New Era of Ultra-Broadband Terahertz Spectroscopy

30 THz-bandwidth spintronic THz emission enabled by a new class of compact fs lasers

The realization of practical 30 THz bandwidths marks a major milestone in the evolution of THz technology. Enabled by a new generation of compact and easy-to-use laser sources, ultra-broadband THz spectroscopy can now deliver spectral information far beyond the reach of conventional few-THz systems. Access to frequencies up to 30 THz unlocks new opportunities for material fingerprinting, semiconductor inspection, battery analysis, process monitoring, and non-destructive testing, paving the way for the next generation of scientific and industrial THz applications

Background

Currently, terahertz (THz) technology is mainly used for industrial applications, such as non-destructive coating- and paint-thickness measurements in the automotive industry. Yet these applications represent only a fraction of its potential. Moving from THz systems, with bandwidths of a few terahertz, toward more than 30 THz would yield significantly richer information about materials and physical processes. This approach could enable non-destructive spectroscopic analysis of pharmaceuticals, batteries, semiconductors and advanced materials, revealing their composition, purity and structural properties without physical contact. Beyond sensing, the enormous 30 THz bandwidth would be highly interesting for future communication systems, potentially enabling data transmission rates in the terabit-per-second regime (Figure 1).

However, broadband and gapless THz pulse generation from 1 to >30 THz is intimately linked to the availability of ultrashort laser pulses (duration <30 fs), which continues to pose a challenge. Recent advances in compact femtosecond laser technology are beginning to remove this barrier. By combining pulse durations near 30 fs with high average power, operational stability, passive cooling and compact form factors, a new generation of laser platforms is enabling THz bandwidths that were previously difficult to achieve outside specialized research laboratories.

In this white paper, we demonstrate how a compact 30 fs laser system enables broadband THz emission spectroscopy with experimentally measured bandwidths approaching 30 THz. More importantly, we discuss why this development represents more than a performance milestone. It marks an important step in the evolution of THz technology from a specialized scientific tool toward a practical sensing platform capable of revealing previously inaccessible information about the physical world.

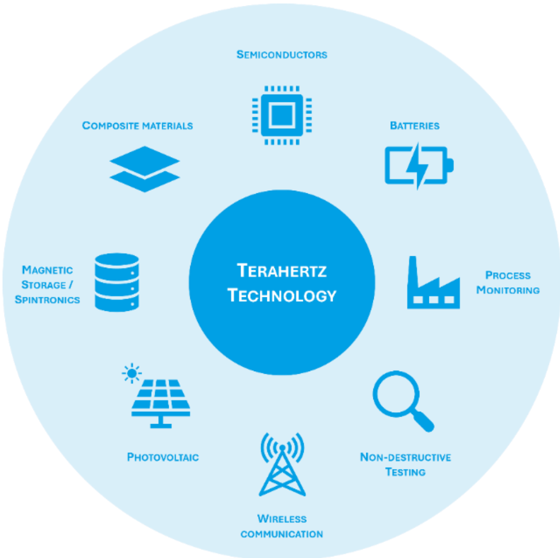

Figure 1: Application potential of THz technology across science and industry. Broadband THz technologies have the potential to be used in a wide range of scientific and industrial applications, such as semiconductors, batteries, wireless communication beyond 6G, photovoltaics, magnetic storage and computing/spintronics as well as composite materials. In addition, broadband THz systems can be used for process monitoring and non-destructive testing of materials.

Understanding Hidden Material Dynamics

Many of the properties that determine the performance of modern materials are governed by processes that occur on extraordinarily short timescales. For example, in advanced semiconductor devices, magnetic storage devices, batteries or emerging quantum systems, relevant functionality often depends on ultrafast charge and/or spin transport, interfacial interactions and lowenergy excitations that unfold within femtoseconds to picoseconds.

Although these processes play a central role in determining efficiency, reliability and overall device performance, they are often difficult to access directly by conventional measurement techniques. While electrical measurements typically provide only incomplete information and can require significant preparation time, optical techniques are often limited to surface observations. As technologies continue to become more complex and more highly integrated, the ability to observe these hidden dynamics is becoming increasingly important.

