Acta Universitaria
DIRECCIÓN DE APOYO A LA INVESTIGACIÓN Y AL POSGRADO

Energy transfer in a hybrid system caused by the excitation of ultrashort plasmonic pulses

Transferencia de energía en un sistema híbrido causada por la excitación de pulsos plasmónicos ultracortos

N. Lozano-Crisóstomo*, J. J. Sánchez-Mondragón*, D. A. May-Arrioja**, G. P. Agrawal***

ABSTRACT

In this paper we model and characterize the near infrared coupling between a plasmonic wire and a silicon nanowire. We also study the coupling parameters' dependence on the dimensions of the directional coupler nanowires.

RESUMEN

En este trabajo modelamos y caracterizamos el acoplamiento entre un nanoalambre metálico y una nanoguía de silicio, en el infrarrojo cercano. Hemos estudiado la dependencia de los parámetros de acoplamiento sobre las dimensiones de las nanoguías que conforman el sistema.

INTRODUCTION

There is no doubt that silicon photonics (Soref, 2006) and plasmonics (Barnes, Dereux & Ebbesen, 2003) have aroused an increasing interest in recent years. Its potential applications on the photonics industry for chip-scale integration have attracted much attention due to the recent progress in silicon-based photonics components, photonic integrated circuits, opto-electronic integrated circuits (Soref, 2008) and plasmonic optical devices (Gramotnev & Bozhevolnyi, 2010). In this work we research the geometrical dependence of the nanowires coupling properties of a hybrid directional coupler built by a silicon nanowire and a plasmonic wire, in close proximity of one another. We model and describe the whole system considering the large silicon material nonlinearity and the surface plasmon polaritons (SPPs') strong dissipation. We report the particular behavior of the coupling parameters with the dimensions of the nanowires.

Theoretical characterization

Recently, comprehensive theories have been developed to describe the propagation of near infrared light waves disseminating through silicon nanowires (Daniel & Agrawal, 2010) and plasmonic waveguides (Rukhlenko, Premaratne & Agrawal, 2011). Within the frame of the slowly varying envelope approximation, 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 herein we describe the propagation of light pulses in a hybrid coupled system. We develop a theoretical model based on recent work regarding silicon nanowires (Daniel & Agrawal, 2010), and plasmonic waveguides (Rukhlenko *et al.*, 2011) to research coupling

Recibido: 11 de noviembre de 2012
Aceptado: 14 de junio de 2013

Keywords:
Plasmonics; silicon photonics; directional coupler.

Palabras clave:
Plasmónica; fotónica del silicio; acoplador direccional.

*Optics Deparment, National Institute for Astrophysics, Optics and Electronics (INAOE). Apdo. postal 51 and 216, Tonantzintla, Puebla, México. 72000. E-mail: nestorlo@inaoep.mx; jsanchez@inaoep.mx
**Departamento de Electrónica, Universidad Autonoma de Tamaulipa. Reynosa, Tamaulipas, México. E-mail: daniel_may_arrioja@hotmail.com
***The Institute of Optics, University of Rochester, Rochester, New York, USA. River Campus, 500 Joseph C. Wilson, Blvd. Rochester, NY. 14627.

properties of the system (figure 1). We have coupled a silicon guided mode, 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. If there is a near-field interaction, light from the silicon nanowire can excite a surface plasmon at the metallic wire directly (Hochberg, Baehr-Jones, Walker & Scherer, 2004). The hybrid directional coupler supports only transverse magnetic (TM) optical modes. SPPs, which can only exist for the TM polarization (Maier, 2007), 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 (Raether, 1988).

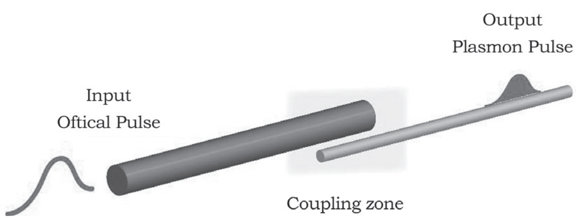

Figure 1. Schematic illustration of the hybrid directional coupler.
Source: Authors own elaboration.

