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Interferometrically enhanced sub-terahertz picosecond imaging utilizing a miniature collapsing-field-domain source

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Progress in terahertz spectroscopy and imaging is mostly associated with femtosecond laser-driven systems, while solid-state sources, mainly sub-millimetre integrated circuits, are still in an early development phase. As simple and cost-efficient an emitter as a Gunn oscillator could cause a breakthrough in the field, provided its frequency limitations could be overcome. Proposed here is an application of the recently discovered collapsing field domains effect that permits sub-THz oscillations in sub-micron semiconductor layers thanks to nanometer-scale powerfully ionizing domains arising due to negative differential mobility in extreme fields. This shifts the frequency limit by an order of magnitude relative to the conventional Gunn effect. Our first miniature picosecond pulsers cover the 100–200 GHz band and promise milliwatts up to ~500 GHz. Thanks to the method of interferometrically enhanced time-domain imaging proposed here and the low single-shot jitter of ~1 ps, our simple imaging system provides sufficient time-domain imaging contrast for fresh-tissue terahertz histology. © 2018 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/). https://doi.org/10.1063/1.5022453

The currently dominant terahertz time-domain spectroscopy and imaging technique is based on laser-driven pulse systems,1–4 the practical use of which is limited by their large size, high cost, and high power consumption. The option of miniaturizing the CW solid-state sources5–7 by means of SiGe CMOS or III–V hetero-bipolar transistor (HBT)/HEMT integrated circuits8,9 compatible with on-chip antennas10 suffers from complexity and low (sub-mW) power. Higher power, in the sub-terahertz range, can be obtained at the expense of further complication, costs, and size by using multipliers and amplifiers,11,12 or in the THz range using quantum cascade lasers,13 which require cryogenic temperatures.

Current trends in high-resolution THz imaging rely on both detector and emitter arrays1,4 offering real-time operation but requiring simple, miniature and energy-efficient solid-state sources. The simplest ever microwave oscillator based on the Gunn effect has an inherent limitation of about 80 GHz on its fundamental mode of operation with traditionally used GaAs. Use of hot electron injection,15 advanced semiconductor materials, and planar technology16 pushed the fundamental-mode frequency to 200–300 GHz, making the performance of the Gunn oscillators in the sub-THz band comparable to that of sub-millimetre IC, although their efficiency and output power remained low.

A recently discovered physical phenomenon termed the collapsing field domain (CFD)17 provides an original approach to the problem. First found in high-voltage (~100–500 V) GaAs bipolar junction transistors (BJTs) during their superfast18,19 (picosecond) avalanche switching, these domains were proved in other experiments.17 Later, the same domains interpreted the old puzzle of superfast switching and lock-on in a bulk GaAs optically triggered switch.20 Despite the fact that the GaAs structures of the high-voltage avalanche transistors mentioned above, optically triggered switches20 and the low-voltage sub-micron THz emitters suggested here differ drastically from each other, the properties of the CFDs in all these structures are the same. The collapsing domains are physically caused by negative differential mobility (NDM) in extreme electric fields (above the ionization threshold),21 and the most detailed experimental and numerical investigation into their properties was undertaken using both hydrodynamic22 and drift-diffusion17,19,23 approaches for high-voltage bipolar transistors. This study inspired the idea of realizing CFD in a miniature, low-voltage source in which a nano-scale domain circulating in a sub-micron active layer would produce pulsed sub-THz emission.

We present here a description of the original source and its operation principle which has allowed sub-picosecond time-domain imaging (TDI) resolution to be achieved and a method to be developed, termed here interferometrically enhanced time-domain imaging (IE-TDI). This method provides an order of magnitude improvement in time-of-flight imaging contrast. The basic architecture of our sub-THz source, having a BJT structure with a submicron n0 collector layer, is shown...
resistivity for heavily doped InGaAs layers ranged from to have a specific contact resistivity to the emitter as low as loop inductance below “external circuit” also realized on the chip provided total ensured as low parasitic inductance as a few pH, while the “external circuit” also realized on the chip provided total loop inductance below ~1 nH. It is important for our device to have a specific contact resistivity to the emitter as low as

$$0.6 \times 10^{-7} \Omega \times \text{cm}^2$$

since the current density in the switching channels reaches ~10⁷ A/cm². In our processes, the contact resistivity for heavily doped InGaAs layers ranged from $2 \times 10^{-7}$ to $6 \times 10^{-7} \Omega \times \text{cm}^2$, while for GaAs heavily doped with tellurium, the resistivity did not typically exceed $0.6 \times 10^{-7} \Omega \times \text{cm}^2$.

