RESEARCH ARTICLE | JANUARY 18 2024

Laser-triggered terahertz radiation from interlayer exchange-coupled spintronic emitters

Roman Adam; Derang Cao; Daniel E. Bürgler; Sarah Heidtfeld; Fangzhou Wang; Christian Greb; Genyu Chen; Jing Cheng; Debamitra Chakraborty; Markus Büscher; Martin Mikulics; Hilde Hardtdegen; Roman Sobolewski; Claus M. Schneider

AIP Conf. Proc. 3054, 070001 (2024)
https://doi.org/10.1063/5.0188731

Laser-Triggered Terahertz Radiation from Interlayer Exchange-Coupled Spintronic Emitters

Roman Adam,[1, a)] Derang Cao,[1, 2] Daniel E. Bürgler,[1] Sarah Heidtfeld,[1] Fangzhou Wang,[1] Christian Greb,[1] Genyu Chen,[3] Jing Cheng,[3] Debamitra Chakraborty,[3] Markus Büscher,[1, 4] Martin Mikulics,[5] Hilde Hardtdegen,[5] Roman Sobolewski,[3] and Claus M. Schneider[1,6,7]

[1]*Research Centre Jülich, Peter Grünberg Institute (PGI-6), D-52425 Jülich, Germany*
[2]*College of Physics, C. for Marine Observation and Communications, Qingdao University, 266071 Qingdao, China*
[3]*University of Rochester, Rochester, New York,14627-0231, USA*
[4]*Institut für Laser- und Plasmaphysik, Heinrich-Heine Universität Düsseldorf, 40225 Düsseldorf, Germany*
[5]*Research Centre Jülich, Ernst Ruska Centre, 52425 Jülich, Germany*
[6]*Faculty of Physics, University Duisburg-Essen, 47057 Duisburg, Germany*
[7]*Department of Physics, University of California Davis, Davis, California 95616-5270, USA*

[a)] Corresponding author: r.adam@fz-juelich.de

Abstract. Intensity of THz transients triggered by laser excitation in NM/FM/NM/FM/NM multilayers (FM - ferromagnet, NM - normal metal) can be tuned by the interlayer exchange coupling between the two FM layers. We ascribe this tunability to the constructive and destructive interference of the THz transients generated by closely-spaced NM/FM and FM/NM spintronic THz emitters.

INTRODUCTION

THz radiation generated by optical excitation of few nanometers thin NM/FM/NM/FM/NM multilayers established a powerful link between THz- and spin-based electronics. Earlier experiments demonstrated that optical laser pulse impinging at the surface of FM/HM/FM multilayers can trigger a superdiffusive spin-current pulse carrying spin current $\boldsymbol{J}_S$, across the interface from the ferromagnet into the metal [1,2]. In the case of a metal with a sizable spin–orbit coupling, $\boldsymbol{J}_S$ can trigger, via the inverse spin-Hall effect (ISHE), a transverse charge-current $\boldsymbol{J}_C$ following $\boldsymbol{J}_C = D_{ISHE} (\boldsymbol{\sigma} \times \boldsymbol{J}_S)$ [3-6]. Resulting electromagnetic bursts generated by $\boldsymbol{J}_C$ feature a broadband spectrum containing frequencies extending into the THz radiation spectrum. Our measurements show that the intensity of the THz transients can be tuned by the strength and sign of the interlayer exchange coupling (IEC) between ferromagnetic thin films.