We consider a system where the different regions are characterized by a set of constitutive parameters μ and ε, both, in general, frequency dependent. Therefore, 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 (Pfeiffer, Economou & Ngai, 1974). The material dispersion of silicon is well approximated by $n_1^2 = \mathrm{A} + \mathrm{B}/\lambda^2 + \mathrm{C}\lambda_1^2/(\lambda - \lambda_1^2)$, which is the modified Sellmeier equation, where $\lambda_1 = 1.1071\ \mu\mathrm{m}^2$, A = 11.6858, B = 0.939816 μm, and C = 8.10461×10^{-3}.

Before relation has a well behavior for wavelengths around 1.5 μm (Chen, Chen, Chuu & Brandes, 2009). For the conducting wire, we use the following well relation: $n_2^2 = n_\infty\ [1 - \omega_p^2/\omega\ (\omega + i/\tau)]$, where $n_\infty = 9.6$ (for Ag). The plasma energy ($\hbar\omega_p$)of bulk silver is 3.76 *eV*, and $\tau = 3.1\times10^{-14}$ is the relaxation time due to ohmic metal loss (Tong, Lou & Mazur, 2004).

By researching the silicon and the surface guided modes (Stratton, 1941), we can perform the numerical solutions of the complex mode index of the waveguides in regard to the radius of each one (figure 2).

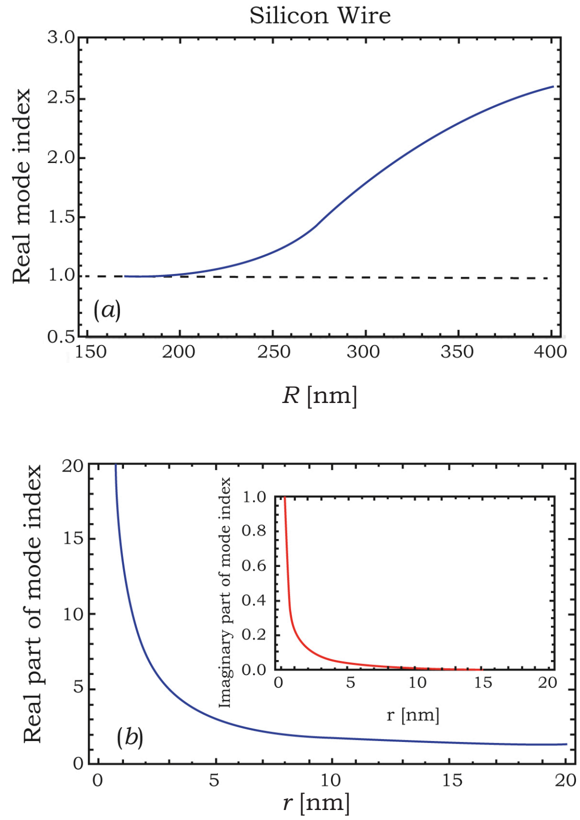

Figure 2. (a) Real mode index versus the radii of the silicon nanowire at $\lambda = 1.55\ \mu$m. The dashed line shows the critical value. (b) Complex mode index versus the radii of the metallic nanowire at $\lambda = 1.55\ \mu$m.
Source: Authors own elaboration.