Of prime importance for device operation is avalanche switching, which implies avalanche injection into the $n_0$ layer ($\leq 0.7 \mu \text{m}$ in thickness) of the impact-generated holes that in turn cause electron injection from the emitter across the p–base. Biased initially to the voltage close to the base–emitter resistance. Direct on-chip connections of the emitter and collector ohmic contacts to the antenna flares ensured as low parasitic inductance as a few pH, while the “external circuit” also realized on the chip provided total loop inductance below ~1 nH.

Initial measurements of the resulting THz emission have been made using a large elliptical mirror. The chip was placed at one focus of the mirror while the receivers (zero bias Schottky detectors of Virginia Diodes equipped with horn antennas) were mounted near the other focus. The travel time of CFD across the $n_0$ layer (10 ps) determines the period of sub-THz emission, while the wave train length is determined by the current pulse duration (discharge time of capacitor C). Sub-THz current oscillations pass across the on-chip antenna and cause emission of the wavetrain [coloured blue in Fig. 1(a)], with a central oscillation frequency $f_0$ determined by the domain transit time.

The low-ohmic load and very low $\beta$ prevent the collector voltage reduction due to base current amplification that would happen in “linear” hetero-bipolar transistor (HBT) amplifiers. (HBT with low-ohmic load might be applicable as well, but with various complications. In particular, a static high-field domain in hetero-emitter competing with moving CFDs may appear, and thus the development of a HBT-based avalanche sub-THz source is an open question). The electron injection modifies the collector field domain in such a way that the peak in the electric field arises at the $n_0$–n’-collector interface, exceeding the ionization threshold. The resulting double injection of the electrons and holes creates electron-hole plasma in the $n_0$ layer. Then, CFD forms at the base-collector interface and starts moving towards the $n^+$ subcollector provided the current density exceeds ~1 MA/cm². [Note the three domains of ~0.4–0.6 MV/cm in amplitude and ~100–50 nm in width simulated in this work and shown in Fig. 1(a)]. Despite the extreme current density in the channel and the electric field amplitudes, there is no danger for the device, as a CFD circulates for only a limited time (~100 ps) and the lattice overheating after a single avalanche switching is only ~30 K.

Unlike the large number of CFDs coexisting in the $n_0$ layer of a high-voltage transistor, the single CFD circulates in the submicron $n_0$ collector of this our device as in a Gunn diode: nucleating near the anode (base) and annihilating at the cathode ($n^+$-subcollector). The travel time of CFD across the $n_0$ layer (<10 ps) determines the period of sub-THz emission, while the wave train length is determined by the current pulse duration (discharge time of capacitor C). Sub-THz current oscillations pass across the on-chip antenna and cause emission of the wavetrain [coloured blue in Fig. 1(a)], with a central oscillation frequency $f_0$ determined by the domain transit time.
replaced with a Golay cell. Alternatively, for the transmission imaging mode, the source was glued onto hyper-hemispherical silicon lens and the THz pulse was further collimated using a polytetrafluoroethylene (PTFE) lens of focal length 10 mm.

Figure 2 illustrates the advantage of using for the transmission TDI a second-generation source with single-shot jitter reduced from the \(~10\) ps (typical of the first generation) to \(~1\) ps and a somewhat increased central frequency of the wavetrain. The much better shape stability and lower jitter of the second-generation source require detailed discussions and will be presented elsewhere.

Due to the significant improvement in the spatial resolution and quality of the image (compare (a) and (b) in Fig. 2), more challenging applications can now be addressed. Sub-picosecond precision is needed, e.g., for differentiating healthy and malignant areas in freshly excised tissue slices, and this may open the way to intra-operative real-time histology in cancer surgery (as a replacement for the laboratory-demonstrated optoelectronic THz TDI approach, which suffers from the large setup size, high costs, etc.). In our transmission experiments with fresh samples of breast tissue, the time delay corresponding to a slice thickness of 200 \(\mu m\) was around 1 ps, with the jitter reduced to \(~0.1–0.3\) ps by averaging 100 measurements. Such accuracy is not sufficient for reliable cancer detection, while any further increase in slice thickness would reduce the transmitted signal. To solve this dilemma, we suggest interferometric enhancement (IE) for a significant improvement in TDI contrast. This IE-TDI method utilizes the reflection mode and the intrinsic properties of the wavetrains emitted by our source.

