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Nonlinear infrared plasmonic waveguide arrays

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ABSTRACT

The large negative permittivity of noble metals in the infrared region prevents the possibility of highly confined plasmons in simple waveguide structures such as thin films or rods. This is a critical obstacle to applications of nonlinear plasmonics in the telecommunication wavelength region. We theoretically propose and numerically demonstrate that such limitation can be overcome by exploiting inter-element coupling effects in a plasmonic waveguide array. The supermodes of a plasmonic array span a large range of effective indices, making these structures ideal for broadband mode-multiplexed interconnects for integrated photonic devices. We show such plasmonic waveguide arrays can significantly enhance nonlinear optical interactions when operating in a high-index, tightly bound supermode. For example, a third-order nonlinear coefficient in such a waveguide can be more than three orders of magnitude larger compared to silicon waveguides of similar dimensions. These findings open new design possibilities towards the application of plasmonics in integrated optical devices in the telecommunications spectral region.

Surface plasmon polaritons offer a host of properties which are highly desirable for enhancing the performance of photonic devices [1–3]. The electromagnetic field associated with a guided plasmonic mode can be concentrated in sub-diffraction regions in close proximity of a metal-dielectric interface, with a concurrent enhancement of the field amplitude. This is of great importance for nonlinear optics applications. For instance third order processes such as four wave mixing would benefit from the third power of the field enhancement. For these effects to take place efficiently, the relative permittivity of the plasmonic material should be negative, with a magnitude of the same order as the corresponding quantity in the surrounding dielectric.

Such condition is easily met in the visible region using noble metals, but the problem becomes far more challenging at longer wavelengths. More sophisticated design principles must be devised in order to fully exploit the potential of plasmonic effects over spectral regions of great practical importance, such as the near IR communication band. In the near IR the absolute

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value of the relative permittivity of noble metals is about two orders of magnitude larger than the one of most available dielectrics [4]. As a consequence the modes of a plasmonic waveguide such as a metallic thin film are inherently weakly guided, extending mostly in the surrounding dielectric, with negligible field enhancement at the metal-dielectric interfaces. In the past few years great efforts have been devoted to finding alternative materials for plasmonic applications [5–8]. Metamaterial-based strategies have also emerged. In particular the use of patterned metallic surfaces has been shown to produce tightly bound plasmon-like modes [9, 10]—the so-called "spoof plasmons"—down to the THz [11].

Here we propose a different approach for IR plasmonics based on the concept of plasmonic waveguide arrays. Using the single metallic thin-film waveguide as fundamental building block we exploit the coupling between multiple elements in order to obtain an overall structure able to strongly confine the fields, while granting the significant field enhancement factors necessary to boost nonlinear interactions.

The physical principle behind the operation of a plasmonic array is the splitting of the modes of the single elements due to the inter-element coupling. This leads to a set of modes with higher effective index and tighter confinement, and another manifold with lower effective indexes [12]. This well-known effect has a new useful property stemming from the plasmonic nature of the waveguiding elements: There is in principle no upper bound to the achievable effective index of the array, so higher and higher enhancement factors can be achieved by adding extra elements to the array. This is in stark contrast with dielectric arrays, where the maximum effective index cannot exceed the refractive index of the waveguide material. In addition to the achievable strong field enhancement, a plasmonic array, which comprises multiple interfaces, can take full advantage of the strong surface nonlinearity of metals such as silver or gold, further enhancing the nonlinear performance [13–16]. Exploiting these remarkable properties of plasmonic arrays and the compatibility with silicon on insulator systems, we envision a new class of compact and fully integrated nonlinear devices such as on-chip optical parametric amplifiers and oscillators.

It is well known that coupling effects modify the modal properties of adjacent waveguides, in dielectric [12, 17] as well as in plasmonic systems, see i.e. Refs. [18–20]. In particular in the case of evanescent coupling between two identical photonic waveguides, a first order perturbation solution yields the propagation constants of the eigenmodes (or supermodes) of the whole system in terms of the propagation constant β_0 of the isolated units and the coupling coefficient κ in the following simple analytical form [12] $\beta = \beta_0 \pm \kappa$. In the case of an array of N identical photonic waveguides the propagation constants of the N supermodes takes on values in the range $\beta_0 - 2\kappa \leqslant \beta_n \leqslant \beta_0 + 2\kappa$ according to

$$\beta_n = \beta_0 + 2\kappa \cos\left(n\frac{\pi}{N+1}\right), \quad n = 1,\ldots N$$