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 *m*th mode, are added in the coupled-mode equations directly from the coupled-mode approach. They are given by

$$\kappa_m = (\mu_0\varepsilon_0\ /[2(\sigma_m + i\varpi_m)N_m])\int_0^{2\pi}\int_0^{\infty}\boldsymbol{e}_m^{*}\Delta n_m^2\,\boldsymbol{e}_m\,\rho d\rho d\phi,$$

where

$$\varpi_m = (\Im[\beta_m]/[2\omega_0\mu_0 N_m])\int_0^{2\pi}\int_0^{\infty}|\,e_{\rho m}|^2\,\rho d\rho d\phi,$$

is the Plasmonic attenuation factor previously defined (Hochberg *et al.*, 2004) and

$$\sigma_m = 1 + (\Re[\beta_m] / [2\omega_0 \mu_0 N_m]) \int_0^{2\pi} \int_0^{\infty} |\boldsymbol{e}_m|^2 \rho \, d\rho d\phi$$

is the new factor defined here, which represents a modulation factor. Here $\mathbf{e}_m$ is the mth TM linear electric mode structure in the absence of other guided modes, is, β_m in general, the 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 refractive index due to the presence of the mth guide mode.

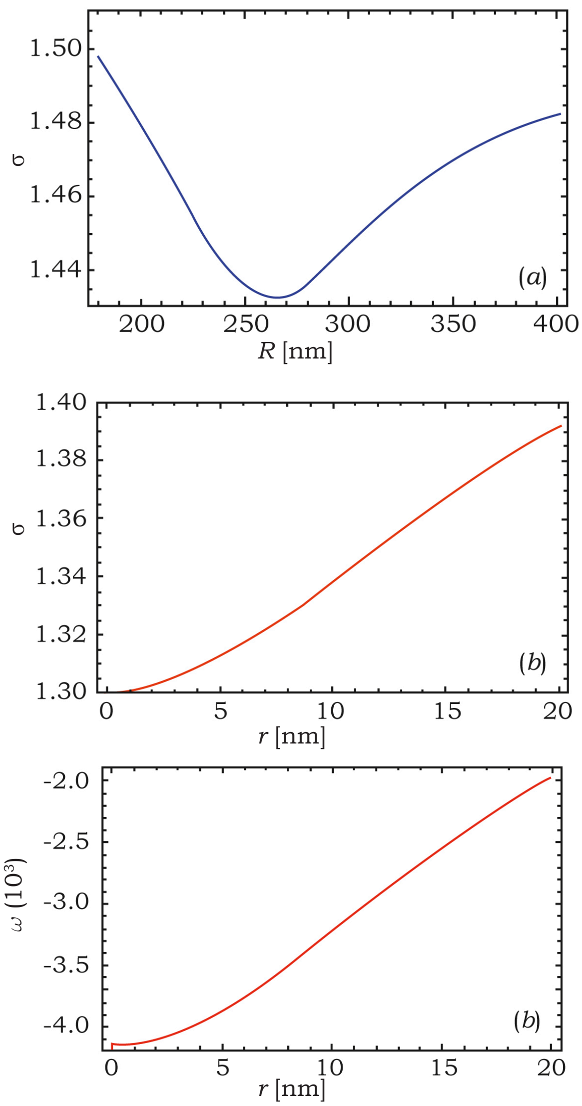

Figure 3. (a) Modulation factor as function of the radius of the silicon nanowire at λ = 1.55 μm. (b) Modulation factor as function of the radius of the metallic wire at λ = 1.55 μm. (c) Plasmonic attenuation factor ϖ_m (Rukhlenko *et al.*, 2011) as function of the radius of the metallic nanowire.

