AIP Advances

A THz driven split-ring resonator based ultrafast relativistic electron streak camera

F

Cite as: AIP Advances **9**, 085209 (2019); https://doi.org/10.1063/1.5080374
Submitted: 08 November 2018 . Accepted: 15 July 2019 . Published Online: 12 August 2019

X. L. Shen, E. C. Snively, J. Giner Navarro, D. Cesar, and P. Musumeci

COLLECTIONS

Paper published as part of the special topic on Chemical Physics, Energy, Fluids and Plasmas, Materials Science and Mathematical Physics

F This paper was selected as Featured

ARTICLES YOU MAY BE INTERESTED IN

A THz driven split-ring resonator based ultrafast relativistic electron streak camera

Cite as: AIP Advances 9, 085209 (2019); doi: 10.1063/1.5080374
Submitted: 8 November 2018 • Accepted: 15 July 2019 •
Published Online: 12 August 2019

View Online Export Citation CrossMark

X. L. Shen,[a] E. C. Snively, J. Giner Navarro, D. Cesar, and P. Musumeci

AFFILIATIONS

Department of Physics and Astronomy, UCLA, Los Angeles, California 90095, USA

[a]Electronic mail: shenxinglai@gmail.com

ABSTRACT

The use of sub-wavelength metal structures to locally enhance high frequency electromagnetic fields, generally known as plasmonics, enables breakthrough opportunities across diverse fields of research such as nonlinear optics, biosensing, photovoltaics and others. Here we study the application of sub-wavelength metallic resonators tuned in the THz frequency range for manipulation and diagnostics of relativistic electron beams. In this work, we report on the use of a double-sided split-ring structure driven by a near single cycle THz field generated by optical rectification to impart a time-dependent angular deviation (streak) on a 4.5 MeV electron beam. Electrons passing through the small gap reveal field enhancement factors larger than 10, in good agreement with finite difference time domain simulations. This work paves the way for further application of high frequency metallic structures in compact particle accelerators such as for THz-based relativistic electron streaking at fs and sub-fs temporal resolution.

The fast-paced progress of modern fabrication technologies has enabled the development of ultrasmall structures that can be used to confine high frequency electromagnetic waves to sub-wavelength spatial scales. This is tremendously useful for localizing the electromagnetic energy to achieve better spatial resolution in sensing or light-harvesting applications or increasing the field intensity to much larger levels than what would be possible simply by focusing using conventional optics, beating the limits of diffraction.[1]

One of the many opportunities for this novel branch of research is in accelerator and beam physics, which is traditionally concerned with harnessing high electric fields for charged particle acceleration, beam diagnostics and phase space manipulation, and actively exploring ways to extend the frequency range of accelerators, typically operating in radiofrequency bands, to realize more compact devices featuring shorter electron beams. For example, an interesting development at this regard is the introduction of THz electromagnetic waves for the acceleration, manipulation and diagnosis of ultrafast electron beams.[2–7] An important application of this research is in the field of ultrafast electron diffraction (UED)[8–10] where the temporal resolution of ultrafast structural dynamics studies is being pushed to tens of fs by the introduction of accelerator and beam physics methods.[11–13]

In this framework, laser generated THz-driven streaking cameras have been proposed[14] to achieve fs and sub-fs resolution for temporal characterization of ultrafast electron beams and their relative time-of-arrival with respect to a reference laser clock. The inherent advantages of laser-generated THz pulses are the higher frequency and the inherent synchronization with the electron beam. This scheme has been successfully demonstrated[2] with non relativistic electrons and more recently extended to relativistic energies.[5,6] In the latter case, the temporal resolution is mainly limited by the available THz field strengths.

In these experiments, THz pulses have been generated by optical rectification.[15–17] While highest reported THz fields on the order of GV/m have been achieved,[18] in small scale laboratories with mJ-level infrared driver laser systems, it is much more common to obtain field levels of 1-10 MV/m.

