Front-induced transitions control THz waves

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Relativistically moving dielectric perturbations can be used to manipulate light in new and exciting ways beyond the capabilities of traditional nonlinear optics. Adiabatic interaction with the moving front modulates the wave simultaneously in both space and time, and manifests a front-induced transition in both wave vector and frequency yielding exotic effects including non-reciprocity and time-reversal¹⁷⁻⁷. Here, we introduce a technique called SLIPSTREAM, Spacetime Light-Induced Photonic STRucturEs for Advanced Manipulation. The technique is based on the creation of relativistic fronts in a semiconductor-filled planar waveguide by photoexcitation of mobile charge carriers. Here we demonstrate the capabilities of SLIPSTREAM for novel manipulation of THz light pulses through relativistic front-induced transitions. In the sub-luminal front velocity regime, we generate temporally stretched THz waveforms, with a quasi-static field lasting for several picoseconds tunable with the front interaction distance. In the super-luminal regime, the carrier front outpaces the THz pulse and a time-reversal operation is performed via a front-induced intraband transition. We anticipate our platform will be a versatile tool for future applications in the THz spectral band requiring direct and advanced control of light at the sub-cycle level.

Light in the terahertz (THz) band, already immensely important for spectroscopy and imaging applications⁸, has been touted as a frontier for next generation high-speed wireless communications⁹⁻¹¹. As with other spectral bands, the advancement of future THz technologies will be done in lockstep with the development of new methods for controlling the spatial and temporal properties of THz light. While significant advances have been made on controlling the spatial evolution of THz waves with metasurfaces and wavefront engineering¹²⁻¹⁵, methods for actively controlling the temporal properties of THz light on the level of the electric field cycle are typically only possible through self-induced temporal phase modulation using intense THz pulses¹⁶⁻²⁴. Only recently an arbitrary THz pulse shaper was introduced, employing a hybrid digital wave synthesis technique using light-induced structures in a waveguide²⁵. Such planar waveguide approaches have the benefit of being amenable to chip-scale integration²⁶.

Alternative approaches to nonlinear optics, however, draw on the concept of time-varying linear media introduced first by Morgenthaler³⁻⁷,²⁷. These ideas were tested in experiments involving plasma physics via the rapid ionization of gases²⁸ or sudden carrier injection through optical excitation in semiconductors²⁹. Temporal modulation is attractive for wavelength conversion as it does not require nonlinear media or strong field interactions. Subsequently, several studies have emerged, focused on temporally modulated photonic crystals³⁰,³¹ and cavities³²,³³ for wavelength conversion applications. The non-adiabatic modulation of meta-atoms was recently demonstrated as a means to achieve wavelength conversion in the THz band³⁴. In addition, sub-cycle slicing using intense optical pulses illuminating semiconductor surfaces is also capable of pulse narrowing and spectral expansion in the THz band³⁵,³⁶.

Simultaneous control over the wavevector and frequency of light through combined spatial and temporal modulation can produce a variety of exotic photonic operations¹,³⁷,³⁸. These spacetime, front-induced transitions can be used to time-reverse a light pulse,¹²,¹³,⁴⁰, for example, which has important applications in dispersion compensation⁴¹ and imaging through random scattering media⁴². THz interactions with moving fronts were first investigated in pioneering experiments using photoexcitation in a semiconductor to create an overdense, reflective plasma interaction that is counter-propagating with the incoming THz wave. Considerable spectral broadening was observed via relativistic Doppler shifts⁴³⁻⁴⁵. Here we introduce SLIPSTREAM for exploring front-induced transitions in the THz band and use it to demonstrate two unconventional photonic operations: the temporal stretching and time-reversal of THz pulses.

