technique.

Here we demonstrate that tapered waveguides can be employed for overcoming the effect of losses amplifying the field amplitude as happens for isolated plasmonic waveguides [17–19]. This solution is also effective to enhance the switching performance of plasmonic couplers. In order to measure performance we consider how fast is the change from one state of the coupler to the other when input power is increased. Ideally one would desire a fast change but it was shown that power losses in the metals completely spoil the sharpness of the change [16].

2. Model and approach

We consider a coupler formed by two close tapered waveguides with a dielectric core showing the Kerr nonlinearity and surrounded by metallic layers. In order to maintain the separation between both waveguides constant, we made both internal waveguide borders parallel to the z-axis (which will be considered the propagation direction) and lie both external borders forming an angle α so that the waveguide width decreases linearly with distance as shown in Fig. 1. Considering the TM mode described by the electric and magnetic fields $\mathbf{E} = E_x\mathbf{x} + E_z\mathbf{z}$ and $\mathbf{H} = H_y\mathbf{y}$, we can write the permittivity of the medium as follows,

$$\varepsilon(\mathbf{r}) = \begin{cases} \varepsilon_m; & \text{for metallic claddings,} \\ \varepsilon_d + |\mathbf{E}_x|^2 + |\mathbf{E}_z|^2; & \text{for nonlinear cores,} \end{cases} \tag{1}$$

where ε_m is a complex number with negative real part and an imaginary part which accounts for the loss in the metallic claddings and ε_d the linear permittivity of the dielectric cores. The Kerr coefficient γ does not appear in the above equation since we have rescaled the fields $\mathbf{E}$ and $\mathbf{H}$ by the factor $\gamma^{-1/2}$. Additionally we will consider spatial variables rescaled by the vacuum wavenumber $k_0 = \omega/c$, being ω the frequency and c the speed of light in vacuum.

In order to study the dynamics of this system a simple model to describe the effect of losses as well as the tapering shape was already proposed [17, 18] for a single waveguide. It showed that for small tapering angles ($\alpha \sim 1$ deg.) the effect of power concentration due to the taper fully compensated the power loss in the metal claddings. This model can be in principle also applied to the present directional coupler considering mode amplitudes at each of the waveguides

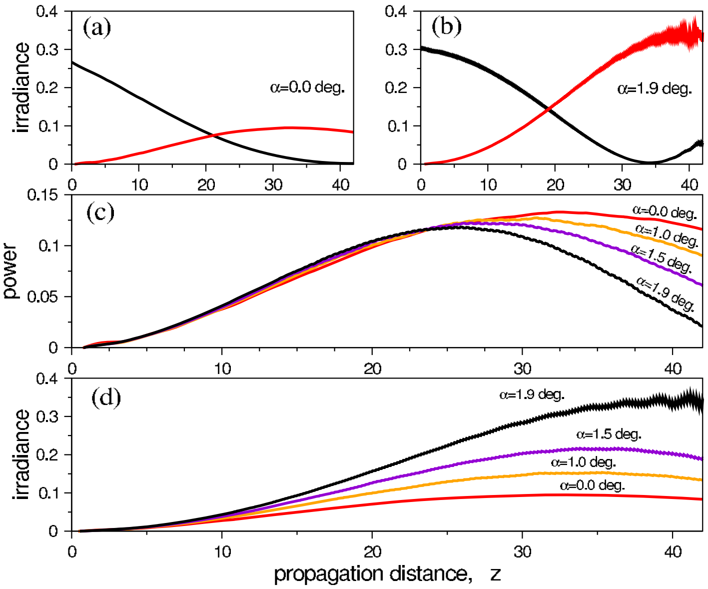


Fig. 2. Numerical experiments for a linear regime and different taper angles. (a-b) Irradiance at each of the cores of the coupler for a non-tapered coupler and for a loss compensating angle $\alpha = 1.9$ deg. respectively. (c) Coupled power into the second waveguide versus propagation distance for different taper angles. (d) Irradiance at each waveguide core versus propagation distance.