Sub-wavelength structures such as split ring resonators (SRR) have been proposed in order to overcome the diffraction limit in focusing of the electromagnetic intensity as they effectively work by collecting the incident radiation from a large area and concentrating it in a sub-wavelength volume, which can lead to large field enhancement.[19] In a recent experiment, Ryabov and Baum[20] have used pulses of low energy electrons to obtain time-resolved map of the collective carrier motion and electromagnetic fields with subcycle and subwavelength resolution in the gap of these rings. Because of the resonant behavior, a well-designed split ring resonator can achieve field enhancement larger than 10x resulting in proportional increase in temporal resolution for the same drive field.[21]

In this paper, we demonstrate the use of a THz-driven split-ring resonator shaped to provide a large enhancement of the field in its gap (see Fig. 1(a)) to temporally streak an ultrafast relativistic electron beam. Experimental results obtained using the 4.5 MeV electron beam from the Pegasus radiofrequency photoinjector[22] and a synchronized THz source providing an incident field strength of 4 MV/m, indicate field enhancement by more than a factor of 10 in good agreement with our simulation results. We also discuss the possibility to stack multiple SRR structures to achieve even higher field enhancement. This work paves the way to the use of plasmonic sub-wavelength structures to enhance electromagnetic fields with application in THz-driven fs/sub-fs resolution streak cameras.

A conventional SRR is usually a metallic square loop with a split or gap on one side. When radiation is incident on the structure, charge density oscillations are induced on the metal surface leading to an accumulation of charge carriers around the gap region.[14] By tuning the illumination frequency to the fundamental resonance of SRR, strong circulating currents are excited that lead to a large field enhancement in the gap.

Under some assumptions such as that the losses inside the metal are negligible,[23] the equivalent LC circuit picture is often used to describe the physical behavior of SRRs, where the gap acts as a parallel plate capacitor and the metal ring acts like a coil and provides an inductive contribution. So the frequency of SRR resonances can be controlled by the dimensions of the structure.[24,25] To obtain a more accurate prediction of the behavior of SRR, finite difference time domain (FDTD) simulations are often utilized. In the same way, it can be shown that the field enhancement in the gap, scales inversely with the gap volume.[21]

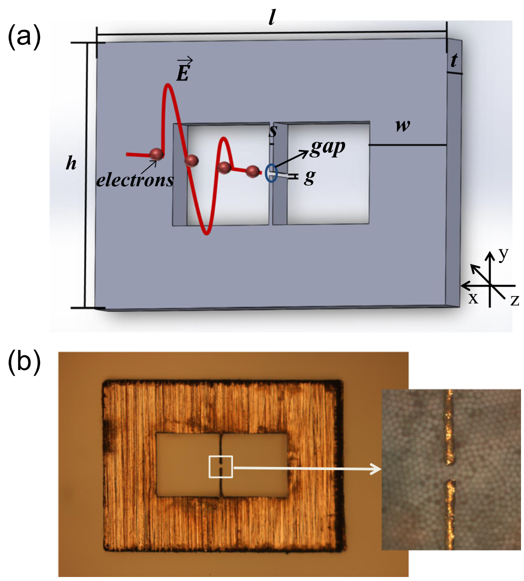

FIG. 1. (a) Novel split ring resonator (SRR) design and schematic figure of this THz driven SRR based relativistic electron streaking camera (b) SRR picture under 500× microscope with a picture of the enlarged tip.

An electron beam passing through the SRR gap experiences a transverse kick due to the electric and magnetic field in the gap whose sign and magnitude depend on the relative phase between the electron and the wave. After some propagation distance, the longitudinal bunch density is mapped onto the transverse axis and can be easily measured on a fluorescent screen. The shortest temporal scale that can be resolved is inversely proportional to the field strength in the gap. The temporal resolution can be described as:

$$\frac{\Delta s}{\beta c} = \frac{\gamma \Delta d}{\beta c L_d} / \frac{\partial P_\perp}{\partial s} = \frac{\gamma \Delta d}{\beta c L_d} / \frac{\partial \int e(E_y + \beta c B_x) dt}{\partial s} \tag{1}$$

where s is the longitudinal coordinate along the beam, β and γ are the usual relativistic factors, Δd is the smallest electron spot size that can be resolved on the screen, determined by the minimum of screen spatial resolution and beam spot size and L_d is the drift length. $P_\perp$ is the transverse kick that electrons acquire traversing the SRR gap which is obtained by integrating the electromagnetic fields E_y and B_x along the particle trajectory in the gap.