We used an original reflection-mode setup permitting only a \(~30\%) reduction in the amplitude of the emitted pulse instead of the \(75\%) reduction optimistically expected in the traditional scheme employing a THz beamsplitter. A hollow dielectric waveguide with an internal diameter of 20 mm (termed a beamguide\(^{29}\) ) was excited at the centre by an emitter chip glued onto a Si lens, and the resulting wavefront was focused on the tissue slice using a PTFE lens (25.4 mm in diameter, focal length 25 mm). The reflected wave spreading back in the beamguide crossed the excitation point and was collected by a horn into the waveguide of the Schottky detector. The system resolution was \(~3.5\) mm.

The tissue slice was placed on a quartz substrate backed with a metal mirror, and the contrast between the cancerous and healthy tissues was then evaluated from the variations in the time delay of the reflected signal during 2-D scanning of the sample. The waves reflected from the metal mirror and the quartz surface [Fig. 3(a)] interfere constructively [Fig. 3(b)] or destructively [Fig. 3(c)], causing shifts in the leading edge of the resultant pulse [Fig. 3(d)]. The time delay in the envelope of the reflected sub-THz pulse was calculated by the spectral method. The results of the numerical calculations and corresponding experimental points are given in Fig. 3(e) for two substrate materials, quartz and polyethylene terephthalate (PETP). The shape of wavetrain used is shown in Fig. 3(e).

**FIG. 3.** Principle of contrast enhancement for a time-delay image. (a)–(d) Interference of wavetrains reflected from the metal mirror [coloured black in the draft (a) and graphs (b) and (c)] and those reflected from the top surface of the dielectric layer (blue) modifies the resulting wavetrain shape in a manner dependent on the dielectric thickness \(d\) (magenta for \(d_1\) and red for \(d_2\)). In-phase interference for thickness \(d_1\) in (b) results in a reduced delay \(\Delta d\) in the wavetrain envelope as recorded by the Schottky detector (d), because top reflection lifts the leading edge whereas the reverse phase (c) acts conversely, thus increasing the delay. (e) The simulated (solid black) and measured (scattered black) values for the dependence of the pulse delay \(\Delta d\) on the dielectric thickness are shown together with interference-ignored delay \((\text{dielectric layer})\) in (b) results in a reduced delay \(\Delta d\) in the wavetrain envelope as recorded by the Schottky detector (d), because top reflection lifts the leading edge whereas the reverse phase (c) acts conversely, thus increasing the delay. (e) The simulated (solid black) and measured (scattered black) values for the dependence of the pulse delay \(\Delta d\) on the dielectric thickness are shown together with interference-ignored delay \((\text{dielectric layer})\) in (b) results in a reduced delay \(\Delta d\) in the wavetrain envelope as recorded by the Schottky detector (d), because top reflection lifts the leading edge whereas the reverse phase (c) acts conversely, thus increasing the delay. (e) The simulated (solid black) and measured (scattered black) values for the dependence of the pulse delay \(\Delta d\) on the dielectric thickness are shown together with interference-ignored delay \((\text{dielectric layer})\) in (b) results in a reduced delay \(\Delta d\) in the wavetrain envelope as recorded by the Schottky detector (d), because top reflection lifts the leading edge whereas the reverse phase (c) acts conversely, thus increasing the delay. (e) The simulated (solid black) and measured (scattered black) values for the dependence of the pulse delay \(\Delta d\) on the dielectric thickness are shown together with interference-ignored delay \((\text{dielectric layer})\) in (b) results in a reduced delay \(\Delta d\) in the wavetrain envelope as recorded by the Schottky detector (d), because top reflection lifts the leading edge whereas the reverse phase (c) acts conversely, thus increasing the delay. (e) The simulated (solid black) and measured (scattered black) values for the dependence of the pulse delay \(\Delta d\) on the dielectric thickness are shown together with interference-ignored delay (linear, relative to that in air, dashed black line) for PETP (refractive index \(n = 1.6\) ) in the quartz substrate (\(n = 1.95\) ), as presented by the orange line (dashed line for “linear” regime, ignoring interference) and experimental points. The fractions of the curve highlighted in blue and red are those used in cancer mapping, as shown in Fig. 4. For 1.0 mm and 1.2 mm quartz substrates the dependence of the delay on thickness is an order of magnitude steeper than that shown by the dashed line, implying drastic contrast enhancement.
The amplitude image [Fig. 4(c)], while the time-delay image [Fig. 4(e)], corresponding to the current medical trend for point-of-care diagnostics. Malignant tissue requires recording TDI delay differences of conventional amplitude and time-delay images (Fig. 4).

