Experimental demonstration of plasmon-soliton waves

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Abstract: We report the experimental observation of plasmon-soliton waves. The demonstration is performed in a chalcogenide-based four-layer planar geometry. It reveals a plasmon-enhanced Kerr self-focusing undergone by a TM polarized beam propagating inside the structure.
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Merging the fields of plasmonics and nonlinear optics authorizes a variety of fascinating and original physical phenomena. In this study, we specifically investigate the combination of the strong light confinement of surface plasmon polaritons (SPP) with the beam self-trapping effect in nonlinear optical Kerr medium. Although this idea of plasmon-soliton wave has been the subject of several theoretical papers [1-4], no experimental evidence had yet been revealed. Among the practical challenges inherent to this plasmon assisted self-focusing are the large propagation losses associated with plasmons, the request for a strong Kerr coefficient and the limitations due to the damage threshold intensity of the structure. In the present study, a proper architecture has been studied and fabricated allowing the first experimental observation of hybrid plasmon-soliton waves.

To be able to trigger the nonlinearity at moderate light power and simultaneously allow propagation over several millimeters distance, a metal-dielectric structure was designed [5]. It consists of a four–layer planar geometry made of a transparent Kerr dielectric layer placed on a lower refractive index medium with a thin top dielectric layer covered by a metallic film. For our structure the Kerr medium is a 3µm thick chalcogenide film ($Ge_{28.1}Sb_{6.3}Se_{65.6}$) with a high refractive index deposited by RF magnetron sputtering on an oxidized silicon substrate. Note that this waveguide structure was previously used to demonstrate the formation of spatial solitons [6] thanks to the large third order nonlinearity of the chalcogenide glass. To exploit the plasmonic effect, part of the structure is then covered with a thin 10nm SiO_2 layer and a 30nm thick gold layer. Samples are 5.5 mm along propagation direction.

Performed numerical simulations show that the designed plasmonic structure (PS) supports a fundamental TE mode profile at NIR wavelengths whose transverse profile along X-axis (perpendicular to the layers) is not affected by the metal layer while the TM mode is clearly confined at the SiO_2-metal-chalcogenide interfaces due to the plasmonic effect. In nonlinear regime, this dissimilarity gives an eightfold enhancement of the effective nonlinearity parameter for the TM mode compared to the TE mode.

Optical characterizations are performed with an optical parametric oscillator generating 200 fs pulses at 1550nm at a repetition rate of 80 MHz (Fig. 1a). The experimental analysis consists in injecting a typical 4×31 µm^2 (FWHM) elliptical laser beam into the waveguide. At low power, the beam diffracts along Y-axis to about 40 µm at the exit face independently of light polarization or waveguide structure. This output beam profile evolution is then monitored versus light power.

Different arrangements are tested to unambiguously reveal the distinctive nonlinear self-focusing enhancement in presence of the plasmon-soliton wave. In particular, experiments are conducted with and without the metallic layer and for both TE and TM polarizations. In addition, several PS dimensions and locations along propagation in the sample are considered. As an example, Fig. 1b-g presents the self-focusing behavior observed at the exit face of the 5.5 mm long sample for two different input intensities. Fig. 1b,c depicts the behavior of a TM polarized beam but without any PS along the travelling path. In this case, a standard self-focusing effect that leads to a spatial soliton [6] for an intensity near 0.62 GW/cm^2 is observed. Once a 660µm long PS is present before the exit face of the sample, the TM polarized beam now experiences an enhanced self-focusing (Fig 1d-e). Indeed, at the moderate input intensity of 0.62 GW/cm² (Fig. 1d) the output mode profile reaches a FWHM of 19.2 µm that is much narrower than the 30µm width observed without PS (Fig. 1b). Further increase of the input intensity to 1.17 GW/cm² leads to a more efficient trapping as witnessed by the beam size of of 12 µm in Fig. 1e. This typical result illustrates the presence of the hybrid plasmon-soliton wave that benefits from an enhanced self-focusing nonlinearity. Note that such behavior is not observed when the light polarization is set to TE (Fig. 1 f,g) as expected from theory.

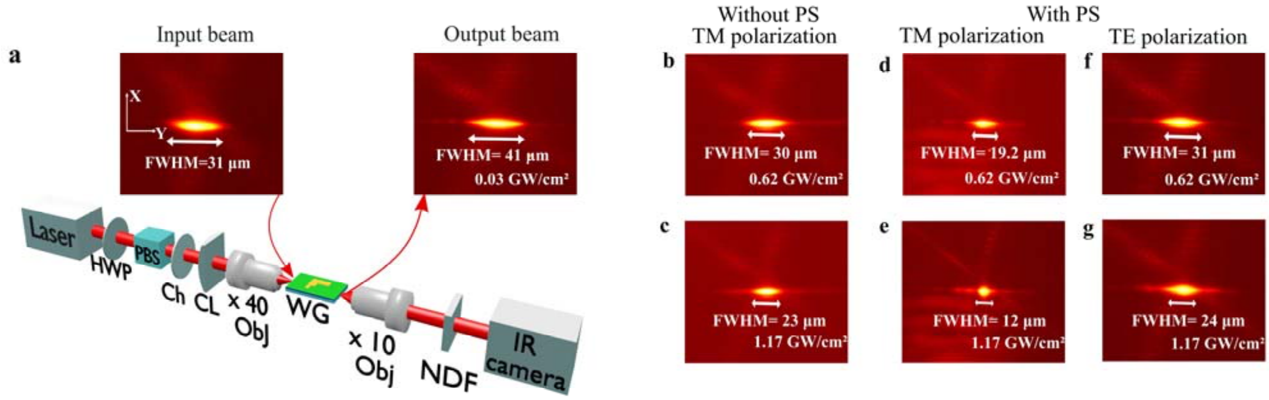

Figure.1: a, Experimental setup used for the observation of the plasmon-soliton wave and intensity distribution of the injected and output beam in linear regime. HWP; half wave plate, PBS; polarizing beam splitter, Ch; chopper, CL; cylindrical lens, Obj; microscope objective, NDF; neutral density filters. b-g, Intensity distribution of self-focused output beams for two input intensities without PS (b,c) and with a 600µm long PS located before the exit face for TM polarization (d,e) and for TE polarization (f,g).

To conclude, a compelling spatial confinement of a TM polarized plasmon-soliton wave has been reported in a Kerr plasmonic structure. The designed structure consists of a slab waveguide made of a highly nonlinear chalcogenide layer covered with nanolayers of silica and gold. The thickness of the silica layer has been tailored to benefit from the enhanced self-focusing effect due to the high-intensity plasmon while limiting the detrimental effect of propagation losses induced by the metal. Experimental observations are confirmed by numerical predictions obtained using an improved model of nonlinear propagation combining FEM modal results and spatial nonlinear Schrödinger equation.

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