The SRR we designed for our experiment uses two rectangular copper rings which share one side and it is shown in Fig. 1(a). The dimensions are optimized with FDTD simulations using a commercial software Lumerical to match the properties of our THz source. A compromise has been made during the optimization between i) maximizing the field enhancement factor and ii) maintaining a physical size of the structure which would ease mounting and manufacturing challenges. Referring to Fig. 1(a), the dimension of our SRR structure are $l = 910\mu m$, $h = 650\mu m$, $t = 100\mu m$, $w = 200\mu m$. For the gap dimension design, another compromise between streaking power and acceptance aperture for the electron beam has to be made. In our case, the width of the pillar and the vertical clear gap for the beam are both set to 10 μm, so the transverse active area of the device is 10 μm by 10 μm.

As shown in Fig. 1(a), a vertically-polarized incident THz pulse co-propagates with electrons along the z-axis. An image taken with a microscope of the SRR structure is shown in Fig. 1(b), with an enlarged image of the gap. The structure has been manufactured using ultrafast laser machining of a sheet copper metal 100 μm thick.

One thing to notice is that the gap region has a square profile, but the low resolution (several μm) in manufacturing results in rounded corners as shown in Fig. 1(b). As the field enhancement is strongly dependent on the vertical gap size, these rounded corners will be responsible for a non uniformity of the field enhancement in the horizontal coordinate.

FDTD simulations based on the structure will be discussed next. The input THz waveform used in the simulation is shown in Fig. 2(a) and is directly retrieved by an electro-optic sampling measurement of the experimentally used THz pulses. The spectrum of the radiation is centered at a frequency of 0.7 THz and the peak electric field strength is 4 MV/m.

In Fig. 2(b) we show the simulated time dependent electromagnetic force in the center of the gap. The peak field strength is 40 MV/m, which indicates that the field enhancement in the gap center is in excess of 10. Since the thickness of the structure is only 100 μm, we can neglect the variation of the transverse position induced by the field deflection when calculating the particle motion.

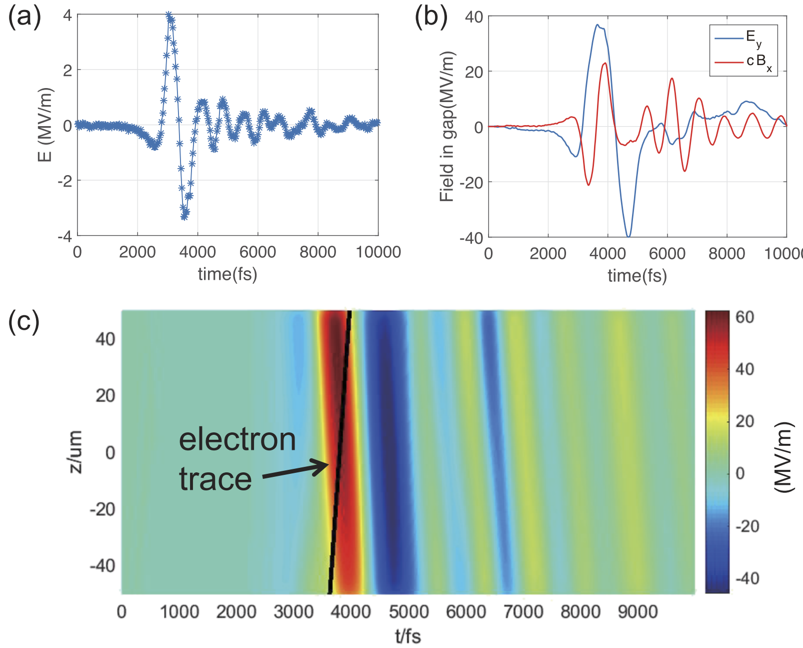

FIG. 2. (a) Input THz waveform (b) Simulated electric field and magnetic field in the center of gap (c) Simulated time dependent deflecting force E_y + $v_z \times B_x$ along z-axis in the center of gap,together with the electron trace which can get the maximum transverse kick.