Typically evanescent coupling between nearest neighbors in a waveguide array is much smaller than the propagation constant ($\kappa \ll \beta_0$), therefore the effective index of any particular supermode in a dielectric waveguide array cannot be much larger or much smaller than the effective index of a single isolated waveguide. This is consistent with the propagation constant $\beta_0 = k_0 n_{\mathrm{eff}}$ in a waveguide of index n_{w} and background $n_{\mathrm{b}} < n_{\mathrm{w}}$, the transverse dependence of the fields is sinusoidal with a transverse wavenumber $k_{\mathrm{T}} = k_0\sqrt{n_{\mathrm{w}}^2 - n_{\mathrm{eff}}^2}$ within the waveguide core, and exponentially decaying outside with decay constant $\alpha_{\mathrm{T}} = k_0\sqrt{n_{\mathrm{eff}}^2 - n_{\mathrm{b}}^2}$. As a consequence the modal effective index n_{eff} cannot exceed the highest refractive index and the guiding structure cannot fall below the index of the background material.

The situation is rather different in the case of plasmonic waveguides in which the transverse electromagnetic field distribution is described by real exponentials, rather than sinusoids. In this case the transverse wavevector in the plasmonic core is purely imaginary and is given by $k_{\mathrm{T}} = k_0\sqrt{\varepsilon_{\mathrm{pl}} - n_{\mathrm{eff}}^2}$ where $\varepsilon_{\mathrm{pl}} < 0$ is the relative permittivity of the plasmonic material. Interestingly the nature of the solution does not directly provide in principle an upper bound for the effective index of the mode. It is therefore conceivable that the geometry of the structure could be modified so as to support modes with an extremely large effective index n_{eff}.

Exploiting the mode splitting that originates from coupling effects, we can in fact access modes with very high effective indexes by coupling multiple plasmonic waveguides. From a heuristic point we can consider ideal hyperbolic media as a limiting case in which infinitely thin metal and dielectric layers are stacked. In this limit the behavior of the longitudinal wavevector for large values of the transverse wavevector tends to the linear asymptotes of the hyperbolic dispersion curve. As a consequence a fast spatial oscillation of the electromagnetic field in the direction of the optical axis is associated with guided modes in the transverse direction with very high effective indices. This mechanism has been exploited for the realization of deep sub-diffraction resonators [21].

A practical upper bound can be analytically established in the case of infinite arrays of alternating metal and dielectric layers. A portion of the geometry is shown in Fig. 1(a). In the limit of layer thicknesses much smaller than the operating wavelength and the optical skin-depth the maximum effective index is asymptotic to the following expression (Eq. (1))

$$n_{\max} \sim \mathrm{Re}\left[n_{\mathrm{d}} \sqrt{1 - \frac{1}{\pi^2}\left(\frac{\lambda^2}{h_{\mathrm{d}} h_{\mathrm{m}} \varepsilon_{\mathrm{m}}}\right)} \right] \qquad (1)$$
$$h_{\mathrm{d}} h_{\mathrm{m}} \ll \lambda^2$$

Expressing the metallic permittivity in terms of a Drude model of the form $\varepsilon_{\mathrm{m}} = \varepsilon_{\infty} - \omega_{\mathrm{p}}^2 / [\omega(\omega + \mathrm{i}\gamma)]$ and under the condition $|\varepsilon_{\mathrm{m}}| \gg \varepsilon_{\infty}$, which is typically verified for noble metals in the IR spectral region, the asymptotic expression (Eq. (1)) reduces to the following simple form (Eq. (2))

$$n_{\max} \sim \frac{n_{\mathrm{d}}}{\pi}\left(\frac{\lambda_{\mathrm{p}}}{\sqrt{h_{\mathrm{d}}\, h_{\mathrm{m}}}}\right) \qquad (2)$$
$$h_{\mathrm{d}} \ll \lambda,\ h_{\mathrm{m}} \ll \lambda,\ \omega \gg 2\pi\gamma,\ \varepsilon_{\infty} \ll |\varepsilon_{\mathrm{m}}|$$

