Properties of Highly-Nonlinear Hybrid Silicon-Plasmonic Waveguides

Alexandros Pitilakis[1] and Emmanouil E. Kriezis[1]
Department of Electrical and Computer Engineering, Aristotle University of Thessaloniki, Thessaloniki 54124, Greece

Nonlinear hybrid silicon-plasmonic (HSP) waveguides are comprised of a low-index dielectric with a high nonlinear-index (n_2) occupying the area between a metal and a high-index dielectric, i.e. silicon. Fusing plasmonic and index-contrast guiding mechanisms [1], HSP waveguides can increase the lateral confinement thus boosting the nonlinear parameter (γ); this effect is maximized as the gap between metal and silicon reaches the 10nm-scale and can be exploited in practical integrated circuits. The HSP design incorporates silicon so as to maintain fabrication-compatibility and seamless coupling to the dominant silicon-on-insulator (SOI) platform. However, silicon exhibits two-photon absorption (TPA) below λ=2200nm, which increases the losses and additionally generates free-carriers which, in turn, give rise to secondary nonlinear free-carrier effects (FCE) [2]. The temporal dynamics of FCE are in the 1ns-scale and, above a certain power-threshold, they induce considerable dispersion and absorption (FCD and FCA, respectively) perturbing the guided wave. Both TPA and FCA absorb power thus hindering all $\chi^{(3)}$-related effects as a whole while FCD counteracts the Kerr-effect and thus imposes an obstacle for this type of nonlinear applications in compact integrated photonic components.

In order to take advantage of the ultimate HSP confinement, an inverted metal-wedge [3] laterally aligned with an underlying SOI-wire waveguide is proposed. Acute silver-wedges with a sub-nm tip-curvature radius can lead to a remarkable increase in γ when a highly-nonlinear material, such as the DDMEBT polymer [4], fills the nano-sized gap. Evidently, this blend of distinct materials and sharp features incorporated in the HSP waveguide requires for a rigorous treatment: a set of figures-of-merit is established and used to optimize the proposed waveguide, resulting in an extremely high $\gamma>10^4$ $m^{-1}W^{-1}$ delivered on the length-scale of $L_{pr}\approx 30\mu m$ (for a DDMEBT gap of 20nm, Si-wire of 200×220nm^2, Ag-wedge of 100nm-height, 52^o-angle and 1nm-tip-radius), Fig. 1(a). Additionally, the FCD power-threshold is increased above 1W, even in the CW regime where FCE are strongest. Thus, apart of the manifestation of nonlinear effects at propagation lengths of few tens of microns, the high FCD power-threshold is a comparative advantage of wedge-HSP over SOI wires or nonlinear-slot guides and it is attributed to the small fraction of the optical field penetrating Si areas.

The increase of the FCE power-threshold can allow for higher-powers in Si-based integrated waveguides. By means of an iterative self-consistent eigenmode solver approach (SCEMS) [5], we show that as the optical power increases beyond ~0.1W, the mode profile of the highly nonlinear wedge-HSP guide undergoes a non-negligible change due to self-focusing. This change is subsequently reflected on the various parameters, as rigorously extracted for the vectorial nonlinear Schrödinger equation (NLSE) formulation [2]. For this HSP waveguide and for a peak-power of 4W, γ drops by 8% while the TPA-ratio increases by 12%, Fig. 1(b); the dispersion characteristics are also altered. This subtle but important aspect that stems from the nearly-instantaneous self-focusing can affect the overall nonlinear behavior in both pulsed and CW high-power regimes, Fig. 1(c).

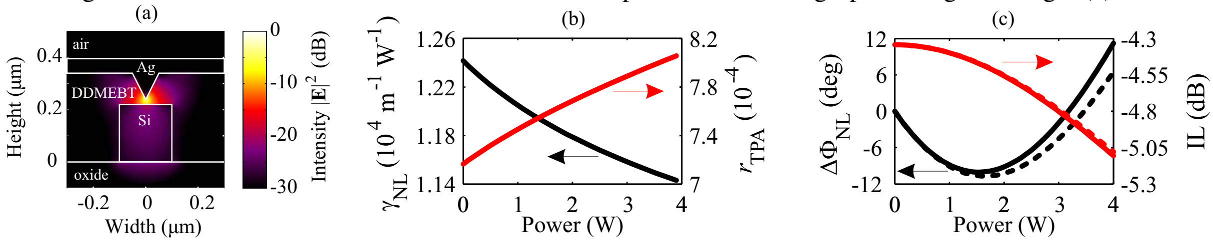

Fig. 1. (a) Intensity-distribution of the TM_{00} eigenmode of the HSP waveguide. (b) SCEMS-calculated nonlinear parameter and TPA-ratio dependence on the optical power. (c) NLSE-calculated nonlinear phase-shift and insertion losses vs. CW-power at the output of a 30μm-long HSP waveguide, with (solid) and without (dashed) the power-dependence of the nonlinear parameters. Negative or positive values of $\Delta\Phi_{NL}$ indicate a domination of Kerr-effect or FCD, respectively.

This research has been co-financed by the European Union (European Social Fund, ESF) and Greek national funds through the Operational Program “Education and Lifelong Learning” of the National Strategic Reference Framework (NSRF) – Research Funding Program: Heracleitus II.

References

[1] M. Wu, Z. Han, V. Vien, “Conductor-Gap-Silicon Plasmonic Waveguides and Passive Components at Subwavelength Scale,” *Opt. Express*, **18**, 11728-11736, (2010).
[2] B. A. Daniel and G. P. Agrawal, “Vectorial Nonlinear Propagation in Silicon Nanowire Waveguides: Polarization Effects,” *J. Opt. Soc. Am. B*, **27**, 956-965, (2010).
[3] Y. Bian, Z. Zheng, Y. Liu, J. Liu, J. Zhu and T. Zhou, “Hybrid Wedge Plasmon Polariton Waveguide with Good Fabrication-Error-Tolerance for Ultra-Deep-Subwavelength Mode Confinement,” *Opt. Express*, **19**, 22417-22422, (2011).
[4] C. Koos *et al.*, “All-Optical High-Speed Signal Processing with Silicon-Organic Hybrid Slot Waveguides,” *Nat. Photonics*, **3**, 216-219, (2009).
[5] T. Fujisawa and M. Koshiba, “Finite Element Characterization of Chromatic Dispersion in Nonlinear Holey Fibers,” *Opt. Express*, **11**, 1481-1489, (2003).

978-1-4799-0594-2/13/$31.00 ©2013 IEEE