Temporal Shaping of Light at the Nanoscale with Photonic Funnels

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Abstract: Photonic funnels have been demonstrated as a flexible platform to confine light to deep subwavelength spatial areas. Here we consider the utility of this platform to provide temporal, as well as spatial, light shaping.

Time- and space- control of optical fields have multiple applications across materials science and engineering[1]. However, the majority of existing techniques to shape optical pulses are realized in visible/near-IR spectral ranges and rely on free-space optics. As a result, these tools are limited by the diffraction limit – a fundamental law of nature that prevents concentration of electromagnetic waves in deep subwavelength spatial areas in homogeneous materials[1]. However, subwavelength confinement of light is possible in the near-field proximity of plasmonic and phononic structures that exhibit negative permittivity at the operating frequencies. While the resonances in the majority of plasmonic structures are relatively narrow-band, individual resonances of coupled negative-permittivity inclusions may couple to each other, resulting in broad-band optical phenomena that often rely on hyperbolic dispersion of the modes supported by (composite) metamaterials[2]. Optical response of such materials is typically described in the frequency domain. In particular, we have demonstrated, theoretically and experimentally, broadband confinement of mid-IR light to spatial areas as small as 1/30-th of the free space wavelength in conically-shaped all-semiconductor metamaterials based on periodic arrays of highly doped (plasmonic) and undoped (dielectric) layers[3]. In this work we analyze interaction of electromagnetic *pulses* with photonic pulses in the *time domain*.

The effective medium response of the photonic funnels that is used in this theoretical work is illustrated in Fig.1a. As reported elsewhere[3], the funnels can be fabricated by chemical etch-postprocessing of the initially-flat molecular-beam-epitaxy-grown all-semiconductor multilayer metamaterials to achieve a hyperbolic response at mid-infrared frequencies (Fig 1b). Although the initial design of the platform [3] utilized all-metallic cladding, subsequent studies suggested that coupling to a weakly-guided mode supported by the funnel-air interface can substantially enhance coupling between the free-space plane waves and highly confined modes supported by the hyperbolic funnel core. Importantly, excitation of such weakly guided modes is possible in both transmitted (light incoming through substrate) and reflected (light coming from the top of Fig.1a) geometries.

Ultrafast optical sources are available throughout the electromagnetic spectrum. Here we assume that the funnels are excited by the 300-fs-long pulse with Gaussian envelope, with central frequency corresponding to vacuum wavelength of $\lambda_0 = 9.6\mu m$.

To understand the time-domain evolution of light interaction with photonic funnels, the excitation pulse is represented in the Fourier domain,

$$\vec{E}(\vec{r},t) = \sum A_l \overrightarrow{E_\omega}(\vec{r},\omega_l)\exp(i\omega_l t)$$

with the amplitudes A_l, as well as spectral positions ω_l given by the discrete Fourier transform of the incoming pulse, and the frequency-domain field distribution $\vec{E}_\omega$ is calculated with a finite-element-method solver[4] that utilizes cylindrical symmetry to simplify and speed-up the computations. To validate the proposed numerical framework, Fig.1c illustrates evolution of the incoming electromagnetic pulse, propagating in vacuum, at $r = 0, z = 4\mu m$, the location representing the top of the funnel structure ($t = 0$ represents the point in time when the pulse maximum passes this spatial location).

Upon the initial validation, the numerical framework has been used to calculate the time-dependent intensity distribution above the semiconductor funnel, similar to that realized in our previous experiments. Here, we assume that a layer of highly reflective PEC-like material (gold) covers the $r > 5\mu m$ portion of the air/substrate interface. The resultant time-dependent intensity distribution is summarized in Figs.1d. It is seen that the incoming pulse excites the surface electromagnetic mode that focuses light to the tip of the funnel, resulting in highly concentrated "hot spot" whose spatial dimensions are comparable to those of the tip of the funnel. The intensity of such hot spot [that lags the incoming pulse by ~300 fs] is approximately ~4 times higher than the intensity of the incoming pulse.