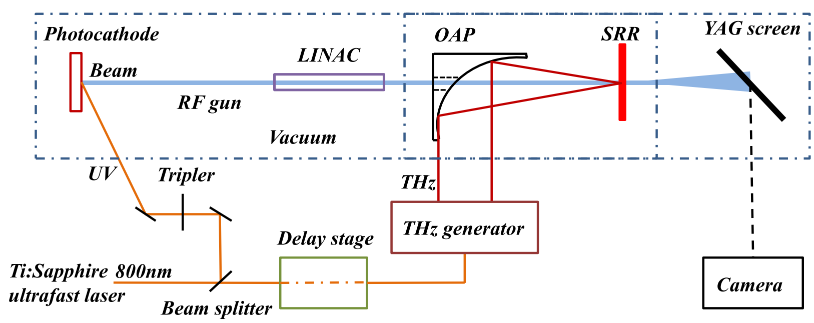

FIG. 3. Schematic of the experimental setup.

The time dependent deflecting force $E_y + v_z \times B_x$ along z-axis in the transverse center of gap is shown in Fig. 2(c). The total transverse induced kick is calculated by integrating the Lorentz force along the trajectory. As an example, the electron trajectory which experiences the maximum kick for electrons with beam energy of 4.5 MeV is also plotted in Fig. 2(c). The maximum transverse momentum acquired by passing through the SRR is 5.0 keV/c.

The SRR structure has been tested experimentally in the UCLA Pegasus beam line. Fig. 3 shows a schematic of the setup and Table I lists the main parameters of the experiment. A Ti:sapphire ultrafast laser pulse at 800 nm is split with a 25-75 beamsplitter into two pulses. The smaller fraction is used after frequency conversion to UV for electron beam generation; the remaining pulse is used to drive the THz source. The photoemitted electron beam is accelerated to 3 MeV in a 1.6 cell S-band RF gun.[22] A S-band high impedance linac structure is used to compress the beam bunch length.[11] After the linac, the total beam energy is 4.5 MeV, and the compressed rms bunch length on the structure is < 100 fs. A solenoid is used before the structure to focus the beam in the small active area of the SRR.

Using a pulse-front-tilted optical rectification scheme in a LiNbO3 crystal,[26] the larger portion of the IR pulse is used to generate a nearly single-cycle 1 μJ THz output pulse with about 0.1% conversion efficiency. A system of off-axis parabolic (OAP) mirrors transports the THz pulse into vacuum through a high-density polyethylene window (80% transmission) and a f = 10 cm off-axis parabolic mirror focuses the THz beam onto the structure with a

TABLE I. Key parameters in the experiment.

Parameter	Nominal value
Beam energy	4.5 MeV
Initial bunch length	500 fs
Compressed bunch length	< 100 fs
Charge	2 pC
THz pulse focused spot size	1 mm
Distance from structure to screen	0.6 m
Normalized emittance	150 nm

spot size around 1 mm. The electron beam is brought into collinear propagation through a 2 mm hole in the focusing OAP. A small fraction of the IR is split before the THz setup and used for in-situ electro optic sampling to characterize the input THz pulse (not shown in Fig. 3).

The structure is mounted on a 3D translation stage, with an orientation consistent with the incident vertical THz pulse polarization. When the relativistic electron beam overlaps with the THz pulses both temporally and spatially on the SRR structure, THz-induced streaking is observed. To tune the temporal overlap, an adjustable delay line is used to control the path length of the IR pulse prior the THz generation setup. Time-dependent angular streaking is measured on a 100 μm thick YAG screen located 0.6 m downstream from the structure. The rms point spread function of the screen-detector system is 25 μm.

When the electron beam is focused before the structure, a point-projection image of the SRR structure can be formed on the screen to allow clearer identification of the electrons passing through the 10 μm by 10 μm gap. A horizontal wedge-shape 15 μm wide slit made of Kapton film is used to further isolate the region of interest in the point-projection image.

The wedge slit imaged with electrons on the screen is shown in Fig. 4(a), with the THz pulse blocked. The red box indicates the location of the gap inside the structure. Fig. 4(b) shows a sample screen image with THz on. From this figure, we notice that the deflection is not uniform horizontally, which is consistent with the analysis of the profile of the manufactured structure. The spatial distribution of electrons is also correlated with the spatial distribution of THz field intensity in the gap suggesting that a small electron beam probe can be used to measure the THz transverse profile.

