Ultrabroadband single-cycle terahertz pulses with peak fields of 300 kV cm^{-1} from a metallic spintronic emitter

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Supplementary material

A Sample preparation details

The magnetic heterostructures were grown in a Singulus Rotaris© sputter tool equipped with targets of 100 mm diameter. Typical deposition conditions were a sputter power of 800 W at an Argon pressure of 2 to $4\cdot10^{-3}$ mbar. The resulting deposition rates are 1.2 Å s^{-1} for the FM layer and 2.1 Å s^{-1} for the NM layers. A short plasma etch with a 500 eV Ar-ion beam was applied to the substrate (fused silica, thickness of 500 µm, diameter of 7.5 cm) to clean the surface from organic contaminants.

B Pulse energy of a Gaussian beam

In the frequency domain, the energy of the THz electromagnetic pulse with cylindrically symmetric beam profile is given by

$$W = \frac{2\pi}{Z_0}\int_{-\infty}^{\infty}\mathrm{d}\omega\int_{0}^{\infty}\mathrm{d}r\, r|E'_{\mathrm{THz}}(\omega,r)|^2. \tag{S1}$$

Here, $E'_{\mathrm{THz}}(\omega,r)$ is the amplitude spectrum at distance r from the optical axis (propagation direction), and $Z_0 \approx 377\,\Omega$ is the free-space impedance. As the pump beam incident on the emitter is a collimated Gaussian beam with diameter $2b$ (full width at half intensity maximum), the THz beam directly behind the emitter is collimated and Gaussian also. Therefore, we assume a radial field profile of the form

$$E'_{\mathrm{THz}}(\omega,r) = E'_{\mathrm{THz}}(\omega)\exp\left(-\ln 2\frac{r^2}{b^2}\right) \tag{S2}$$

where $2b$ is the THz beam diameter (full width at half field maximum), and $E'_{\mathrm{THz}}(\omega)$ is the complex-valued Fourier amplitude measured on the optical axis. After integrating Eq. (S1), we find

$$W = \frac{\pi b^2}{Z_0 2\ln 2}\int_{-\infty}^{\infty}\mathrm{d}\omega\,|E'_{\mathrm{THz}}(\omega)|^2. \tag{S3}$$

Note that in our experiment, we sample the THz electric field $E_{\mathrm{THz}}(\omega)$ which results from focusing of the collimated beam with on-axis field $E'_{\mathrm{THz}}(\omega)$ [see Fig. 1(c) of the main text]. The two fields are related by

$$E_{\mathrm{THz}}(\omega) = -\mathrm{i}\omega E'_{\mathrm{THz}}(\omega)\frac{b^2\ln 2}{2cf} \tag{S4}$$

where c is the vacuum speed of light, and f is the focal length of the parabolic mirror. Substituting Eq. (S4) into Eq. (S3) finally yields

$$W = \frac{c^2 f^2 2\pi\ln 2}{Z_0 b^2}\int_{-\infty}^{\infty}\mathrm{d}\omega\,\frac{|E_{\mathrm{THz}}(\omega)|^2}{\omega^2}. \tag{S5}$$

Using $f = 5.1$ cm and $b = 2.4$ cm, we find a pulse energy of $W = 4.1$ nJ, which agrees very well with the power measurements [see Fig. 2(b) of the main text].