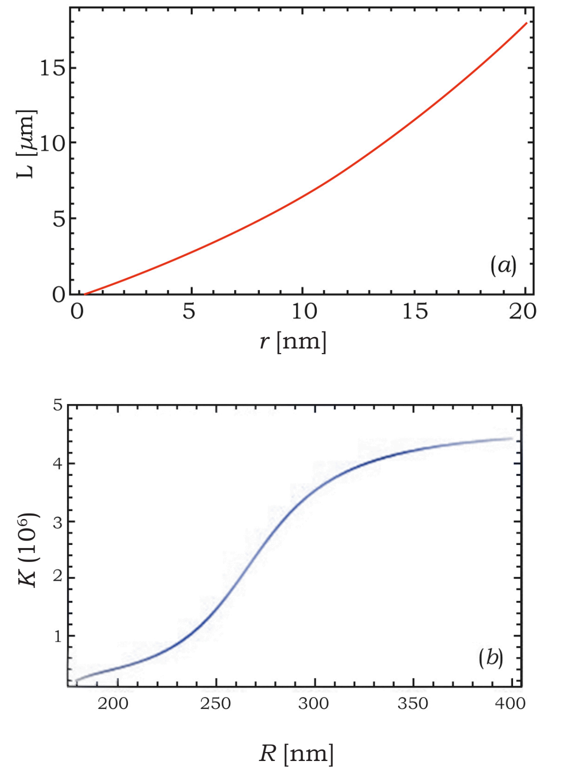

Figure 4. (a) Propagation length of SPPs versus the radius of the metallic wire at λ = 1.55 μm. (b) Self-coupling term of the silicon guided mode.
Source: Authors own elaboration.

CONCLUSION

In this paper 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.

ACKNOWLEDGMENT

N. Lozano-Crisóstomo expresses a special thanks to the *Consejo Nacional de Ciencia y Tecnología* (Conacyt) for his graduate scholarship number 235214, and to his advisers Profs. G. P. Agrawal and J. J. Sánchez-Mondragón for his guidance and considerations. This research was supported by Conacyt under contract CB-2008/101378. He also acknowledge to the *Secretaría de Educación Pública-Subsecretaría de Educación Superior-Dirección General de Educación Superior Universitaria* project 2012-01-21-002-205 and (Conacyt) project 000000000189688 for supporting the LAOP Workshop 2012, where this work was presented.

REFERENCES

Barnes, W. L., Dereux, A. & Ebbesen, T. W. (2003). Surface Plasmon Subwavelength Optics. *Nature, 424*(6950), 824-830.

Chen, Y. N., Chen, G. Y., Chuu, D. S. & Brandes, T. (2009). Quantum-dot exciton dynamics with a surface plasmon: Band-edge quantum optics. *Physics Review A, 79*(3), 033815.

Daniel, B. A. & Agrawal, G. P. (2010). Vectorial nonlinear propagation in silicon nanowire waveguides: polarization effects. *Journal of the Optical Society of America B, 27*(5), 956-965.

Gramotnev, D. K. & Bozhevolnyi, S. I. (2010). Plasmonics beyond the diffraction limit. *Nature Photonics, 4*(2), 83-91.

Hochberg, M., Baehr-Jones, T., Walker, C. & Scherer, A. (2004). Integrated plasmon and dielectric waveguides. *Optics Express,12*(22), 5481-5485.

Maier, S. A. (2007). *Plasmonics: Fundamentals and Applications.* New York: Springer.

Pfeiffer, C. A., Economou, E. N. & Ngai, K. L. (1974). Surface polaritons in a circulary cylindrical interface: Surface plasmons. *Physics Review B,10*(8), 3038-3051.

Raether, H. (1988). *Surface Plasmons.* Berlin: Springer.

Rukhlenko, I. D., Premaratne, M. & Agrawal, G. P. (2011). Nonlinear propagation in silicon-based plasmonic waveguides from the standpoint of applications. *Optics Express, 19*(1), 206-217.

Soref, R. A. (2006). The past, Present, and Future of Silicon Photonics. *IEEE Journal of Selected Topics in Quantum Electronics, 12*(6), 1678-1687.

Soref, R. A. (2008). The achievements and Challenges of Silicon Photonics, invited lead article. *Advances in Optical Technology*, *2008* (Special issue on Silicon Photonics), *ID 472305*.

Stratton, J. A. (1941). *Electromagnetic Theory.* New York: McGraw-Hill.

Tong, L., Lou, J. & Mazur, E. (2004). Single-mode guiding properties of subwavelength-diameter silica and silicon wire waveguides. *Optics Express, 12*(6), 10525-1035.