Active Spintronic-metasurface Terahertz Emitters with Tunable Chirality
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Abstract: In this work, we propose a novel spintronic-metasurface terahertz emitter for the generation and manipulation of coherent broadband terahertz waves. The ellipticity of the chiral terahertz waves can reach >0.75 over the entire 1-5 THz broadband and the polarization state can be easily controlled by an external magnetic field. © 2022 The Author(s)

Coherent terahertz sources driven by femtosecond laser pulses can now routinely generate sub-picosecond few-cycle terahertz waves with exceptionally stable carrier waveforms, which can be used in numerous fundamental studies and practical applications. The ability to manipulate the three-dimensional (3D) electric-field vector of such broadband terahertz waveforms can substantially broaden the applications of the terahertz technologies and open up new possibilities for studies of coherent light–matter interactions [1]. Therefore, a great amount of research has been devoted to generating chiral terahertz waves and realizing full control over the 3D field-vectors in their amplitude, phase, frequency, polarization, and spatial properties [2,3]. The novel spintronic terahertz emitter composed of magnetic multilayer heterostructures exhibit the advantages of being low-cost, highly reliable, efficient, and flexible [4]. Moreover, because the micro-nano fabrication of metal thin films is technologically well established, these spintronic emitters can be easily made into various metasurface structures, opening up great potential for applications. When excited by femtosecond laser pulses, the laser-induced transient currents, which are inherent to the spintronic emitters [4], can serve as efficient and active driving sources of the metasurface, the properties of which can be well controlled by the excitation lasers and external fields.

In this work, we propose a novel spintronic-metasurface terahertz emitter, consisting of metasurface-patterned ferromagnetic (FM) and nonmagnetic (NM) heterostructures [5]. Taking the prototypical stripe-patterned metasurface as an example, we demonstrate the generation and manipulation of chiral terahertz waveforms in an efficient and highly flexible manner. The ellipticity can reach >0.75 for a broad terahertz bandwidth (1 to 5 THz), and the generation efficiency is comparable to the nonlinear crystals commercially available. Furthermore, by simply varying the transient spintronic-origin currents with an orientated external magnetic field, the emitter functionality can be actively controlled, leading to continuous tuning of the terahertz polarization state and helicity. Our work opens a new pathway to active metasurface-tailored spintronic devices for efficient generation and control over the electric-field vectors in the terahertz regime.

**Fig 1.** Generation of chiral terahertz waves from a stripe-patterned spintronic-metasurface emitter. (a) Schematic of the experimental setup. (b) Terahertz waveforms of E' under different field angles θ0. The peak-to-peak field amplitude (Vpp) is defined as V1 − V2. (c) Same as (b) for E2. (d) The peak-to-peak field amplitude (Vpp) of E' and E2 as a function of θ0.

Figure 1(a) illustrates the schematic of the experimental setup. The metasurface emitter is composed of stripe-patterned FM/NM heterostructures. The FM/NM heterostructure consists of NM Pt (thickness of 3 nm) capped with FM Fe50Co50 (1.4 nm) and supported by a thick SiO2 or Al2O3 substrate. In the experiments, the stripe orientation is fixed along the x axis, while the magnetization of the FM layer (M) is saturated by an oriented external magnetic
field \( \mathbf{H} \) with a field magnitude of 200 mT, and the field orientation can be continuously adjusted in the \( x-y \) plane. The field angle \( \theta_H \) is defined as the angle between \( \mathbf{H} \) and the stripe orientation (\( x \) axis), as shown in Fig. 1(a). Under femtosecond laser illumination, the longitudinal spin current \( j_s \) arising in the FM layer is converted into a transverse charge current \( j_c \) via the inverse spin-Hall effect (ISHE) in the NM layer, given by \( j_c = \gamma j_s \times \mathbf{M}/|\mathbf{M}| \), where \( \gamma \) is the spin-Hall angle of the NM layer \([7]\). As a result, in our experiments, the laser-induced charge current \( j_c \) always flows perpendicularly to \( \mathbf{H} \) and serves as an active driving source of the stripe-patterned metasurface.

The electro-optic sampling (EOS) signals for the terahertz-wave components polarized parallel\( (E_p) \) and perpendicular\( (E_n) \) to the stripes are plotted in Fig. 1(b) and (c). Clearly, the perpendicular electric-field amplitude \( E_n \) is strongly suppressed compared to \( E_p \). The results of the peak-to-peak amplitude \( V_{pp} \) as a function of \( \theta_H \) are summarized in Fig. 1(d). The results of both \( E_p \) and \( E_n \) exhibit a sinusoidal behavior, while a ~90 deg angle shift can be observed. Furthermore, our results in Figs. 1(b) and 1(c) show that the terahertz waveforms, respectively, for the two orthogonal polarizations, possess almost identical temporal waveforms. This conclusion is further corroborated by the normalized spectra shown in Fig. 2(a), which displays identical spectral shapes for each polarization, although the spectrum of \( E_n \) is blue-shifted compared to \( E_p \) \([6,7]\). Most interestingly, the phase difference \( (\phi_n - \phi_p) \) stays close to \( \pm \pi/2 \) throughout the entire spectrum [see Fig. 2(b)]. This clearly indicates the generation of chiral terahertz waves.

The broadband quarter-wave phase difference naturally leads to chiral terahertz emission. In Fig. 2(c), we plot a typical time dependence of the electric-field vector for a chiral terahertz waveform obtained in our experiments. Here, a stripe pattern with the stripe width \( d = 10 \mu m \) is excited by the laser pulses under \( \theta_H = -17 \) deg. The broadband ellipticity can be \( >0.75 \) when \( d < 10 \mu m \). The generation of the chiral terahertz waveforms can be well captured by our numerical simulation [see Fig. 2(c)]. As clearly shown in Fig. 2(d), the ellipticity and handedness of the emitted terahertz radiation can be conveniently and continuously controlled by changing the field angle \( \theta_H \).

![Fig 2. Generation and manipulation of chiral terahertz waveforms. (a) Normalized spectra of \( E_p \) and \( E_n \) under different field angles \( \theta_H \). (b) The relative phase difference between the parallel and the perpendicular components \( \phi_p - \phi_n \) under different field angles \( \theta_H \). The colored regions represent the experimental errors. (c) Typical time dependence of the electric-field vector for a chiral terahertz waveform generated from a metasurface emitter. (d) The parametric plots of \( E_p(t) \) and \( E_n(t) \) with different \( \theta_H \).](image)

Our work opens a new pathway to metasurface-tailored spintronic emitters for efficient generation and control of terahertz waves. The combination of ultrabroadband, efficient spintronic emitters and metasurfaces with predesigned functionality could lead to many more types of emitting devices for different spatial and temporal terahertz waveforms.

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