Giant nonlinear optical enhancement in chalcogenide glass fibers with deep-subwavelength metallic nanowires

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Abstract: A nanostructured chalcogenide-metal optical fiber is proposed. This hybrid nanofiber enables both very strong field confinement and extreme nonlinear light-matter interactions, much larger than a bare chalcogenide nanowire of comparable diameter.
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OCIS codes: (060.2390) Fiber optics, infrared; (190.4370) Nonlinear optics, fibers; (240.6680) Surface Plasmons

1. Introduction

Recent advances in micro and nano-fabrication techniques have sparked considerable research on microstructured optical fibers with subwavelength features, and using new materials such as high refractive index compound glasses. These so-called *emerging waveguides* allow the exploration of new operation regimes where tight field confinement, enhanced light-matter nonlinear interactions and dispersion engineering can combine to enable long interaction lengths inside nonlinear media [1]. In parallel, the integration of plasmonics with fiber optics has shown immense potential for the transmission and modulation of optical signals on the subwavelength scale [2].

In this paper, we present a new type of nonlinear metallo-dielectric nanostructured optical fiber (NOF): the chalcogenide fiber with deep-subwavelength metallic inclusions. We demonstrate that the extreme field intensities obtained at the tips of the subwavelength metallic inclusions enable giant nonlinear optical enhancements to be achieved with this chalco-metallic NOF. In order to attain such high nonlinearities, acute light-metal interaction is necessary and we show there is a trade-off in the form of high ohmic absorption losses.

2. Geometry and modal properties of chalco-metallic fibers

When fabricating a fiber comprising several dielectric rods (or capillaries) using the stack-and-draw procedure, the empty interstitial holes that may occur between adjacent rods are usually treated as unwanted defects. Here we fill these nanovoids with metal such that the intense fields localized at the sharp tips of the triangle-shaped metallic nanowires enhance the nonlinear light-matter interaction inside the chalcogenide glass matrix (Fig. 1). In this regard, a practical method for fabricating metal nanowires embedded in chalcogenide glass was recently demonstrated [3].

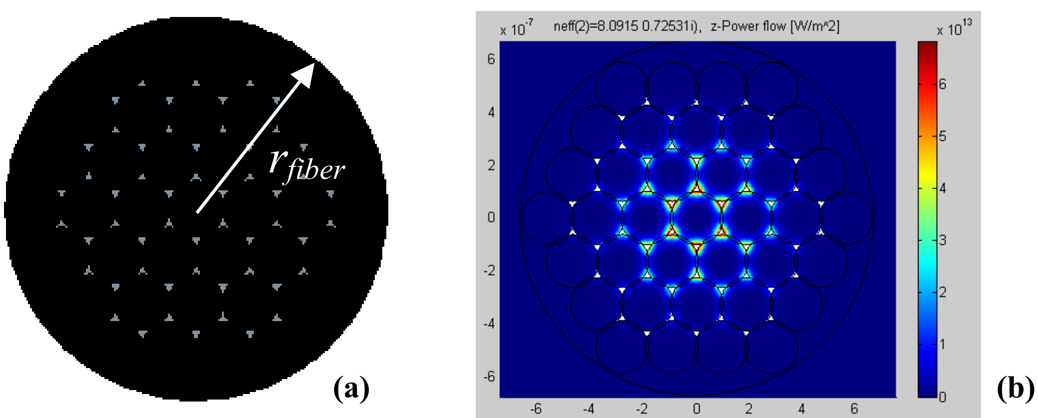

Fig. 1 (a) Refractive index map, and (b) S_z - distribution of the fundamental HE_{11}-like plasmonic supermode inside a chalco-metallic fiber (r_{rod} = 0.100 μm) at λ=3.0 μm

The chosen metal is gold (Au) while the dielectric material is As_2Se_3 chalcogenide glass because of its large bulk transmission window inside the middle-infrared (2 - 14 μm) and its large nonlinear index value: $n_2 = 1.1 \times 10^{-17}$ m^2/W. Since the proposed NOF is operated inside the mid-IR, far from the surface plasmon resonances of noble metals that usually occur in the visible spectrum, the transmission spectrum of the NOF is free from sharp absorption bands.

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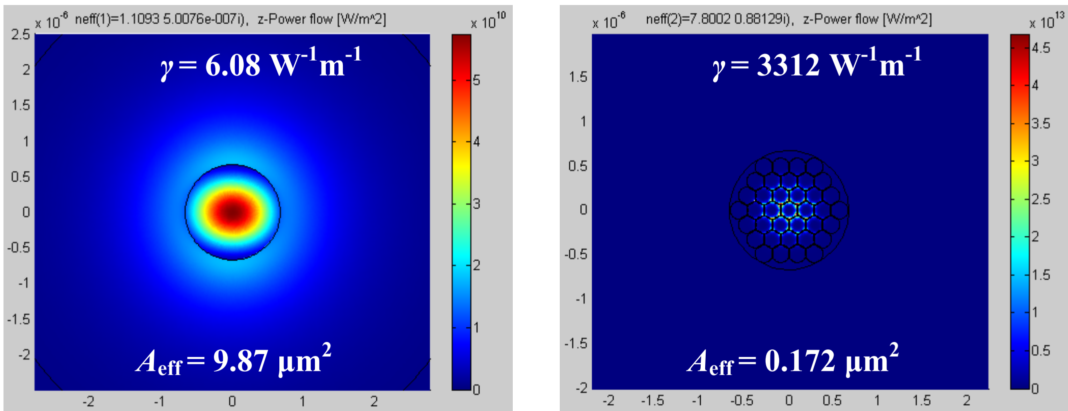
3. Field confinement and nonlinear properties of chalco-metallic fibers