The plasma wavelength is expressed in terms of the plasma frequency as $\lambda_{\mathrm{p}} = 2\pi c / \omega_{\mathrm{p}}$. The imaginary part of the modal index can be obtained under the same assumptions and yields the following expression (Eq. (3))

$$\kappa \sim \frac{n_{\mathrm{d}}}{\pi}\left(\frac{\lambda_{\mathrm{p}}}{\sqrt{h_{\mathrm{d}} h_{\mathrm{m}}}}\right)\frac{\gamma}{2\omega} \qquad (3)$$

Under the same conditions the minimum effective index (for transverse magnetic (TM) modes) is simply the index of the dielectric layers ($n_{\min} \sim n_{\mathrm{d}}$). It is interesting to notice from Eq. (2) that the range of the effective index can be extended by reducing the layers

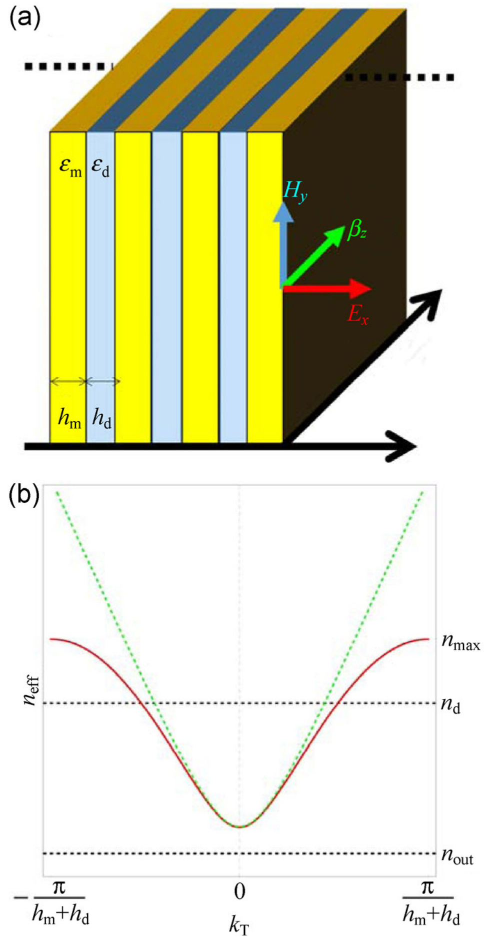

Figure 1 (a) Infinite array of metallic layers separated by dielectric layers. The optical wave is propagating along *z* direction. (b) Dispersion of an infinite plasmonic array. The red curve is the dispersion in the case of layers of finite thickness. The dotted green line is the hyperbolic dispersion of a structure with infinitely thin layers. In contrast with coupled dielectric waveguides, in plasmonic arrays the maximum supermode effective index is not limited by the index of the dielectric (n_{d}), but only by the array transverse period. h_{m}, h_{d} and n_{out} denote the thickness of metal layers, dielectric layers, and index of outside materials, respectively.

thickness. This unique property, with no analogue in dielectric systems, allows for efficient directional coupling of a finely structured plasmonic array with essentially any type of dielectric or plasmonic waveguide placed in proximity of the array. The large density of modes along with the quasi-hyperbolic dispersion of the system guarantees that one or more modes with small wavevector detuning with respect to the modes of an adjacent waveguide can be found.

We have verified through full-wave numerical simulations that the properties analytically derived for infinite periodic plasmonic arrays are shared to a large extent by finite arrays with a relatively small number of elements. We have conducted a parametric study of the system shown in Fig. 2(a). The system is an array of 5 gold layers of width 350 nm and thickness 20 nm, separated by silicon layers of thickness varying from 10 to 40 nm. The background material is considered air, and the wavelength of operation ranges from 1,280 to 1,340 nm. For comparison we have considered also a pure silicon waveguide of similar dimensions (width 350 nm, thickness 200 nm) as shown in Fig. 2(b). The effective index of the array supermode is up to one order of magnitude larger than the effective index of the pure Si nano-waveguide, as shown in Fig. 2(c). As expected the effective index of the supermode increases as the thickness of the dielectric spacer is reduced, as a consequence of the increased coupling strength between the plasmonic elements. Varying the thickness of the metallic layers leads to a qualitatively similar behavior, as shown in Fig. 2(d). The plasmonic array shown in Fig. 2 supports 12 TM modes in the wavelength range 1,280–1,340 nm, as opposed to the similarly sized silicon waveguide which supports