The measured deflection as a function of time delay between electron beam and THz pulses is retrieved by comparing the position of the kicked beam centroid with THz on and THz off and is shown in Fig. 4(c), together with the simulation results. The pulse length of the beam itself is responsible for the vertical uncertainty in the measurement. The horizontal error in the measurement is due to the arrival time jitter of electron beam which has been measured for the Pegasus RF gun to be ~ 400 fs rms.[27]

In Fig. 4(c), we compare the experimental results with the simulations and find them in good agreement. The measurement confirms that our novel THz-driven SRR design has a field enhancement of more than 10 inside the structure gap.

According to Eq. (1), the temporal resolution of a streak camera can be estimated by using $\frac{\Delta d}{L_d}$ divided by the gradient of the time dependent angular deflection $\frac{\partial P_\perp/\gamma}{\partial s/\beta c}$. When the electron pulses pass through the structure approximately at the zero-crossing of the time-dependent deflection, the gradient is maximum, which corresponds to an optimum in temporal resolution.

In our experiment, the maximum angular kick gradient is 4 μrad/fs, while $\frac{\Delta d}{L_d}$ is around 40 μrad mostly limited by the spatial resolution of screen, yielding a temporal resolution of 10 fs, comparable with what has been obtained in recent work,[5] and with great potential for further improvement. In our experiment, the peak input THz field strength is 4 MV/m, which can easily be increased using higher pump energy on the optical rectification crystal or tighter focusing. With 10 MV/m field strength, the gradient would linearly scale up to 10 μrad/fs. Coupling this larger kick gradient with improvements in the spatial resolution at the final screen, and a smaller intrinsic beam divergence ($\frac{\Delta d}{L_d}$ $\approx$ 20 μrad only limited

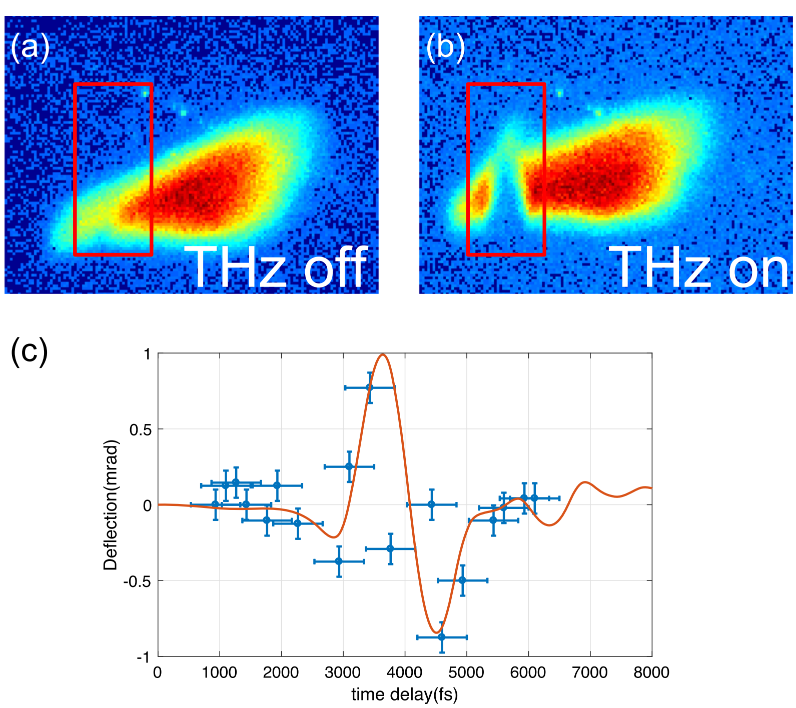

FIG. 4. (a) Electron image on the screen when THz pulses are off, red box indicates the gap location (b) Electron image on the screen when THz pulses are on, red box indicates the gap location (c) Measured deflection as a function of time delay between electron beam and THz pulses compared with simulation results.

