Time Domain Phase Engineering of Metasurfaces Enables Passive Ultrafast Photonic Streaking

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Abstract: We describe a time-domain nano-photonic design principle for controlling electromagnetic waves at femtosecond timescales and illustrate a metasurface design that numerically demonstrates streaking of ultrafast pulses passively using arrays of resonance-based dielectric metasurfaces.

1. Introduction

Ultrafast beam steering in which a pulse is switched at the ultrafast timescale or streaking in which continuous steering occurs throughout the ultrafast duration is an enabling capability for ultrafast imaging [1] which is used as a characterization tool across ultrafast science. Here we demonstrate a photonic ultrafast imaging approach which involves engineering the temporal phase of the ultrafast event by designing a spatio-temporal impulse response on a metasurface that causes self-streaking of the event. Metasurfaces have recently been used to demonstrate ultrafast beam steering [2-4]. However, there has been very little work done to engineer the temporal response of dielectric metasurfaces for shaping ultrafast pulses. These demonstrations typically involve a pump-probe experimental geometry, where the ultrafast steering is initiated by an external ultrafast source. Here we demonstrate the possibility to steer an ultrafast pulse without the application of any external gating or control source to induce the steering

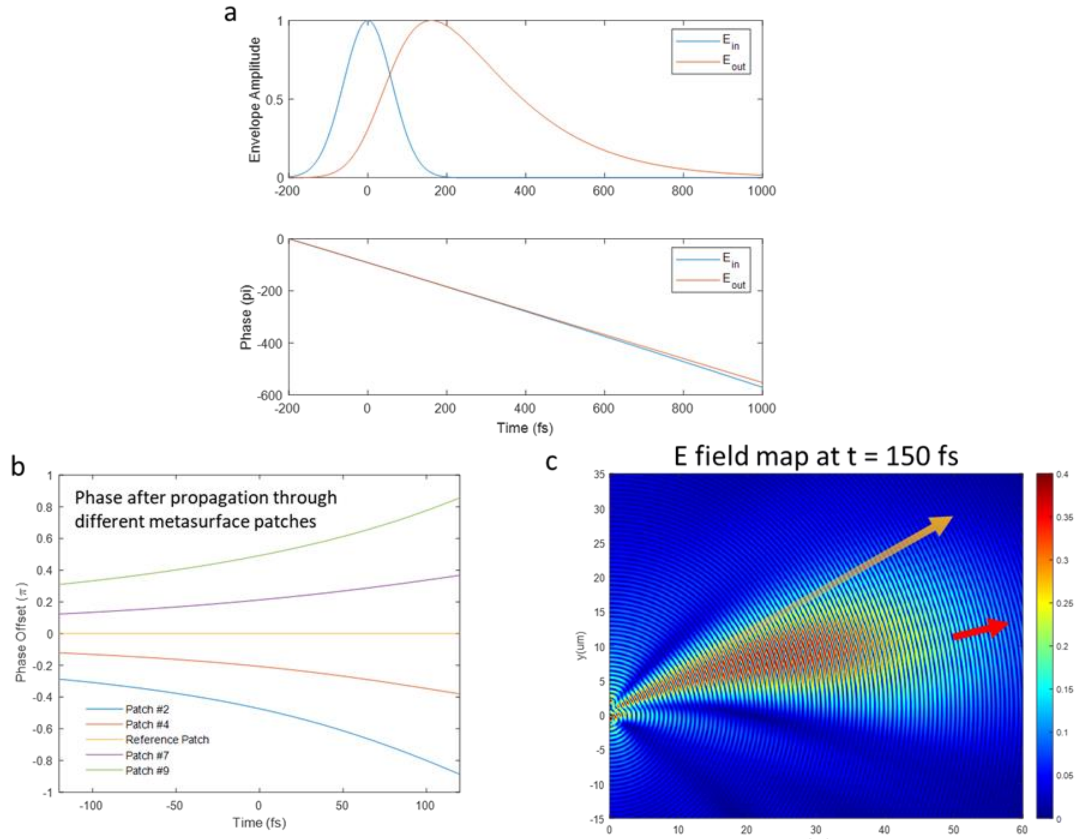

Fig 1. (a) Ultrafast 80 fs pulse interaction with a resonator defined by its quality factor (Q) and center frequency (ω). the input pulse amplitude and phase are shown in blue, while the pulse after interaction with the resonator is shown in orange (b) Coupled mode theory analytic calculations of the pulse propagating through various metasurfaces (having different Q and ω) (c) FDTD simulation at t = 150 fs showing the electric field map of the pulse interacting with the metasurface sequence from (b), streaking behavior is observed where light from the pulse at early times is steered more shallowly (red arrow) than light from latter portions of the pulse (yellow arrow).