The poorest cancer/image correlation was observed in the amplitude image [Fig. 4(c)], while the time-delay image [Fig. 4(d)] is considerably better, despite the fact that the time-delay contrast of ~1 ps does not seem to be quite sufficient. Significant improvements were achieved using IE-TDI even for thinner tissue samples of 100 μm, providing a direct contrast of +5 ps for a 1.2 mm quartz submount and a reverse contrast of ~13 ps for 1.0 mm (see images (e) and (f) in Fig. 4).

More complicated differentiation between fibrous and malignant tissue requires recording TDI delay differences of ~0.2 ps, which are hardly measurable by conventional transmission, while IE-TDI can resolve this challenging task. The proposed method is therefore well suited for intra-operative detection of malignant tissues and corresponds to the current medical trend for point-of-care diagnostics.

In summary, the miniature sub-THz source suggested here is well suited for high-resolution imaging arrays, and its combination with the IE-TDI method approaches the time-domain contrast obtainable at present only with bulky and costly optoelectronic systems.

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FIG. 4. Images of similar (but not precisely identical) slices made one-by-one using the same fresh-frozen breast tumour specimen. (a) Photo; (b) histology, in which the cancer area is tinged violet-pink, the pink “islands” corresponding to the fibrous tissue and the transparent zone to the fat tissue. (c) Amplitude image of a slice of thickness 100 μm mounted on a 1.2 mm quartz submount and measured in the reflection mode. (d) Time-domain image of a slice of thickness 200 μm on a 1.2 mm quartz submount obtained in the transmission mode. (e) Time-domain image of a slice of thickness 100 μm on a 1.2 mm quartz submount in the reflection mode, and (f) time-domain image of a slice of thickness 100 μm on a 1.0 mm quartz submount obtained in the reflection mode. The transmission image in (d) shows a small positive cancerous area contrast ~1 ps (comparable to the single-shot jitter), the reflection image in (e) achieves a ~3 to 4-fold improvement with positive (+5 ps) contrast (see slope highlighted in red in Fig. 3(e)), and (f) presents an even better negative contrast (~13 ps) corresponding to the slope highlighted in blue in Fig. 3(e).