Further analysis reveals that the concentration of the field at the location of the funnel results in the broadening of the incoming pulse (Fig.1e). Such broadening, however, can be mitigated by pre-shaping of the incoming radiation to compensate for the time-domain dynamics caused by the funnel.

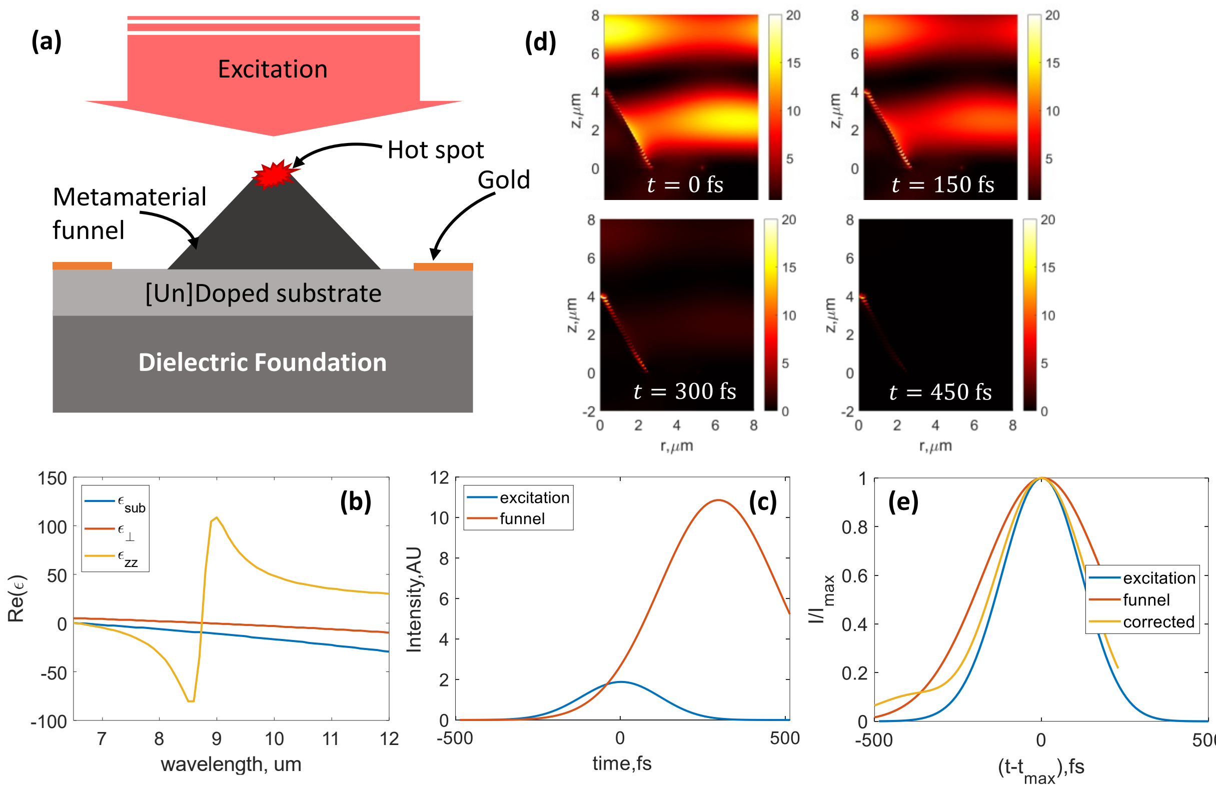

Figure 1: (a) Cross-sectional schematic of funnel geometry. (b) Permittivity of the doped substrate and of the effective medium response of the funnel core. (c) Time-domain dynamics of the intensity of the incoming electromagnetic pulse (propagating through air) and dynamics of intensity within the funnel hot-spot; (d) snap-shots of the spatial distribution of intensity in the vicinity of the funnel structures, and (e) analysis of pulse width of the incoming pulse (blue), delayed pulse in the hot-spot (orange), and the corrected pulse at the funnel tip (yellow); all pulses are shifted in time and normalized to their respective intensity maxima

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