Nonlinear Plasmon-Polaritons

Ilya Shadrivov
Nonlinear Physics Centre, Research School of Physics and Engineering,
Australian National University, Canberra ACT 0200 Australia

Recent advances in the study of light localization and guiding in metal-dielectric structures demonstrate a strong potential of surface plasmon polaritons for nanoscale light manipulation, with further perspectives for subwavelength all-optical devices [1]. Tight confinement of the electromagnetic energy and field enhancement in plasmonic systems can be employed for efficient nonlinear interactions. Here we will focus our studies on the third and second order nonlinear processes, demonstrating that by using tapered metal-dielectric-metal slot waveguide one can mitigate the effect of losses for enhanced nonlinear interaction. We predict that by carefully designing the slot waveguides one can also achieve phase-matching required for second harmonic generation (SHG) and parametric amplification.

Plasmon self-focusing in tapered slot waveguides. Among various methods of light focusing in plasmonic structures, the tapering of plasmonic waveguides was suggested as one of the most efficient and promising approaches [2,3], which allows creating light spots much smaller than the operating wavelength. Recent studies of tapered plasmonic slot waveguides revealed that at certain tapering angles the amplitude of a plasmon mode at the metal-dielectric interface may increase, effectively overcoming losses in the system [4]. We study nonlinear transverse self-action of plasmon beams propagating in tapered metal-dielectric-metal waveguides with the Kerr-type nonlinear dielectric. We demonstrate that in contrast to the light focusing in straight waveguides, an appropriate choice of the taper angle allows an effective compensation of attenuation with the formation of spatial plasmon-soliton. For larger tapering angles, we observe significant soliton narrowing leading to three-dimensional spatial light nanofocusing.

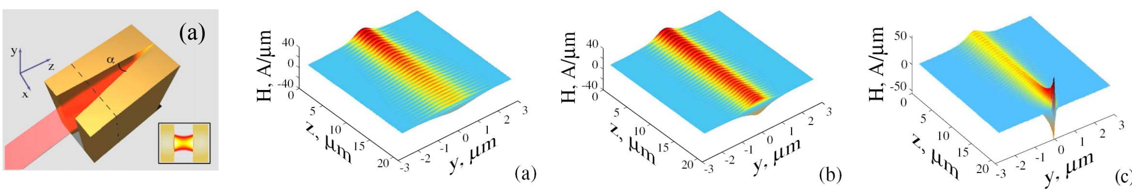

Fig. 1 (a) Schematic of a three-dimensional plasmon mode focusing in a tapered metal-dielectric-metal slot waveguide. Focusing occurs in the horizontal plane, due to a taper, and in the vertical plane, due to the nonlinear self-action; Variation of the magnetic field in the nonlinear slot waveguide for three different values of the tapering angle: (b) below optimal, 0.8deg (c) near optimal 1.2deg and (d) above optimal 1.6deg.

First, we consider linear two-dimensional tapered waveguides. Assuming an adiabatic change of the waveguide width along plasmon propagation, we apply the slowly-varying envelope approximation and describe analytically the evolution of the plasmon amplitude at the metal-dielectric interface.

$$\frac{d(|A|^2\,\zeta)}{dz}+\Gamma\,|A|^2=0, \qquad (1)$$

where A is the plasmon amplitude, $\zeta=\int E_x H_y dx$ is the normalized energy flow in the eigenmode, $\Gamma=\int \varepsilon''(E_x^2+E_z^2)dx$ describes the losses in the system, and ε'' is the imaginary part of permittivity across the structure ($\varepsilon''=0$ in the slot).

According to Eq. (1), effective losses are described by $d\zeta/dz+\Gamma$. Noticing that the value ζ, corresponding to the eigenmode energy flow capacity, decreases with the decreasing slot width, which corresponds to the effective compensation of amplitude decay due to tapering. We find the optimal shape of a taper, for which the amplitude of the plasmon mode remains constant, corresponding to the effective loss compensation [5]. It appears that the shape of this optimal taper is well described as a linearly tapered waveguide with some optimal angle $\alpha_{opt}=1.1\deg$. For the tapering angles larger than α_{opt}, we observe the plasmon nanofocusing close to the taper tip, as was originally predicted in Ref. [4]. In the three-dimensional case, nanofocusing is not achieved due to diffraction of plasmonic beams in the transverse dimension. It is well known that the beam diffraction can be compensated by the beam self-action in Kerr nonlinear media, and at certain conditions the spatial solitons may be formed [6-7].