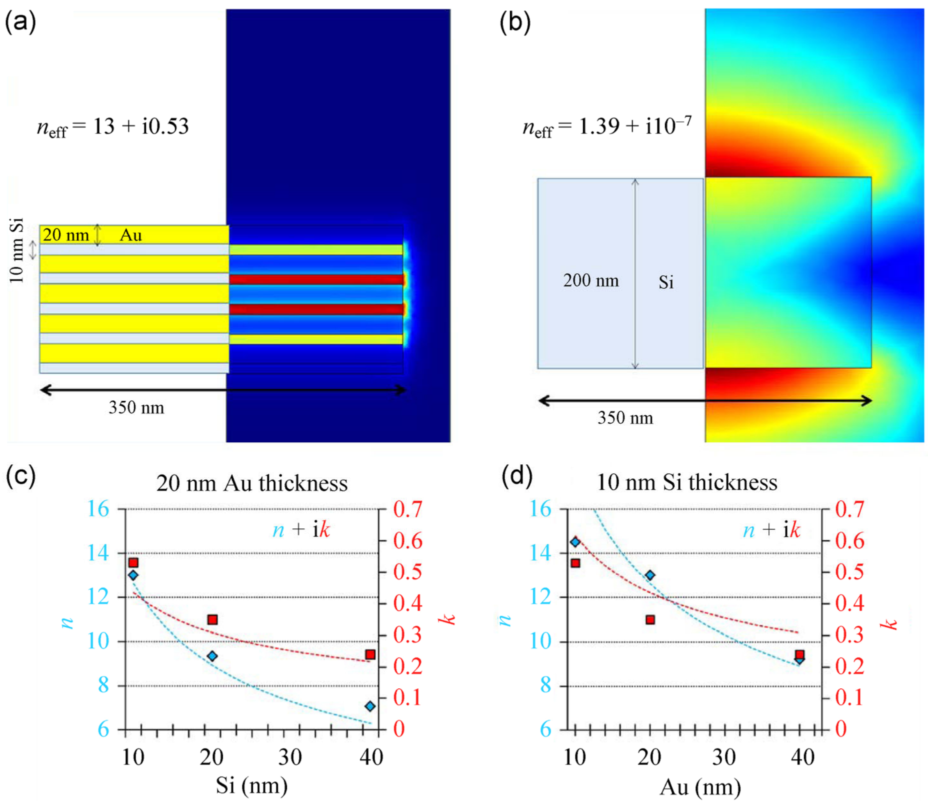

Figure 2 (a) Geometry (left half) and modal electric field distribution (right half) in a 5 element plasmonic array at an excitation wavelength of 1,300 nm. In (b) a Si waveguide of comparable cross-section is shown. In (c) the modal complex index for different dielectric thicknesses is shown. The markers are the values obtained from full-wave numerical simulations and the dashed lines are the values obtained from the asymptotic expressions (Eqs. (2) and (3)). Notice that although Eqs. (2) and (3) have been derived for infinite slab arrays, they approximate fairly well a 5-element array of finite-size waveguides. The modal effective index in the plasmonic arrays increases as the dielectric thickness is reduced, and is consistently much larger than in the case of the Si guide. In (d) the thickness of the metallic layers is varied, with qualitatively similar results.

2 modes only. For plasmonic arrays composed of a number $N \gg 1$ of elements the number of allowed modes M scales like $M \sim 2N$. The heavily multimode nature of plasmonic arrays holds promise for broadband mode-multiplexed ultra-compact interconnects.

The large effective index enabled by plasmonic arrays results in a strong field confinement and enhancement that can be exploited to boost nonlinear optical interactions. In particular we have considered here third order nonlinear interactions. A useful metric to describe four-wave mixing processes in guided-wave systems is the nonlinear parameter γ which accounts for the intrinsic nonlinear properties of the materials as well as the electric field distribution in the structure. The nonlinear parameter γ is determined as follows (Eq. (4)) [22]

$$\gamma = \frac{2\pi}{\lambda}\frac{\bar{n}_2}{A_{\text{eff}}} \tag{4}$$

In the Eq. (4) $\bar{n}_2$ is an intensity-weighted average of the intensity dependent refractive index which accounts for the modal distribution ($\boldsymbol{e}_0$, $\boldsymbol{h}_0$) as well as the inhomogeneity in the n_2 coefficient

$$\bar{n}_2 = \frac{\varepsilon_0}{\mu_0}\frac{\left|\int_A \varepsilon(\boldsymbol{r})n_2(\boldsymbol{r})\left(2|\boldsymbol{e}_0|^4+|\boldsymbol{e}_0^2|^2\right)\mathrm{d}A\right|^2}{\int_A \left|\left(\boldsymbol{e}_0\times\boldsymbol{h}_0^*\right)\cdot\hat{\boldsymbol{z}}\right|^2\mathrm{d}A}$$