The SLIPSTREAM technique is based on the same compact platform for spatio-temporal manipulation we have previously introduced, capable of performing a range of photonic operations including pulse steering⁴⁶, mode control⁴⁷, spectral shaping⁴⁸, arbitrary pulse shaping⁴⁹ and phase control⁴⁹. As shown schematically in Fig. 1a, a parallel plate waveguide (PPWG) supporting
dispersionless, low loss, TEM THz propagation is formed by coating both sides of a $d = 50\,$µm-thick high resistivity float zone silicon ($\rho > 10,000\,$Ω·cm) slab with optically transparent and conducting indium tin oxide (sheet resistance of $1\,$Ω/sq). The transparency of the ITO coatings allows optical excitation of the silicon through the top plate with a near-infrared (1035 nm, 190 fs, 30 µJ) pump pulse derived from a Yb:KGW amplified femtosecond laser system (Light Conversion, PHAROS). This excitation is close to the indirect band gap of Si, with pump penetration depths exceeding 100 µm, ensuring a homogeneous excitation across the Si slab. The pump pulse has its pulse front tilted using a diffraction grating, producing a linear gradient in the pump arrival time along the waveguide propagation axis. In this manner, as the pump pulse front illuminates the silicon, a moving front of photoinduced carrier density is created within the PPWG. A portion of the NIR beam is split off to a CMOS camera to record the pump intensity spatial profile.

The photoexcitation of a moving front results in the emission of a phase-locked THz pulse within the waveguide that propagates in the TEM mode. Since no electrical bias is applied and the plates are grounded, the sole source of THz emission is due to transient currents created by built-in Schottky fields, oppositely oriented at the metal-semiconductor interfaces, upon arrival of the pump pulse at the top and bottom waveguide plates, as in Fig. 1b. Photoinjecting free carriers within the band bending regions at these interfaces leads to the transient currents $J_{\text{top}}(t, z)$ and $J_{\text{bot}}(t - \zeta, z)$ directed normal to the waveguide plates and temporally separated by the transit time of the NIR pump pulse $\zeta$. These delayed and transient currents emit THz light in the same manner as an Auston switch and similar to a continuous version of a segmented dc-to-ac radiation converter.50–57

Once coupled out of the PPWG, the THz emission is detected by free-space electro-optic sampling in a 5-mm-thick (110) GaP crystal.

The emitted THz electric field transients, shown in Fig. 1c, depend critically on the pulse front velocity, $v_f$, with respect
to the THz TEM mode phase velocity $c/n_{Si}$ with refractive index $n_{Si} = 3.418^{38}$. The front velocity is continuously tunable from the sub-luminal to super-luminal regime with the femtosecond pump pulse front tilt angle. In the sub-luminal regime, $v_f < c/n_{Si}$, a THz plateau pulse is created with a stretch of quasi-dc electric field bookended by unipolar structure, shown in the top panel of Fig. 1c. The emitted THz waves escape the excitation front which produces a superposition of linearly delayed single cycle pulses along the propagation axis. The result is a temporally stretched THz pulse whose duration is tunable with front velocity and total propagation distance. At the luminal condition $v_f = c/n_{Si}$, the emitted THz pulse is of single cycle duration, as all emission points add in phase along the entire propagation axis. This produces the maximum amplitude THz emission as shown in the integrated spectral power in Fig. 1d. Tuning the front to the super-luminal regime $v_f = 1.5 c/n_{Si}$, the pulse character remains single cycle but loses some high frequency components as the front overtakes the THz wave and it experiences losses in the plasma, here with a plasma frequency $\omega_p/2\pi \approx 1$ THz.

In the sub-luminal regime, the duration of the THz field plateau is tunable with propagation length as shown in Fig. 2. Truncated carrier density profiles, calibrated from camera images and power measurements, are given in Fig. 2a with the subsequently measured THz pulses plotted in Fig. 2b. The positions of two sharp knife edges in the beam map directly to start $t_{\text{start}}$ and stop times $t_{\text{end}}$ of the THz pulse, corresponding to the measured pulse arising from the leading and trailing edge of the carrier density front, respectively. Sliding either knife edge by $\Delta z$ and measuring the pulse duration change $\Delta t$ allows a precise calibration of the front velocity through

$$v_f = \frac{1}{\Delta t/\Delta z + n/c},$$

which in this case yields a sub-luminal velocity of $v_f = 0.86 c/n_{Si}$. The amplitude of the plateau follows the Gaussian profile...
The two insets of Fig. 3a show that increasing the plasma frequency from low (blue) to high (red) adds curvature to the band, flattening at low THz frequencies. Front-induced transitions on a dispersion diagram, from an initial state \((\omega_1, \beta_1)\) to a final state \((\omega_2, \beta_2)\), can be understood through the dispersion relation

\[
\frac{\omega_2}{\beta_2} \approx \frac{c}{n_{Si}} \left( 1 + \frac{\omega_1^2 \tau^2}{2} \right).
\] 

The amplitude spectra of only the pulses displaying time-reversal in c for all fluences explored, categorized above critical fluence (and below in the inset). e, Integrated spectral power of the time-reversed THz pulses (squares) and those arising 10 ps later (circles).
When the front stops at the edge of the photoexcited region, the blueshifted forward THz wave is ejected. In scenario 3, the A) can be projected up to higher frequency states whereas its backwards counterpart (pulse B) is undetected, lost to the plasma. 