The wavelength of interest in the present study is λ=3.0 µm, and to simplify analysis the investigation focuses on the case of N = 3 layers of rods (of equal radiuses r_{rod}) with gold-filled interstices. Using fully vectorial finite-element simulations, we first sought to find the cut-off fiber radius ($r_c \cong 0.670$ µm) of the first higher-order HE mode (HE_{21}) for the reference case of the As_2Se_3 nanowire (i.e. rod-in-air) in an infinite air cladding (Fig. 3). By comparing the bare nanowire to a chalco-metallic NOF of the same diameter (Fig. 2) at a longer mid-IR wavelength λ=6.0 µm, one can appreciate the exceptionally strong field confinement in chalco-metallic fibers [Fig. 2(b)]; whilst in the case of the nanowire power leakage into the surroundings is very significant [Fig. 2(a)].



(a) (b)

Fig. 2 Fundamental mode S_z distribution at λ=6.0 µm in (a) As_2Se_3 nanowire, and in (b) a chalco-metallic NOF of same radius r_{fiber} = 0.67 µm

In Fig. 3 we demonstrate that the As_2Se_3-gold chalco-metallic fibers yield an effective area that is more than 50 times smaller than a comparable nanowire, as well as nonlinearities γ>10 000 W^{-1}m^{-1} at λ=3.0 µm, corresponding to enhancement factors greater than 100 of the nonlinear parameter (γ) compared to nanowires of the same diameter.

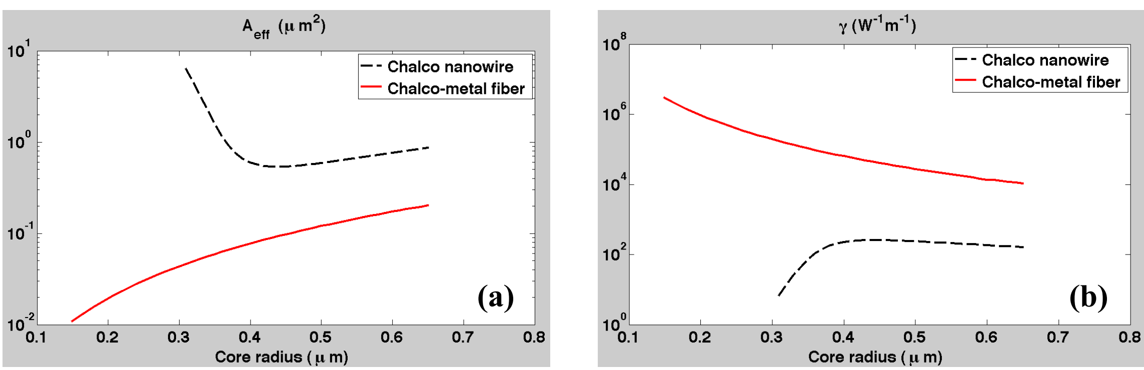


Fig. 3. (a) Effective mode area, and (b) nonlinearity, of a chalcogenide nanowire and a chalco-metallic nanofiber at λ=3.0 µm as a function of the core radius.

Moreover, we calculated that the group velocity of the fundamental plasmonic supermode is greatly reduced. Consequently this novel type of fiber not only provides a platform for achieving high figure of merit nanoscale nonlinear light-matter interactions, but also constitutes an alternative path to investigate slow-light applications via non-resonant means (in contrast to photonic crystals and resonating cavities). Hence the proposed chalco-metallic fibers are relevant to the study of extreme nonlinear light-matter interactions and slow-light guiding systems for highly-integrated nano-photonic devices, and it broadens the scope of both conventional and exotic physical phenomenae which can be conveniently studied through the use of micro(-nano)structured optical fibers.

References

[1] G. Brambilla *et al.*, "Optical fiber nanowires and microwires: fabrication and applications," Adv. Opt. Photon. **1** 107-161 (2009)
[2] M. A. Schmidt *et al.*, "Waveguiding and plasmon resonances in two-dimensional photonic lattices of gold and silver nanowires," Phys. Rev. B **77** 033417 (2008)
[3] A. Mazhorova *et al.*, "Composite THz materials using aligned metallic and semiconductor microwires, experiments and interpretation," Opt. Express **18** 24632-24647 (2010)