The parameter A_{eff} is the effective area of the mode and is given by

$$A_{\text{eff}} = \frac{\left|\int_A \left(\boldsymbol{e}_0\times\boldsymbol{h}_0^*\right)\cdot\hat{\boldsymbol{z}}\,\mathrm{d}A\right|^2}{\int_A \left|\left(\boldsymbol{e}_0\times\boldsymbol{h}_0^*\right)\cdot\hat{\boldsymbol{z}}\right|^2\mathrm{d}A}$$

Figure 3 shows a comparison of the nonlinear parameter γ for different thicknesses of the silicon spacers and for a uniform silicon waveguide of thickness H. As the thickness of the dielectric spacer is reduced the value of the nonlinear parameter increases as a consequence of the stronger field confinement and enhancement. The nonlinear parameter is increased by up to three orders of magnitude compared to a Si waveguide of thickness 200 nm. This strong enhancement of the nonlinear parameter comes at the price of a shorter propagation length as shown in Fig. 3(b). While the short propagation length afforded by plasmonic arrays reduces the efficiency of nonlinear conversion in comparison with long dielectric waveguides, the very large value of the nonlinear parameters indicates a strongly enhanced light matter interaction which could be exploited in sensing applications relying and nonlinear spectroscopy of specimens placed in proximity of the plasmonic array. The introduction of gain media in some of the dielectric regions could significantly enhance the propagation length of the plasmonic modes, as recently demonstrated in Refs. [23, 24], boosting therefore the nonlinear conversion efficiency and making plasmonic arrays ideally suitable for applications in optical communication devices.

In conclusion the proposed array technology overcomes the limitations of noble metals for IR plasmonics applications enabling large sets of supermodes with a very broad range of effective indices. This unique feature paves the way towards a very robust modal multiplexing in optical interconnects relying compact

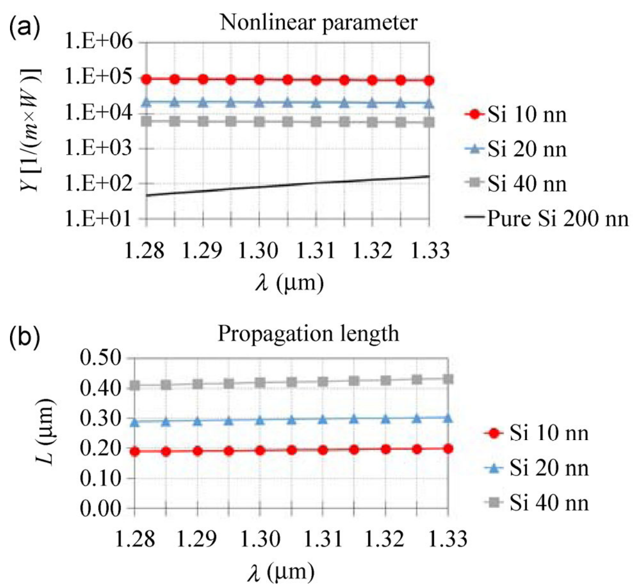

Figure 3 (a) The nonlinear parameter gamma at different dielectric thickness, while keeping fixed the metal thickness at 20 nm. It can be enhanced by over three orders of magnitude in comparison with the case of a Si waveguide of similar cross-section (black solid curve). The nonlinear parameter increases monotonically with the decrease of the thickness of the dielectric layers. This increased light-matter interaction is accompanied by stronger absorption and therefore shorter propagation length, as evidenced in (b).

heavily multimode waveguides. We have shown that plasmonic arrays can significantly enhance nonlinear optical interactions compared with dielectric waveguides of similar dimensions. These findings open new design possibilities for optical interconnects and nonlinear plasmonics in the infrared region. The same design principles relying on mode coupling are general and can be extended to other spectral regions, including the THz and the visible range.

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