Understanding the Limits of Sub-diffraction Focusing of Light with Photonic Funnels

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Abstract: We analyze, numerically and experimentally, deep subwavelength focusing of light in new material platform, photonic funnels, implemented at infrared frequencies with semiconductor-based hyperbolic metamaterials, as function of material concentration, geometric profile, and cladding characteristics.

Multiple fundamental light-matter interaction processes, including light emission and absorption, happen at the nanoscale but manifest themselves at the microscale. An efficient optical link between micro- and nano-scale therefore has potential to affect both fundamental sciences (in understanding these phenomena) and applied sciences (in better utilizing such understanding). Unfortunately, the diffraction limit prevents efficient electromagnetic coupling between nano- and micro-scale areas [1]. While the diffraction limit is a universal phenomenon, it affects long-wavelength frequencies much stronger than their short-wavelength counterparts. In particular, focusing and out-coupling of mid- and long-wave infrared light from sub-micron areas is extremely inefficient [2]. The few existing solutions to this problem rely on resonances [3]. Photonic funnels, a platform based on conically-shaped structures with anisotropic (hyperbolic) metamaterial cores has been recently shown to provide a non-resonant solution [4] to the problem of micro- to nano coupling of radiation. Here we present a comprehensive analysis of light focusing with photonic funnels.

The photonic funnels, realized in our work, utilize the semiconductor-based designer metal platform to achieve a hyperbolic response at mid-infrared frequencies [5]. The initially planar hyperbolic metamaterials, with the help of multiple chemical etching and gold deposition steps, are shaped into the funnel structures (Fig.1a,b), with a gold cladding layer optically insulating the hyperbolic core from the surrounding environment. Due to the unique hyperbolic dispersion of light propagating in strongly anisotropic composites, the funnel-shaped waveguides support propagating volumetric modes even when the waveguide cross-section is significantly smaller than the free space wavelength [6] (Fig.1b). Importantly, our numerical solutions of Maxwell equations suggest that the funnel structure efficiently confines light even in the absence of metallic cladding (Fig.1d).

The transmission of light through the funnels, as fabricated, was characterized using the Quantum Cascade Laser (QCL)-coupled microscope transmission setup. Experimental results agree with theoretical predictions as functions of incident wavelength and output funnel diameter (Fig.1e). However, while the numerical solutions agree with average experimental data over three orders of magnitude of transmission, it is clearly seen that the transmission of light through two funnels with close output diameters can be drastically different from each other.

Fig.1(f,g) provide a likely explanation to this phenomenon. Indeed, the optical characteristics of the photonic funnel are extremely dependent on geometrical parameters such as height of the funnel core and extent of the metallic cladding, material concentration, and funnel curvature. In particular, as the height of the cladding is increased and the height of the cladding approaches the height of the funnel, a pronounced local maximum emerges across the hyperbolic frequency range in funnels subwavelength openings. On the other hand, the curvature of the funnel affects the overall amplitude of the transmission rather than its spectral shape. This work reports systematic analysis of the overall transmission (as well as of the spatial distribution of light around the funnel tip) as the function of both geometrical and material parameters.

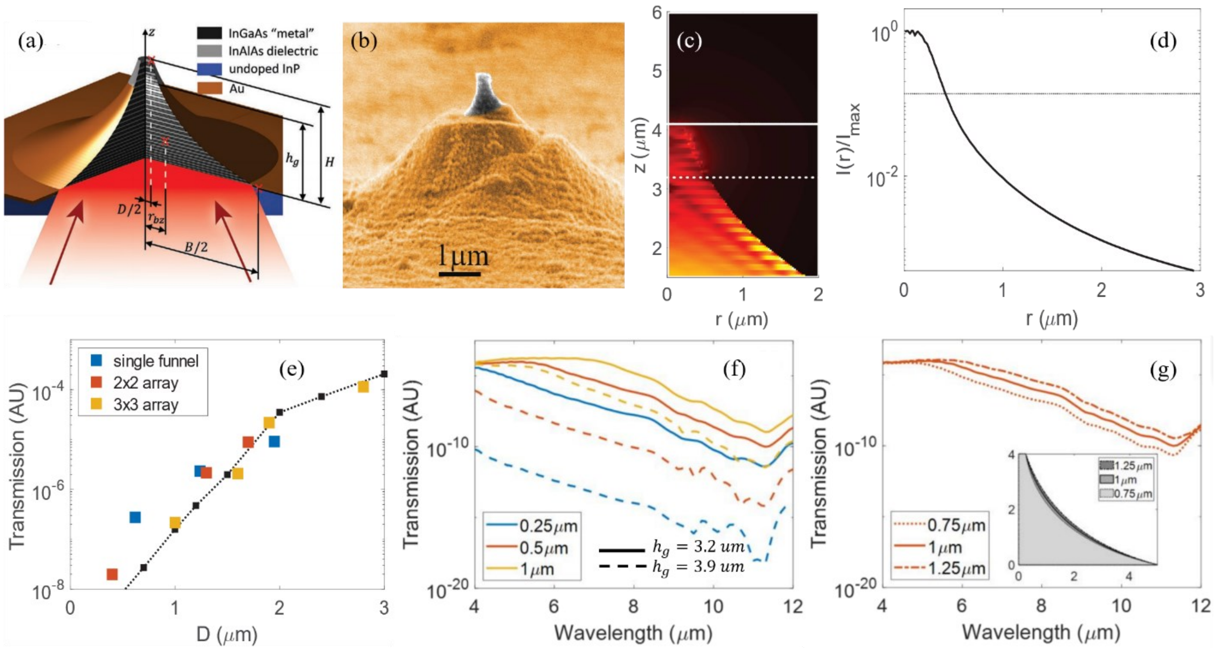

Figure 1: (a) Illustration of photonic funnel with relevant geometric parameters and materials used for numerical studies. (b) The experimentally realized structure with deeply subwavelength output funnel diameter. The intensity profile (c) at $\lambda_0 = 9.5um$. (d) Intensity at point 100 nm above the funnel tip (illustrated as solid white line in panel (c)) with dashed horizontal line indicating $\frac{I}{I_{\max}} = 1/e^2$. (e) The calculated transmission (dashed black line with solid black squares) is seen to agree with experimental values (colored squares) over three orders of magnitude of funnel output diameter. The spectral response of the funnel structure (f,g) as a function a cladding height (h_g) and waveguide curvature. Inset of (g) illustrates COMSOL modelled structure with varying curvatures.

Optimization of photonic funnels operating in the mid-infrared that provides an avenue towards successful implementation of efficient sub-wavelength concentration of mid-infrared radiation. This, in turn, yields the realization of efficient nanophotonic sensing applications utilizing the coupling capabilities of the photonic funnel or designing subdiffraction-limited resolution optical probes. The results of the study can be straightforwardly mapped to visible and near-infrared frequencies where multi-layered hyperbolic metamaterials can be realized with noble metals and transparent conducting oxides, respectively [7].

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