For the study of nonlinear tapered plasmonic slot waveguides, we apply the slowly varying approximation and derive the effective nonlinear Schrödinger equation with the coefficients varying with plasmonic beam propagation, depending on the tapering angle [8]:

$$A_{yy}I+2jA_z\zeta+j(\zeta_z+\Gamma)A+N\,|A|^2\,A=0\,, \qquad (2)$$

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where A is the slowly varying amplitude, the indices y,z define the corresponding partial derivatives; $I=\int (E_x^2+E_z^2)dx$, $\zeta=\int E_x H_y dx$, $\Gamma=\int \varepsilon''(E_x^2+E_z^2)dx$, $N=\int \eta(E_x^2+E_z^2)^2 dx$ are effective plasmon intensity, z-component of Poynting vector, losses and nonlinear coefficient, respectively, **E** and **H** are electric and magnetic fields of the guided mode.

We solve this equation by the beam propagation method, and study the soliton propagation in the taper for three different tapering angles, i.e. below optimal angle, near optimal angle, and larger than the optimal angle. For the soliton launched in a tapered waveguide with the angles below the optimal tapering angle, Fig. 1(b), we observe the dynamics similar to the beam propagation in planar nonlinear waveguides where the plasmon beam broadens due to strong losses present in the system [6-7]. For the tapering angles close to the optimal angle, Fig. 1(c), we find that the losses can be effectively compensated due to tapering, so that the plasmon beam launched into the system propagates practically without a change of its shape [8]. We find that in this way the soliton beam can propagate for up to 20 µm.

Finally, we consider the beam propagation in the tapers with the tapering angles larger than the optimal angle, see Fig. 1 (d). In this case, the beam width narrows with propagation, and the energy becomes focused in the lateral dimension as well, causing the plasmon amplitude to increase even more than being expected in the two-dimensional case [4]. Therefore, the energy focusing due to tapering and spatial beam narrowing with nonlinear amplitude concentration can be observed simultaneously [8].

Parametric frequency conversion with plasmons. We study parametric plasmon-plasmon interaction in metal dielectric structures with second order nonlinear dielectric for the example of lithium niobate. We investigate the problem theoretically and derive a set of equations showing the possibility of plasmonic second harmonic generation [9]:

$$A_1' = -\alpha_1 A_1 + j\Gamma_1 A_1^* A_2 e^{j\Delta\beta z} \qquad A_2' = -\alpha_2 A_2 + j\Gamma_2 A_1^2 e^{-j\Delta\beta z}, \qquad (3)$$

where $A_{1,2}$ – complex amplitudes of plasmons at fundamental and second harmonics, $\Gamma_{1,2}$ – effective nonlinear coefficients, $\alpha_{1,2}$ – effective losses on the system, $\Delta\beta$ – phase mismatch, and prime denotes z-derivative.

For slot waveguide geometries, schematically shown in Fig.2 (a), we observe the phase-matching condition between symmetric and antisymmetric modes, shown on Fig.2 (b). Our analysis reveals that such type of conversion is possible for slot waveguides due to the tensor properties of the nonlinear dielectric susceptibility. We find that the phase matching condition is frequency-dependent, and it can be tuned for different frequencies by the appropriate choice of the slot width. The efficiency curve Fig.2 (c) displays a characteristic interplay between the SH generation and losses, which manifests itself a maximum of the conversion efficiency at approximately 15µm.

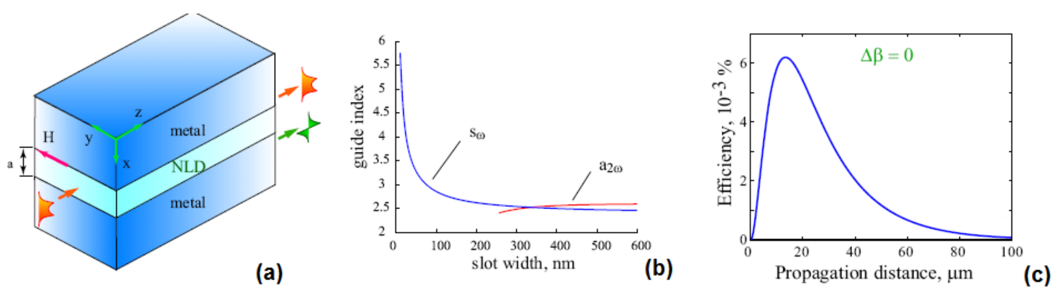

Fig.2. Second-harmonic generation in a nonlinear slot waveguide. (a) Schematic of the structure. (b) Dependence of the wavenumbers of plasmons on the fundamental frequency (blue) and second harmonics (red) on the slot width. Intersection indicates the phase-matching condition. (c) Efficiency of the second-harmonic generation as a function of the propagation distance.

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