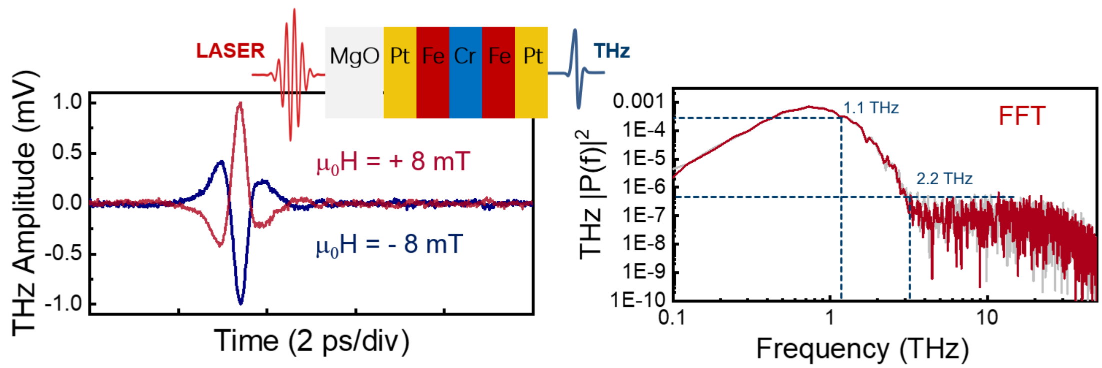
RESULTS

Our THz emitters were fabricated using molecular-beam epitaxy at the base pressure of 2×10^{-10} mbar. After stabilizing substrate temperature at 500°C the Pt/Fe/Cr/Fe/Pt multilayer stacks were deposited on top of the optically polished 10×10 mm^2 MgO substrates with (100) surface orientation. The thickness of the Cr layer varied from 4 to1 nm over a lateral distance of about 8 mm. The thickness of all other layers was 2 nm.

As shown in Fig. 1 (a) the polarity of the THz transients generated by a spintronic THz emitter at the magnetic fields $\mu_0H = \pm 8$ mT reverses and follows the magnetic field orientation reversal. The corresponding fast Fourier transforms displayed in Fig. 2 (b) show a broadband spectra extending up to 2.2 THz with 3 dB cut-off at 1.1 THz, for both THz transients [recorded at $\mu_0H = + 8$ mT (red FFT curve) and at $\mu_0H = - 8$ mT (grey FFT curve)]. The laser

Applied Physics of Condensed Matter (APCOM2023)
AIP Conf. Proc. 3054, 070001-1–070001-3; https://doi.org/10.1063/5.0188731
Published by AIP Publishing. 978-0-7354-4805-6/$30.00

fluence was set to 12.5 nJ/cm^2 and the Cr spacer thickness in this measurement was t_{Cr1} = 2.1 nm. The inset in Fig. 1 (a) shows the schematics of the multilayer with an incident laser pulse and a generated THz transient.



(a) (b)

FIGURE 1. (a) THz transients generated by the spintronic THz emitter containing exchange-coupled ferromagnetic Fe layers at two external magnetic fields ($\mu_0H = \pm 8$ mT) applied parallel to the emitter surface. Inset shows the shematics of the multilayer with the incident laser and the generated THz transients. (b) displays the corresponding power spectra.

Figure 2 (a) shows the variation of the THz peak intensity at two Cr spacer thicknesses t_{Cr1} = 2.1 nm (red dots) and t_{Cr2} = 1.7 nm (blue dots). Due to the spacer thickness-dependent variation of the IEC strength and sign [7] the magnetizations of the two Fe layers can be aligned either parallel (t_{Cr1}) or antiparallel (t_{Cr2}) near zero magnetic field. Both cases are schematically drawn in Fig. 2 (b) and (c), respectively. Here the black, green and red arrows show the direction of the Fe magnetization ($\boldsymbol{M}^{Fe}$), spin- ($\boldsymbol{J}_S$) and charge current ($\boldsymbol{J}_C$) assuming that ISHE is the only mechanism responsible for THz generation. For t_{Cr1} the variation of the peak THz amplitude is similar to the variation the multilayer magnetization with magnetic field (not shown). On the other hand, the THz peak variation shown by the blue hysteresis for t_{Cr2} displays a radically different behavior.

