Hybrid Electro-Optical Pumping of Plasmonic Nanostructures with Gain

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Abstract - **We propose to pump active plasmonic devices, such as plasmonic amplifiers, lossless plasmonic waveguides and nanolasers, simultaneously electrically and optically (hybrid pumping). We show that such a pumping method results not only in a higher modal gain but also in an improved control over the spatial profile of optical gain in the device, which allows to reduce amplification noise, enhance flexibility, and enable new regimes of operation.**

Index terms **- electrical pumping, optical pumping, hybrid pumping, active plasmonics, plasmonic amplifiers, plasmonic nanolasers, amplification noise.**

Plasmonics offers the possibility to overcome the diffraction limit of light by using surface plasmon polaritons (SPPs) and design deep-subwavelength waveguides, detectors and optical sources [1]. However, the practical applications of nanoplasmonics are plagued by high ohmic loss in metals. State-of-the-art techniques of metal film deposition allow one to push the ohmic loss down to its theoretical limits, yet, the propagation distance of highly-localized SPP waves in the visible and near-infrared spectral range remains limited to dozens of micrometers. To overcome this limitation, one has to increase the propagation distance by compensating the ohmic loss through the stimulated emission in a gain medium overlapping with the SPP mode. To achieve optical gain, one can pump the active region either optically [2–4] *or* electrically [5–7], and the last decade witnessed remarkable progress in this direction. At the same time, the case of simultaneous optical and electrical pumping remains unexplored, as well as the potential benefits offered by such an approach.

Here, we propose and study simultaneous optical and electrical pumping of active plasmonic nanostructures. We find that such hybrid pumping not only allows one to achieve the modal gain higher than any type of pumping can give by itself but also allows for fine control over the spatial distribution of gain, which is vital for overcoming spontaneous emission noise limitations in plasmonic devices with gain.

To demonstrate the proof of principle, we investigate the properties of hybrid pumping on a simple structure: a planar plasmonic waveguide composed of the 2-μm-thick p-type InAs layer on gold (Fig. 1a). The waveguide supports an SPP mode propagating along the metal-semiconductor interface. The thickness of the InAs layer is twice the penetration depth of the SPP into InAs, which is enough to guarantee that the SPP electromagnetic field does not interact with the top contact (Fig. 1b). To avoid excessive complexity and investigate the fundamental properties of the hybrid pumping, we assume the top contact to be an ideal ohmic contact, which might be realized by using a transparent electrode [8]. However, we note that the use of a heterojunction is more practical [9]. The structure is pumped electrically by applying the forward bias to the Au/InAs Schottky barrier diode. In addition, it is also pumped optically. As a result, free electrons and holes populate the semiconductor layer giving rise to an optical gain, which can compensate for the propagation losses of the SPP or even amplify it [7]. The operating free-space wavelength of 3.26 μm is dictated by the bandgap energy of InAs, or, more precisely, is close to a maximum of InAs material gain spectrum [10].

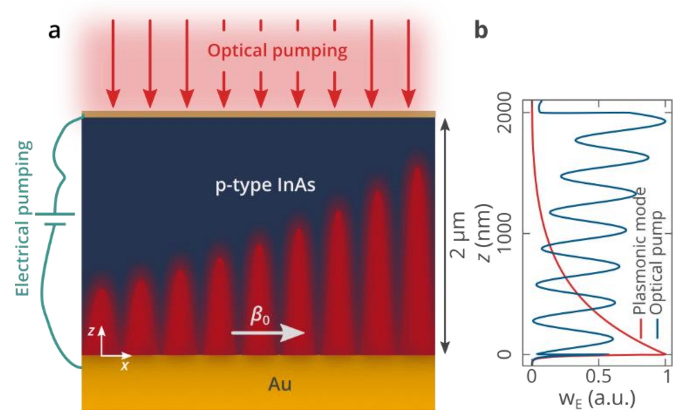

Fig. 1. (a) Schematic view of a planar plasmonic waveguide pumped both electrically and optically. (b) Spatial dependence of the electric energy density (w_E) in the SPP wave and the optical pump laser beam.

The transport of the charge carriers through the structure is studied by solving self-consistently a set of equations comprising the Poisson equation for the electrostatic field, drift-diffusion, and continuity equations. In addition to the spontaneous emission recombination and Auger recombination, we include two spatially-dependent stimulated emission recombination terms representing optical pumping and the amplification of the transmitted signal. We stress out that the optical gain is produced by minority carriers (electrons), which appear in InAs due to both injection from the Au layer through the Schottky barrier and generation of electron-hole pairs by optical pumping: $g\big(n(z),p(z)\big) \approx g(n(z),p_0)$, where $n(z) = H\big(J, P_{pump}, P_{SPP}, z\big)$ is a function of the pump current J, optical pump power P_{pump}, and SPP signal power P_{SPP}. Due to the influence of the optical pumping process and the non-zero SPP signal power on the spatial distribution of electrons and the current through the structure *J*, the problem cannot be treated as a simple linear superposition of independent electrical pumping and optical pumping, and, therefore, it is necessary to solve the problem self-consistently. Since most commercial software packages do not allow to do this, we employ a self-written code [8].

Based on the determined charge carriers distributions, we calculated the material gain profile, and, finally, the modal gain of SPPs as a function of electric current and optical pump power [8]. Figure 2 shows that it is possible to achieve net amplification in the hybridly pumped waveguide even when the power density of the transmitted signal is high. When applied together, optical and electrical pumping provide higher modal gain than pure optical or electrical pumping. For moderately high modal gain values, hybrid pumping adds another degree of freedom, thereby enhancing the flexibility for practical applications. For example, while the optical pump power density cannot be varied locally, an additional small pump current allows one to finely tune the modal gain in the desired part of the large scale plasmonic circuit. This can be used to reconfigure the circuit by efficiently turning parts of the circuit on/off. Another exciting feature is the possibility to decrease the spontaneous emission noise by longitudinal redistribution of gain along the waveguide. Previously, we have shown that even slight variations of modal gain allow up to a 2-fold decrease in noise power, which results in tremendous improvement of signal transmission reliability in terms of bit error ratio (BER) [11].

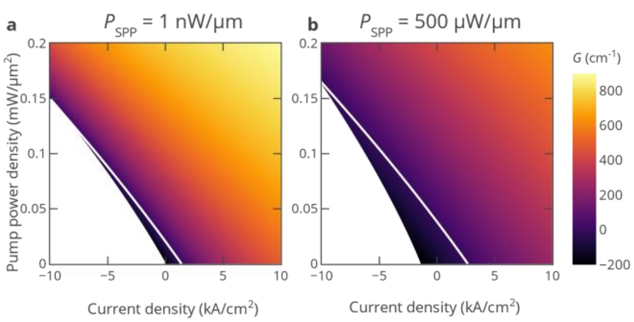

Fig. 2. SPP modal gain as a function of the pump current density and the optical pump power density calculated at low (1 nW/μm, panel a) and high (500 μW/μm, panel b) powers of the SPP signal. The white line in both panels corresponds to the regime of lossless SPP propagation.

Interestingly, when the current density is negative, the power source does negative work, which means that the battery that powers the SPP amplifier accumulates energy, i.e., it is charged. As can be seen from Fig. 2, net SPP amplification can be reached even in the charge mode, and, therefore, recharging can be done during the device operation. Such a property can be attractive for bio-related optoelectronics.

In conclusion, we have shown that the hybrid pumping of plasmonic structures is a feasible approach for SPP amplification with several advantages, including higher modal gain, flexible control over local gain, lower amplification noise, and rechargeability. These findings provide new insights into the development of active plasmonic devices.

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