$A_{1,2}(z)$ and writing the coupled equations:

$$2i\sigma\frac{\partial A_1}{\partial z}+i\left(\frac{\partial\sigma}{\partial z}+\Gamma\right)A_1+N|A_1|^2A_1+KA_2=0, \tag{2}$$

$$2i\sigma\frac{\partial A_2}{\partial z}+i\left(\frac{\partial\sigma}{\partial z}+\Gamma\right)A_2+N|A_n|^2A_2+KA_1=0, \tag{3}$$

where σ, Γ, N and K are parameters calculated applying a perturbation theory to the linear mode in order to describe losses and nonlinear effects, and considering an adiabatic approach to describe the effect of the width change of the waveguide with the propagation distance. In that way, σ describes power carried by the guides and so $\partial_z\sigma$ accounts for the effect of the tapering shape, Γ describes de effect of losses, N the nonlinearity and K is the coupling coefficient describing the power transference between both waveguides [20].

Simulations of the coupled equations above using the beam-propagation method allow to obtain the characteristic switching curve of the nonlinear couplers and show that for increasing tapering angles the power density efficiency notably raises, revealing an effect of loss compensation. Unfortunately this model is too simple to describe the previously showed effect of slope decreasing [16] that spoiled the performance of switching. Consequently, in order to better evaluate the effect of losses and study the performance enhancing of the tapered-waveguide coupler we finally carried out some FDTD simulations.

For the use of FDTD technique we considered a calculation domain divided in different regions according to the distribution of metals and nonlinear dielectrics [see Fig. 1(b)] and a specific model was applied at each region. Besides, the whole domain was surrounded by additional calculation cells to implement suitable perfectly-matched boundary (PML) conditions. To excite the mesh we used the total field-scattered field technique (TF/SF) to generate a plane

#162626 - $15.00 USD Received 7 Feb 2012; revised 21 Mar 2012; accepted 2 Apr 2012; published 9 Apr 2012

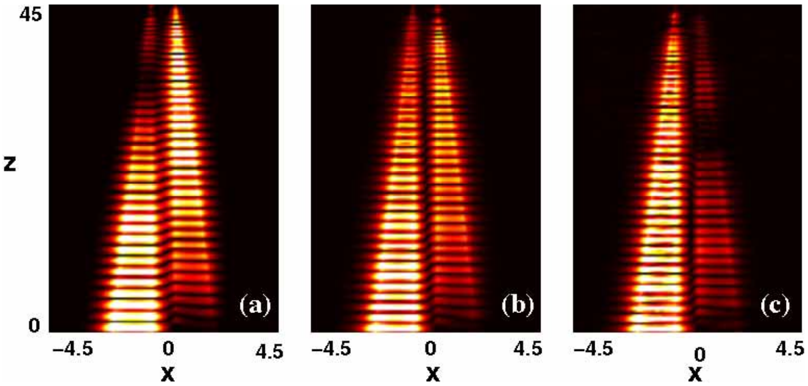


Fig. 3. Different images showing the evolution of the electromagnetic field (magnetic component) for tapered waveguides at an angle $\alpha = 1.9$ deg. (a) corresponds to the linear case, (b) to an intermediate power regime and (c) corresponds to a nonlinear regime.

wave whose amplitude was modulated with the shape of a single waveguide mode, at the position of the left core of the coupler.

In order to model metallic regions we used a scheme for cold plasmas based on Drude's theory, necessary to take into account the strong dispersion of metals. The dispersion is introduced in Maxwell's equations using a polarization current term [21] $\mathbf{J} = \partial_t \mathbf{P}$ which is introduced in the Maxwell's equations, $\partial_t \mathbf{D} = \nabla \times \mathbf{H} - \mathbf{J}$, being $\mathbf{D}$ the electric displacement, and modeled by solving an additional differential equation, $\partial_t \mathbf{J} + \eta \mathbf{J} = \omega_p^2 \mathbf{E}$, where ω_p is the plasma frequency and η is the electron collision frequency describing the power losses. Both parameters can be calculated from Drude's model $\varepsilon(\omega) = 1 - \omega_p^2/(\omega^2 + i\eta\omega)$. For our calculations we took the values $\mathrm{Re}(\varepsilon) = -8.25$ and $\mathrm{Im}(\varepsilon) = 0.3$ deduced from the optical constants of silver at $\lambda \approx 480\,\mathrm{nm}$ [22]. Taking $\omega = 1$, we obtain $\omega_p = 3.043$ and $\eta = 0.031$.

