Nanowires geometry dependence of coupling properties of a hybrid directional coupler

N. Lozano-Crisóstomo [1] , D. A. May-Arrioja [2] , M. Torres-Cisneros [3] , J. A. Andrade-Lucio [4] , J. J. Sánchez-Mondragón [1] , G. P. Agrawal [5]

[1] *Instituto Nacional de Astrofísica, Óptica y Electrónica, Apartado Postal 51 and 216, Tonantzintla, Puebla, C. P. 72840, México*

[2] *Departamento de Ingeniería Electrónica, UAM Reynosa Rodhe, Universidad Autónoma de Tamaulipas, Carretera Reynosa-San Fernando S/N, Reynosa, Tamaulipas 88779, México*

[3] *Dirección de Apoyo a la Investigación y al Posgrado, Universidad de Guanajuato, Guanajuato, México*

[4] *División de Ingenierías, Campus Irapuato-Salamanca (DICIS), Universidad de Guanajuato, Salamanca, Guanajuato, México*

[5] *Institute of Optics, University of Rochester, Rochester, New York 14627, USA*

nestorlo@inaoep.mx

Abstract: In this work we have modeled and characterized the near infrared coupling between a plasmonic wire and a silicon nanowire. We have studied the coupling parameters dependence on the dimensions of the directional coupler nanowires.

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1. Introduction

There is no doubt that silicon photonics and plasmonics have aroused an increasing interest in recent years [1,2]. Its potential applications on the photonics industry for chip-scale integration have attracted much attention because the recent progress on silicon-based photonics components, photonic integrated circuits, optoelectronic integrated circuits [3] and plasmonic optical devices [4,5]. In this work we investigate the geometrical dependence of the nanowires coupling properties of a hybrid directional coupler built by a silicon nanowire and a plasmonic wire, both of them quite close of each other. We model and describe the whole system considering the silicon large material nonlinearity and the SPPs strong dissipation. We report the particular behavior of the coupling parameters with the dimensions of the nanowires.

2. Theoretical Characterization

Recently, comprehensive theories have been developed to describe the propagation of near infrared light waves propagating trough silicon nanowires and plasmonic waveguides. Within the frame of the slowly varying envelope approximation [6,7], they are described by vectorial mode amplitude equations. The processes theoretically studied suggest the way to get a connection between silicon photonics and plasmonics and therein we describe the propagation of light pulses in a hybrid coupled system. We develop a theoretical model based in recent work on silicon nanowires and plasmonic waveguides [6,7] to investigate coupling properties of the system (see Fig. 1). We have coupled a silicon guided mode, in cylindrical coordinates along the cylindrical silicon nanowire of radius R, and a plasmonic mode at the metallic nanowire of radius r. These two nanowires, surrounded by the cladding (air), are assumed of unbounded length.

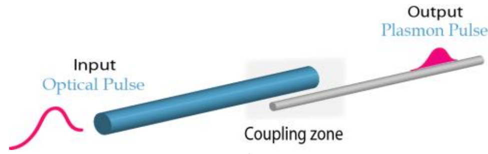

Fig. 1. Schematic illustration of the hybrid directional coupler.

If there is a near-field interaction, light from the silicon nanowire can excite a surface plasmon at the metallic wire directly [8]. The hybrid directional coupler supports only transverse magnetic (TM) optical modes. SPPs, which can only exist for the TM polarization [9], represent electromagnetic waves propagating along a dielectric-metal interface having the electromagnetic field amplitudes strongly enhanced at the interface and decaying exponentially into both the neighboring media [9-10]. We consider a system where the different regions are characterized by a set of constitutive parameters μ and ε, both, in general, frequency dependent. Thereby, for silicon we use μ_0 and ε_1, for the conducting media μ_0 and ε_2, and for air μ_0 and ε_3. Here μ_0 is the magnetic constant, and we have ignored the effect of magnetization for silicon and metal. We assume that the metallic nanowire is a sourceless medium, i.e., the condition that $\nabla \cdot \mathbf{E} = 0$, in the bulk, is supported, which gives rise to the surface plasma oscillations alone [11]. The material dispersion of silicon is well approximated by the modified Sellmeier equation: $n_1^2(\lambda) = A + B/\lambda^2 + C\lambda_1^2/(\lambda^2 - \lambda_1^2)$, where $\lambda_1 = 1.1071\mu m$, $A = 11.6858$, $B = 0.939816\mu m^2$, and $C = 8.10461\times 10^{-3}$. Before relation has a well behavior for wavelengths around $1.5\mu m$ [12]. For the conducting wire, we use the relation: $n_2^2(\omega) = n_\infty\left[1 - \omega_p^2/\omega(\omega + i/\tau)\right]$, where $n_\infty = 9.6$ (for Ag). The plasma energy $(\hbar\omega_p)$ of bulk silver is 3.76 eV, and $\tau = 3.1\times 10^{-14}s$ is the relaxation time due to ohmic metal loss [13].