behavior. To design the metasurface we utilize temporal coupled mode theory (Fig 1a) to model the interaction of our transform limited incident pulse with two cascaded resonances described by their quality factors (Q_A, Q_B) and their wavelength offset ($\Delta\lambda_A$, $\Delta\lambda_B$). Where Q varies from 5 - 100, and $\Delta\lambda$ varies from -200 nm to 200 nm offset from the pulse center wavelength of 1200 nm, which is practical for fabrication. The resonators alter the temporal amplitude and temporal phase ($\varphi(t)$) of the output pulse based on the quality factor (Q) and resonance frequency (ω) of the resonators. The resultant output pulse and its phase is a function of time and the four resonator parameters (t, Q_A, $\Delta\lambda_A$, Q_B, $\Delta\lambda_B$) (Fig 1a). To streak the beam a spatial sequence of metasurface arrays is needed where the desired phase relation between adjacent arrays that are separated by Δx is $\Delta\varphi(t)$ where $\Delta\varphi(t)$ has an ultrafast temporal evolution (Fig 1b), e.g. at -50 fs the phase extent of the phase ramp is ~0.8 π, but grows throughout the pulse duration to 1.2 π at 50 fs. We find the resonator combination for each array in the sequence that yields the best approximation of the desired $\Delta\varphi(t)/\Delta x$ from a library of simulated resonator combinations. An FDTD simulation of the design is shown in Fig 1c showing the streaked beam 150 fs after the input pulse interacts with the resonators (metasurface arrays).

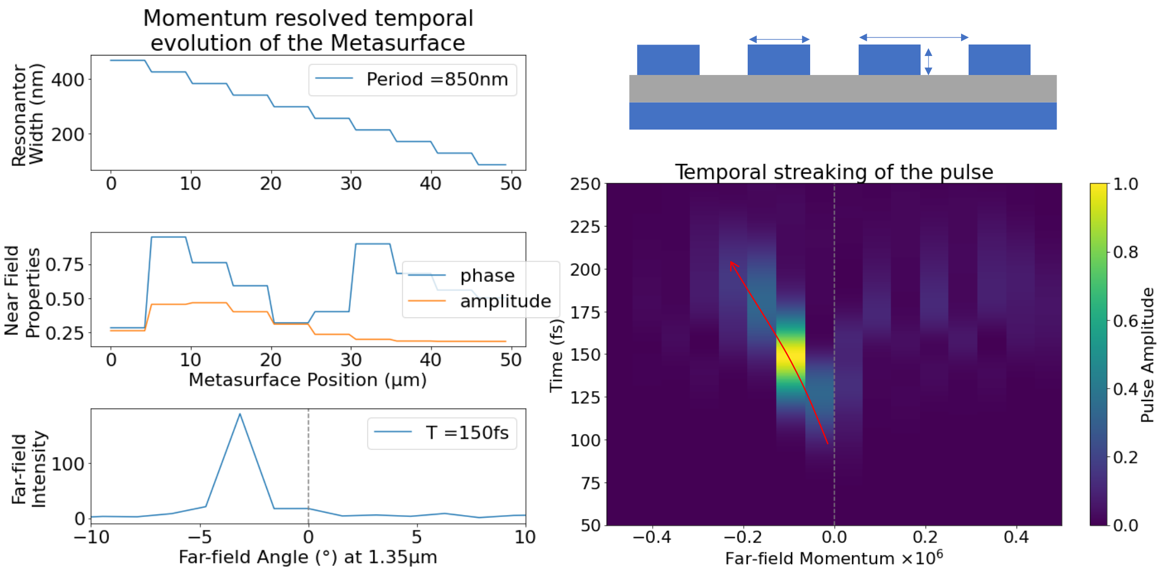

Fig 2. FDTD simulation of a realizable III-V metasurface. (a) The spatial distribution of the resonator width. (b) The associated near-field phase and amplitude properties. (c) The resultant far-field peak at 4° at t =150fs. (d) Schematic of the simulated metasurface consisting of GaAs on low index (n = ~1.7) AlGaO, with meta-atom layout as shown. (e) The temporal evolution of the pulse transmitting through the device is mapped in the color plot as function of the far-field momentum and time.

Additionally, we numerically simulate an experimentally realizable metasurface using commercial FDTD solvers (Lumerical) to demonstrate the passive streaking behavior. The simulated metasurface resonators (Fig 2d) have a square cross section made up of high index semiconductors (III-V) with a constant height (130 nm) who spatial size distribution (Fig 2a) is varied in a manner to realize photonic streaking of an ultrafast (80 fs) pulse. We map the temporal evolution of the pulse through individual resonator arrays before arraying them to realize the necessary near field phase evolution (Fig 2b) enabling the streaking behavior using the space to momentum Fourier transform (Fig 2c). The results of the photonic streaking metasurface are plotted in the colormap (Fig 2e) demonstrating that with time, the pulse streaks towards increasing grating orders in momentum space.

In conclusion, we have designed a passive metasurface that can streak an ultrafast pulse. Designing the response by engineering the time domain phase of the ultrafast pulse provides a new way to conceptualize ultrafast light-matter interaction and metamaterial design, providing new opportunities in the design of ultrafast spatial temporal metasurfaces.

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3. References

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