For the dielectric showing the Kerr nonlinearity we use a model based on an instantaneous response of the medium which is valid for a CW or even for non ultrashort pulses [23]. According to this, we use the relationship $\mathbf{D} = \varepsilon(|\mathbf{E}|^2)\mathbf{E}$ taking the nonlinear permittivity as in Eq. (1). For the simulations we took $\varepsilon_d = 2.25$ (pure silica) though the nonlinear model is general for any Kerr material just rescaling back the fields by the factor $\gamma^{1/2}$, γ is the Kerr coefficient, after the simulation. At each time step, after obtaining the magnetic component and then the two components for the displacement vector, D_x and D_z, the calculation of the electric field components requires the solution of a nonlinear cubic equation at each point of the mesh. This is efficiently done by a single Newton step, starting from the value of the electric components at the previous time step.

3. Results and discussions

First, we consider a linear regime and search for the proper angle range leading to the compensation of loss. To this aim, we perform a set of experiments for different taper angles, measuring total power at each waveguide and also the irradiance inside each of the cores. In Figs. 2(a) and 2(b) plots of the irradiance at each core versus propagation distance are showed for non tapered waveguides and for tapers with an angle $\alpha = 1.9$ deg. We deduced that for angles slightly lower than $\alpha = 2.0$ degrees loss is compensated by the focusing effect of the taper waveguides. We should remark that irradiance is a more convenient parameter than power for this study as it represents the optical density inside the waveguide core, that can result enhanced by a progressive decrease of the core width. The total power, however, will always decrease as an effect of the

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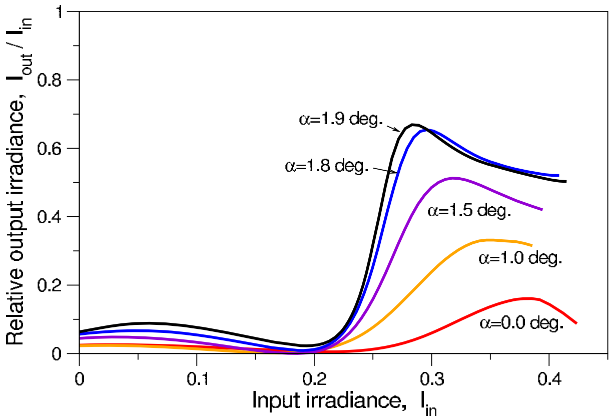

Fig. 4. Switching curve for different taper angles. Mean irradiance inside the excited core after a beat length normalized to the mean input irradiance vs. the mean input irradiance.

optical loss in the metallic layers. In fact Fig. 2(c) shows how total power in the second waveguide decreases when the taper angle increases. This is due to the fact that when the waveguide core width is smaller a larger fraction of the modal field lies inside the metallic cladding and relative loss increase. Nevertheless the irradiance inside the core increases when the angle increases [Fig. 2(d)] because the power concentration inside the core partially compensates loss.

Next, we studied the switching properties of this coupler. In Fig. 3 we show images representing the modulus of the field (magnetic component) simulated for nonlinear cores and different power regimes using tapered waveguides at an angle of $\alpha = 1.9$ deg. The three images correspond to linear, intermediate and nonlinear regimes reached when input power is increasedly larger. Though loss still exist, the irradiance inside the core is enhanced as was shown in Fig. 2(d) and this is the reason why switching results more effective. This is clearly seen in the switching curve shown in Fig. 4 where the relative irradiance for a beat length is plotted against the input irradiance. The case for non tapered waveguides ($\alpha = 0.0$) was already studied in Ref. [16] where we showed how loss spoiled the performance of the coupler when used for power switching. In such a case, though switching is still possible, the slope of the curve was small and the peak reaches less than 20% respect to the case when loss is not considered. As the taper angle increases, the curve slope becomes sharper and reaches a larger fraction of the input irradiance, dramatically improving the efficiency of the device.

4. Conclusions

We have studied numerically linear and nonlinear propagation of surface plasmon polaritons in coupled metal-dielectric-metal slot waveguides and demonstrated that, by an appropriate choice of the tapering angle, we can compensate for the amplitude attenuation and enhance substantially the performance of nonlinear plasmonic directional couplers operating at the nanoscale for all-optical switching. We expect that plasmonic tapers can be useful to improve functionalities of other plasmonic devices as well as enhancing nonlinear effects, including plasmon parametric amplification, second-harmonic generation, and all-optical switching.

Acknowledgments

The authors acknowledge a financial support from Ministerio de Ciencia e Innovación (project MAT2008-06870), Xunta de Galicia (project 10PXIB265118PR), and the Australian Research Council.