The Schottky THz emission mechanism produces an outgoing spherical electromagnetic wave containing components travelling towards the detector (positive $\beta$) as well as those pointed backward into the plasma front (negative $\beta$). For a super-luminal front, the emission is immediately swept up by the plasma so only intra-band front-induced transitions may take place. Considering that only positive wavevectors will be detected, three scenarios are indicated in Fig. 3a: (1 - blue line) $\omega_2/\beta_2 < v_f$, where transitions involving solely positive wavenumbers can occur. For high fluences (3 - green line) $\omega_2/\beta_2 > v_f$, transitions from backward propagating initial states to forward propagating states within the plasma become possible. In this scenario, the backward wave undergoes a time-reversal as the spatial distribution remains unchanged but the group velocity inverts sign. Higher plasma frequencies forbid intra-band scattering at lower frequencies until time-reversal scattering from $-\beta_1$ to $+\beta_2$ takes over. Here, in the intermediate regime, the special case (2 - cyan line) $\omega_2/\beta_2 = v_f$ prohibits all forward initial states from undergoing transitions. The plasma frequency that satisfies this dispersion condition allows equation 2 to be solved for the front velocity.

In summary, we have demonstrated that the SLIPSTREAM platform enables the interaction between THz light and relativistic moving fronts of photoinduced dielectric modulation. In the sub-luminal regime, the relativistic front generates a structured THz pulse displaying a quasi-static electric field profile via the extraction of energy from built-in Schottky fields at metal-semiconductor boundaries. The temporal profile of the electric field can be tailored by the intensity distribution of the optical photoexcitation. This capability allows, for example, applications where long, tunable THz pulses may act as an

\[
\omega = \frac{c}{n_{\text{Si}}} \frac{\beta}{\tau}
\]

where $n_{\text{Si}}$ is the refractive index of silicon, $c$ is the speed of light in vacuum, and $\beta$ is the group velocity. The phase continuity condition is denoted by the dashed black line where a slight super-luminal front velocity of $v_f = 1.0035 \frac{c}{n_{\text{Si}}}$ has been chosen for reasons that will be explained below.

The main diagram in Fig. 3a shows the dispersion relative to unexcited silicon for three possible perturbations with increasing $\omega_p$, labelled by 1, 2 and 3. The dispersion of the plasma is modelled by a Drude response with a fixed scattering time $\tau$ of 0.1 ps and a variable plasma frequency $\omega_p$ set by the pump fluence. In each plot, the phase continuity condition is satisfied by the dashed black line where a slightly super-luminal front velocity of $v_f = 1.0035 \frac{c}{n_{\text{Si}}}$ has been chosen for reasons that will be explained below.

In summary, we have demonstrated that the SLIPSTREAM platform enables the interaction between THz light and relativistic moving fronts of photoinduced dielectric modulation. In the sub-luminal regime, the relativistic front generates a structured THz pulse displaying a quasi-static electric field profile via the extraction of energy from built-in Schottky fields at metal-semiconductor boundaries. The temporal profile of the electric field can be tailored by the intensity distribution of the optical photoexcitation. This capability allows, for example, applications where long, tunable THz pulses may act as an
 ultrafast optical bias. In addition, we showed that when the front velocity is tuned just above luminal in the silicon, the fluence dependence of the dispersion of the carrier plasma is crucial in determining the front-induced transitions that may occur. We observed time-reversal of a THz pulse as the photoinduced dispersion of the dielectric perturbation was optically tuned relative to the front velocity. This work establishes our platform as a practical avenue to explore the interaction of light with moving dielectric fronts. The ability to apply localized dielectric modulation by optical means on a silicon chip has significant implications for investigating, for example, the relativistic Doppler effect, optical horizon analogues, and experimentally novel effects associated with the motion of shocklike dielectric modulations travelling in photonic crystal landscapes.

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