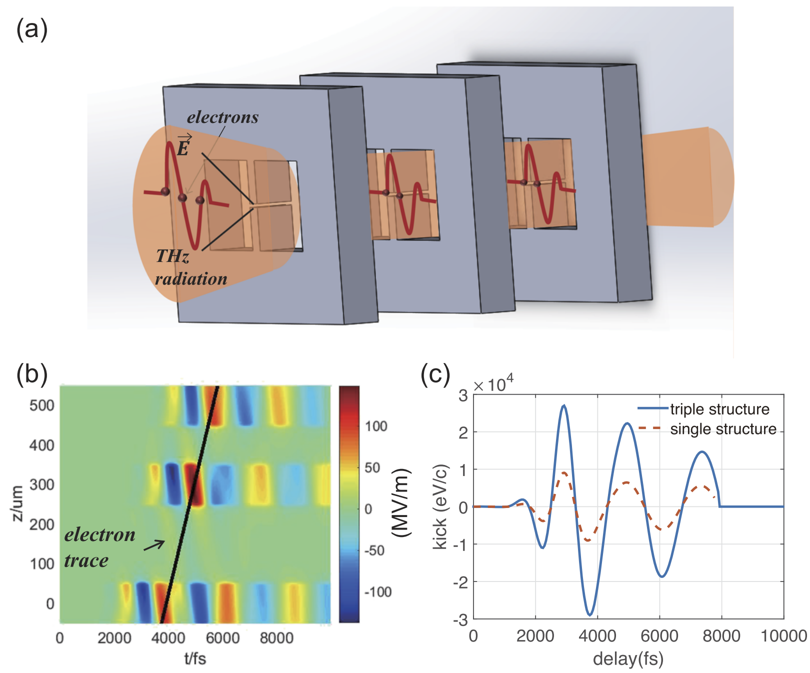

FIG. 5. (a) Schematic of stacking multiple structures (b) Time dependent deflecting force along z-axis in the center of gap, together with the electron trace which can get the maximum kick (c) Simulated time-dependent deflection for stacking multiple structures, compared with the simulated time dependent deflection for single structure.

by the inhomogeneity of the field distribution in the structure), fs resolution for this THz-driven SRR streaking camera could be achieved.

Compared to other schemes based on slotted metal foils for coupling THz to relativistic beams, our SRR structure has another important advantage: the attenuation of THz pulses in the SRR is small, suggesting the possibility to stack multiple structures along the THz pulse focus as shown in Fig. 5(a). Simulations indicate that as the relativistic electron beam co-propagates with the THz pulse, there is minimal dephasing over a relatively long range of many mm. Future multi-structure designs can take advantage of having minimal constraints on inter-structure spacing, so long as the overall length is less than several mm.

A FDTD simulation using three stacked structures is shown as an example. In this case, the attenuation of THz pulses in the SRR structure is kept below 10% and could be further optimized tuning the structure dimensions. The time-dependent deflecting force along the interaction range is shown in Fig. 5(b) with input THz field strength of 10 MV/m. Here the distance between the first structure and the second structure is 200 μm, while the distance between the second structure and the third structure is 100 μm, but simulation indicate that the alignment requirements on the structure inter-distances are very relaxed. The 4.5 MeV electron trajectory that receive the maximum kick (30 keV/c) is also plotted in Fig. 5(b), from which we can see that there is little dephasing between THz pulses and electron beams on each structure. The integrated deflection as a function of time is also shown in Fig. 5(c) showing a deflection gradient as high as 25 μrad/fs. Based on the analysis above, the technique of stacking multiple structures may be a good candidate for further improving the temporal resolution of this SRR streaking method provided a solution to the alignment of the stacked SRR to the beam trajectory can be found.

In this paper, we demonstrate an ultrafast electron streaking camera using a novel THz-driven split-ring resonator designed to enhance the THz field strength by more than an order of magnitude. A streaking experiment for MeV electron beams is conducted to confirm the field enhancement of the SRR. We also discuss the possibility to stack the structure and achieve higher field enhancement (up to 30x) and hence better temporal resolution (fs/sub-fs). This work demonstrate that field intensity enhancement in plasmonic structures can be exploited for relativistic electron beam manipulation, paving the way for significnt advances in interaction efficiency between charged particle beams and electromagnetic waves.

This work has been supported by NSF grant PHY-1734215 and DOE grant DE-SC0009914. The authors acknowledge useful discussions with R. K. Li.