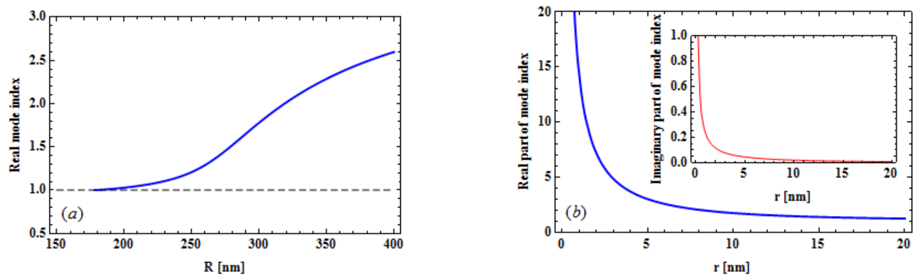

Fig. 2. (a) Real mode index versus the radii of the silicon nanowire at $\lambda = 1.55$ μm. The dashed line shows the critical value. (b) Complex mode index versus the radii of the metallic nanowire at $\lambda = 1.55$ μm.

By investigating the silicon and the surface guided modes [14], we can perform the numerical solutions of the complex mode index of the waveguides with respect to the radius of each one (see Fig. 2).

3. Geometrical dependence of coupling properties

The complex linear self-coupling terms κ_m of each mode in the system, which represent a perturbation of the propagation constant of the mth mode, are added in the coupled-mode equations directly from the coupled-mode approach. They are given by

$$\kappa_m = \left(\omega_0\varepsilon_0/\left[2(\sigma_m + i\varpi_m)N_m\right]\right)\int_0^{2\pi}\int_0^{\infty}\mathbf{e}_m^*\Delta n_m^2\mathbf{e}_m\rho d\rho d\varphi \tag{1}$$

where $\varpi_m = \left(\mathrm{Im}[\beta_m]/[2\omega_0\mu_0 N_m]\right)\int_0^{2\pi}\int_0^{\infty}|e_{\rho m}|^2 \rho d\rho d\varphi$ is the Plasmonic attenuation factor defined similarly in [7], and the new factor defined here is $\sigma_m = 1 + \left(\mathrm{Re}[\beta_m]/[2\omega_0\mu_0 N_m]\right)\int_0^{2\pi}\int_0^{\infty}|\mathbf{e}_m|^2 \rho d\rho d\varphi$ which represents a modulation factor. Here $\mathbf{e}_m$ is the mth TM linear electric mode structure in the absence of other guided modes, β_m is, in general, the mth complex-value propagation constant, ω_0 is the carrier frequency, N_m is the normalization constant, and Δn_m^2 is the change in the refraction index due to the presence of the mth guided mode.

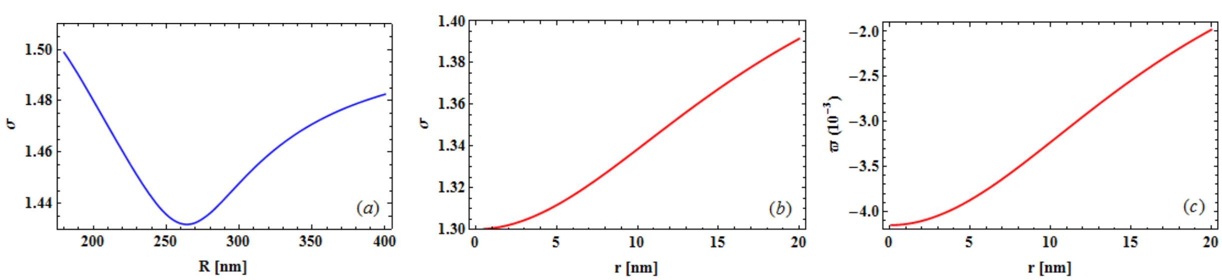

Fig. 3. (a) Modulation factor as function of the radius of the silicon nanowire at $\lambda = 1.55$ μm. (b) Modulation factor as function of the radius of the metallic wire at $\lambda = 1.55$ μm. (c) Plasmonic attenuation factor ϖ [7] as function of the radius of the metallic nanowire.

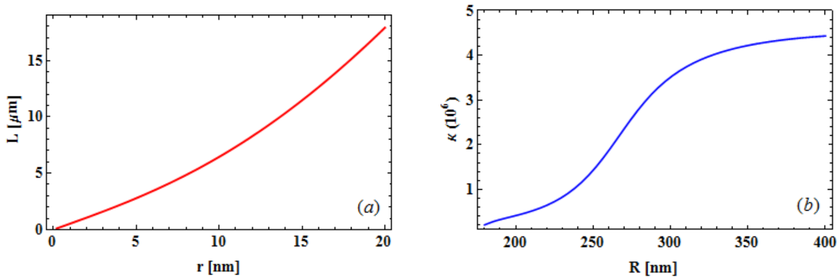

Fig. 4. (a) Propagation length of SPPs versus the radius of the metallic wire at $\lambda = 1.55$ μm . (b) Self-coupling term of the silicon guided mode.

Conclusions

In this work we have developed a theoretical model for the analysis of the coupling properties of a hybrid coupled system which is characterized by a silicon nanowire and a plasmonic wire. We have used cylindrical symmetries for the waveguides to obtain guided modes and to investigate the geometrical dependence. Coupling parameters like the Plasmonic attenuation factor and the modulation factor have been calculated to show the nanowire geometrical dependence of the coupling properties of a hybrid directional coupler.

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