1M. Tonouchi, “Cutting-edge terahertz technology,” Nat. Photonics 1, 97–105 (2007).
2E. Castro-Camus and M. Alfar, “Photoconductive devices for terahertz pulsed spectroscopy: A review [Invited],” Photonics Res. 4, A36–A42 (2016).
3P. U. Jepsen, D. G. Cooke, and M. Koch, “Terahertz spectroscopy and imaging – modern techniques and applications,” Laser Photonics Rev. 5, 124–146 (2011).
4N. Vieweg, F. Röttich, A. Deninger, H. Roehle, R. Dietz, T. Göbel, and M. Schell, “Terahertz-time-domain spectrometer with 90 dB peak dynamic range,” J. Infrared, Millimeter, Terahertz Waves 35, 823–832 (2014).
5O. Momeni and E. Afshari, “High-power terahertz and millimeter-wave oscillator design: A systematic approach,” IEEE J. Solid-State Circuits 46, 583–597 (2011).
6S. Kang, S. V. Thyagarajan, and A. M. Niknejad, “A 240 GHz fully integrated wideband QPSK transmitter in 65 nm CMOS,” IEEE J. Solid-State Circuits 50, 2256–2267 (2015).
7K. Sengupta and A. Hajimiri, “A 0.28 THz power generation and beam-steering array in CMOS based on distributed active radiators,” IEEE J. Solid-State Circuits 47, 3013–3031 (2012).
8M. Seo, M. Urteaga, J. Hacker, A. Young, Z. Griffith, V. Jain, R. Priester, P. Rowell, A. Skalare, A. Peralta, R. Lin, D. Lin, D. Pukala, and M. Rodwell, “InP HBT IC technology for terahertz frequencies: Fundamental oscillators up to 0.57 THz,” IEEE J. Solid-State Circuits 46, 2203–2214 (2011).
9T. Jensen, T. Al-Sawaf, M. Lisker, S. Glisic, M. Elkhoully, T. Kraemer, I. Ostermayr, C. Meliani, B. Tillack, V. Krozer, O. Krueger, and W. Heinrich, “Millimeter-wave hetero-integrated sources in InP-on-BiCMOS technology,” Int. J. Microwave Wireless Technol. 6, 225–233 (2014).
10W. Steyaert and P. Reynaert, “A 0.54 THz signal generator in 40 μm bulk CMOS with 22 GHz tuning range and integrated planar antenna,” IEEE J. Solid-State Circuits 49, 1617–1626 (2014).
11G. Chattopadhyay, “Technology, capabilities, and performance of low power terahertz sources,” IEEE Trans. Terahertz Sci. Technol. 1, 33–53 (2011).
12R. Han and E. Afshari, “A high-power broadband passive terahertz frequency doubler in CMOS,” IEEE Trans. Microwave Theory Tech. 61, 1150–1160 (2013).
13J. Faist, F. Capasso, D. L. Sivco, C. Sirtori, A. L. Hutchinson, and A. Y. Cho, “Quantum cascade laser,” Science 264, 553–556 (1994).
14U. R. Pfeiffer, Y. Zhao, J. Grzyb, R. A. Hadi, N. Sarmah, W. Förster, H. Rücker, and B. Heinemann, “A 0.53 THz reconfigurable source module with up to 1 mW radiated power for diffuse illumination in terahertz imaging applications,” IEEE J. Solid-State Circuits 49, 2938–2950 (2014).
15A. Förster, M. I. Lepsa, D. Freundt, J. Stock, and S. Montanari, “Hot-electron injector Gunn diode for advanced driver assistance systems,” Appl. Phys. A 87, 545–558 (2007).
16A. Khalid, O. M. Dunn, R. F. Macpherson, S. Thom, D. Macintyre, C. Li, M. J. Steer, V. Papageorgiou, I. G. Thayne, M. Kuball, C. H. Oxley, M. Montes Bajo, A. Stephen, J. Glover, and D. R. S. Cumming, “Terahertz oscillations in an In0.53Ga0.47As submicron planar Gunn diode,” J. Appl. Phys. 115, 114502 (2014).
17S. Vainshtein, J. Kostamovaara, V. Yuferov, W. Knap, A. Fatimy, and N. Diakonova, “Terahertz emission from collapsing field domains during switching of a gallium arsenide bipolar transistor,” Phys. Rev. Lett. 99, 176601 (2007).
18. S. Vainshtein, V. Yuferev, and J. Kostamovaara, “Ultra-high field multiple Gunn domains as the physical reason for superfast (picosecond range) switching of a bipolar GaAs transistor,” J. Appl. Phys. 97, 024502 (2005).
19. S. Vainshtein, J. Kostamovaara, Y. Sveshnikov, S. Gurevich, M. Kulagina, V. Yuferev, L. Shestak, and M. Sverdlov, “Superfast high-current switching of a GaAs avalanche transistor,” Electron. Lett. 40, 85–86 (2004).
20. L. Hu, J. Su, Z. Ding, Q. Hao, and X. Yuan, “Investigation on properties of ultrafast switching in a bulk gallium arsenide avalanche semiconductor switch,” J. Appl. Phys. 115, 094503 (2014).
21. S. Vainshtein, V. Yuferev, V. Palankovski, D. S. Ong, and J. Kostamovaara, “Negative differential mobility in GaAs at ultra-high fields: Comparison between an experiment and simulations,” Appl. Phys. Lett. 92, 062114 (2008).
22. V. Palankovski, S. Vainshtein, V. Yuferev, J. Kostamovaara, and V. Egorkin, “Effect of hot-carrier energy relaxation on main properties of collapsing field domains in avalanching GaAs,” Appl. Phys. Lett. 106, 183505 (2015).
23. S. Vainshtein, V. Yuferev, J. Kostamovaara, M. Kulagina, and H. Moilanen, “Significant effect of emitter area on the efficiency, stability and reliability of picosecond switching in a GaAs bipolar transistor structure,” IEEE Trans. Electron Devices 57, 733–741 (2010).
24. T. Bowman, M. El-Shenawee, and L. K. Campbell, “Terahertz transmission vs reflection imaging and model-based characterization for excised breast carcinomas,” Biomed. Opt. Express 7, 3756–3783 (2016).
25. A. M. Hassan, D. C. Hufnagle, M. El-Shenawee, and G. E. Pacey, “Terahertz imaging for margin assessment of breast cancer tumors,” in Proceedings of the 2012 IEEE MTT-S International Microwave Symposium Digest (MTT), 17–22 June (2012), p. 3.
26. E. A. J. Marcatili and R. A. Schmeltzer, “Hollow metallic and dielectric waveguides for long distance optical transmission and lasers,” Bell Syst. Tech. J. 43, 1783–1807 (1964).