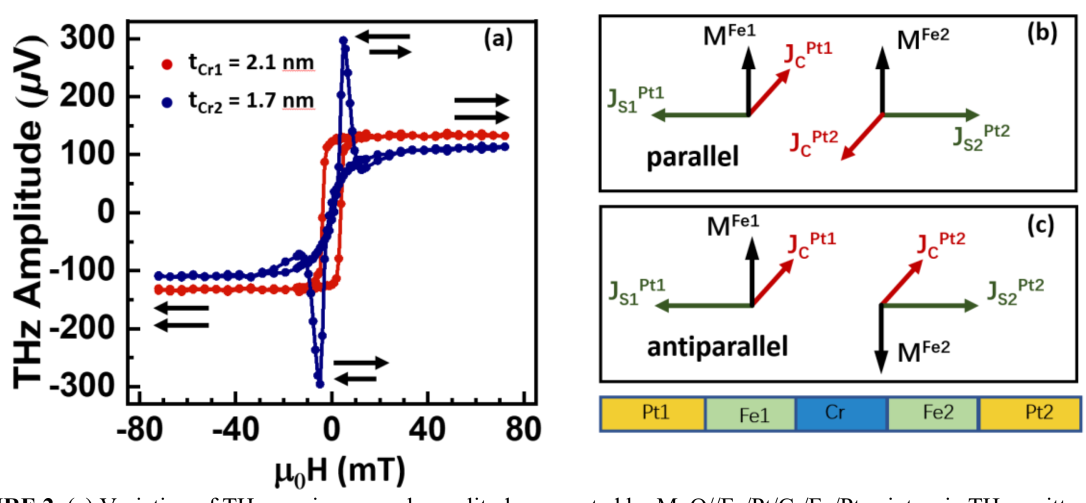


FIGURE 2. (a) Variation of THz maximum peak amplitude generated by MgO//Fe/Pt/Cr/Fe/Pt spintronic THz emitter for 1.7 nm (blue dots) and 2.1 nm (red dots) Cr spacer thickness. Black arrows mark the assumed magnetization alignment for parallel- and antiparallel magetization alignment. The displayed trace shows up to 300% THz signal enhancement at magnetic fields close to m0H = 5 mT for t_{Cr2} = 1.7 nm. (b), (c) Arrows show a direction of the spin- and charge currents ($\boldsymbol{J}_S$ and $\boldsymbol{J}_C$) for the parallel and antiparallel relative magnetization alignment of Fe layers assuming a pure ISHE mechanism for THz generation. The layer sequence is indicated below (c).

Following the blue curve in Fig. 2 (a) from left to right, at the large negative magnetic fields, the peak THz intensity is initially relatively low due to the parallel magnetization alignment (marked by parallel left-pointing arrows).

Continuously decreasing the magnetic field, we reached the interval from -10 mT to + 8 mT in which THz intensity sharply increases and reaches three-fold enhancement with respect to the THz amplitude at the saturation field. The enhancement is due to the antiparallel alignment of Fe-layers magnetization. At the large positive field THz intensity drops again due to a parallel magnetization alignment. Besides of their possible application in hybrid THz spintronic circuits, the detailed understanding of the THz peak amplitude evolution with magnetic field is expected to offer deeper insight into non equilibrium spin and charge dynamics in multilayers.

SUMMARY

We demonstrated that both the polarity and the intensity of the THz transients generated by the Pt/Fe/Cr/Fe/Pt spintronic emitters can be determined by the relative alignment of magnetizations of the Fe layers. Depending on the external magnetic field strength and the Cr spacer thickness, THz transients can have either the same or an opposite polarity. A superposition of the THz transients generated by the two separate exchange-coupled spintronic THz emitters ultimately results in the overall THz signal amplitude drop or increase. In case of t_{Cr} = 1.7 nm the emitters show three-fold intensity enhancement between the parallel and antiparallel magnetization alignments.

ACKNOWLEDGMENTS

The work at the Research Centre Jülich (FZJ) was performed within the JuSPARC strategy project funded by the BMBF. The research at the University of Rochester was supported in part by the DOE Grant DE-SC0022473.

REFERENCES

1. M. Battiato, K. Carva, and P. M. Oppeneer, "Superdiffusive Spin Transport as a Mechanism of Ultrafast Demagnetization," Phys. Rev. Lett., **105**, 027203-1-4, 2010.
2. D. Rudolf, C. La-O-Vorakiat, M. Battiato, R. Adam, J. M. Shaw, E. Turgut, P. Maldonado, S. Mathias, P. Grychtol, H. T. Nembach, T. J. Silva, M. Aeschlimann, H. C. Kapteyn, M. M. Murnane, C. M. Schneider, and P. M. Oppeneer, "Ultrafast magnetization enhancement in metallic multilayers driven by superdiffusive spin current," Nat. Commun. **3**, 1037 (2012).
3. R. Adam, G. Chen, D. E. Bürgler, T. Shou, I. Komissarov, S. Heidtfeld, H. Hardtdegen, M. Mikulics, C.M. Schneider, R. Sobolewski, "Magnetically and optically tunable terahertz radiation from Ta/NiFe/Pt spintronic nanolayers generated by femtosecond laser pulses," Appl. Phys. Lett. **114,** 212405-1-5 (2019).
4. E. Saitoh, M. Ueda, H. Miyajima, and G. Tatara, "Conversion of spin current into charge current at room temperature: Inverse spin-Hall effect," Appl. Phys. Lett. **88,** 182509-1-3 (2006).
5. T. Seifert et al., "Efficient metallic spintronic emitters of ultrabroadband terahertz radiation," Nat. Photon. **10**, 483–488 (2016).
6. T. Kampfrath, K. Tanaka, and K. A. Nelson, "Resonant and nonresonant control over matter and light by intense Terahertz transients," Nat. Photonics **7**, 680-690 (2013).
7. P. Bruno, "Theory of interlayer magnetic coupling," Phys. Rev. B **52**, 411-439 (1995).