REFERENCES

[1] D. K. Gramotnev and S. I. Bozhevolnyi, Nature Photonics **4**, 83 (2010).
[2] C. Kealhofer, W. Schneider, D. Ehberger, A. Ryabov, F. Krausz, and P. Baum, Science **352**, 429 (2016).
[3] W. R. Huang, A. Fallahi, X. Wu, H. Cankaya, A.-L. Calendron, K. Ravi, D. Zhang, E. A. Nanni, K.-H. Hong, and F. X. Kärtner, Optica **3**, 1209 (2016).
[4] D. Zhang, A. Fallahi, M. Hemmer, X. Wu, M. Fakhari, Y. Hua, H. Cankaya, A.-L. Calendron, L. E. Zapata, N. H. Matlis *et al.*, Nature Photonics, **12**, 336 (2018).
[5] L. Zhao, Z. Wang, C. Lu, R. Wang, C. Hu, P. Wang, J. Qi, T. Jiang, S. Liu, Z. Ma *et al.*, Physical Review X **8**, 021061 (2018).
[6] R. Li, M. Hoffmann, E. Nanni, S. Glenzer, A. Lindenberg, B. Ofori-Okai, A. Reid, X. Shen, S. Weathersby, J. Yang *et al.*, preprint arXiv:1805.01979 (2018).
[7] E. Curry, S. Fabbri, J. Maxson, P. Musumeci, and A. Gover, Physical Review Letters **120**, 094801 (2018).
[8] R. D. Miller, Science **343**, 1108 (2014).

[9]M.-F. Lin, V. Kochat, A. Krishnamoorthy, L. Bassman, C. Weninger, Q. Zheng, X. Zhang, A. Apte, C. S. Tiwary, X. Shen *et al.*, Nature Communications **8**, 1745 (2017).
[10]M. Gao, C. Lu, H. Jean-Ruel, L. C. Liu, A. Marx, K. Onda, S.-y. Koshihara, Y. Nakano, X. Shao, T. Hiramatsu *et al.*, Nature **496**, 343 (2013).
[11]J. Maxson, D. Cesar, G. Calmasini, A. Ody, P. Musumeci, and D. Alesini, Physical Review Letters **118**, 154802 (2017).
[12]J. Hoffrogge, J. Paul Stein, M. Krüger, M. Förster, J. Hammer, D. Ehberger, P. Baum, and P. Hommelhoff, Journal of Applied Physics **115**, 094506 (2014).
[13]T. Van Oudheusden, P. Pasmans, S. Van Der Geer, M. De Loos, M. Van Der Wiel, and O. Luiten, Physical Review Letters **105**, 264801 (2010).
[14]J. Fabiańska, G. Kassier, and T. Feurer, Scientific Reports **4**, 5645 (2014).
[15]Y. H. Avetisyan, A. Makaryan, and V. Tadevosyan, *Terahertz Emitters, Receivers, and Applications VIII* (International Society for Optics and Photonics, 2017), Vol. 10383, p. 103830A.
[16]C. Vicario, C. Ruchert, and C. Hauri, Journal of Modern Optics **62**, 1480 (2015).
[17]M. Tonouchi, Nature Photonics **1**, 97 (2007).
[18]J. A. Fülöp, Z. Ollmann, C. Lombosi, C. Skrobol, S. Klingebiel, L. Pálfalvi, F. Krausz, S. Karsch, and J. Hebling, Optics Express **22**, 020155 (2014).
[19]H. Merbold, F. Brunner, A. Cannizzo, and T. Feurer, CHIMIA International Journal for Chemistry **65**, 316 (2011).
[20]A. Ryabov and P. Baum, Science **353**, 374 (2016).
[21]S. Bagiante, F. Enderli, J. Fabiańska, H. Sigg, and T. Feurer, Scientific Reports **5**, 8051 (2015).
[22]D. Alesini, A. Battisti, M. Ferrario, L. Foggetta, V. Lollo, L. Ficcadenti, V. Pettinacci, S. Custodio, E. Pirez, P. Musumeci *et al.*, Physical Review Special Topics-Accelerators and Beams **18**, 092001 (2015).
[23]O. Limaj (2012).
[24]A. K. Azad, A. J. Taylor, E. Smirnova, and J. F. O'Hara, Applied Physics Letters **92**, 011119 (2008).
[25]H.-T. Chen, W. J. Padilla, J. M. Zide, A. C. Gossard, A. J. Taylor, and R. D. Averitt, Nature **444**, 597 (2006).
[26]J. Hebling, G. Almasi, I. Z. Kozma, and J. Kuhl, Optics Express **10**, 1161 (2002).
[27]E. C. Snively, N. T. Yardimci, B. T. Jacobson, M. Jarrahi, P. Musumeci, and A. Murokh, Applied Physics Letter (in press).