Broadband THz emission spectroscopy provides a unique way to address this challenge. As illustrated in Figure 2, an ultrashort optical laser pulse excites a nanometer-thin stack consisting of a ferromagnetic (F) and a non-magnetic (N) layer and triggers ultrafast spintronic processes that subsequently emit a broadband THz electromagnetic pulse [1]. Because the emitted THz transient directly reflects the dynamics of the underlying generation processes inside the material system, it provides a powerful tool for studying physical processes on their natural timescale [2].

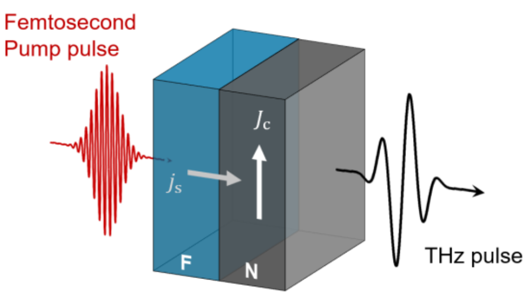

Figure 2: Spintronic terahertz emission spectroscopy. A femtosecond laser pulse (red) excites a thin-film stack consisting of a ferromagnetic layer (F) and a non-magnetic layer (N) and launches a spin current j_s. In N, j_s is converted into a transverse charge current J_c by the inverse spin Hall effect. Due to the pulsed excitation, J_c is time-dependent and acts like an antenna emitting an electromagnetic pulse (black) with frequencies extending to the THz range. Such spintronic terahertz emitters recently became commercially available through TeraSpinTec GmbH.

The scientific value of this approach has been recognized for many years [3]. However, realizing its full potential requires THz pulses with sufficient bandwidth to capture the relevant physical processes. This requirement is directly linked to one of the most important enabling technologies in modern THz spectroscopy: the laser.

The performance of a broadband THz system is ultimately determined by the quality of its optical excitation. While the emitter architecture plays a critical role, the achievable THz bandwidth originates from the properties of the laser system employed. First, femtosecond optical pulses generate equally fast electronic dynamics within the emitter, and these dynamics determine the spectral content of the resulting THz radiation. Second, the detection of broadband THz electric fields using methods, such as electro-optic sampling [4], also depends on the quality of the laser system used, since the optical pulses are employed to sample the THz field. Thus, noise characteristics, power and pointing stability play a central role for obtaining a high signal-to-noise ratio during THz detection. In conclusion, pulse quality and especially its duration become key parameters governing the performance of broadband THz spectroscopy.

For many years, generating sufficiently short optical pulses required large and complex ultrafast laser systems. While these systems enabled groundbreaking scientific discoveries, their size, complexity, and infrastructure requirements limited the broader deployment of THz technology. Recent advances in compact femtosecond laser technology are fundamentally changing this situation.

The VALO Femtosecond Series Tidal-30-3 laser used in this work can deliver sub-30 fs pulse durations at power levels of more than 3 W while operating in a compact, passively cooled architecture. Figure 3 presents a typical pulse characterization of the system, revealing a pulse duration of 28 fs. The measured pulse duration demonstrates that compact femtosecond laser technology is now capable of providing the ultrafast optical excitation required for next-generation THz systems without the complexity traditionally associated with laboratory-scale ultrafast lasers.

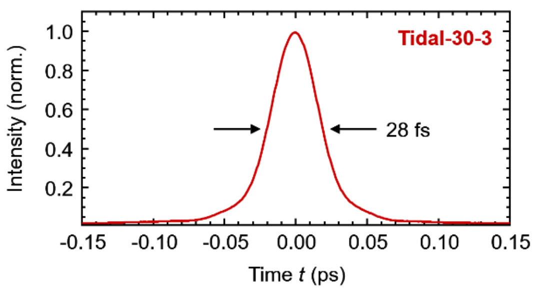

Figure 3: Laser pulse characterization. Intensity autocorrelation signal (red) of femtosecond laser pulses from a VALO Femtosecond Series Tidal-30-3 laser. The pulse duration is measured to be 28 fs.

This development represents more than an improvement in laser performance. It provides a practical foundation for broadband THz generation and creates new opportunities for deploying THz systems beyond highly specialized research environments.

Enabling Ultra-Broadband Spintronic THz Generation

Broadband THz emission spectroscopy measurements were performed using a spintronic THz emitter (TeraSpinTec GmbH) driven by the VALO Femtosecond Series Tidal-30-3 laser. The impact of ultrashort optical excitation becomes apparent when examining the generated THz signals and corresponding spectra that are shown in Figure 4(a)-(b). Even under standard laboratory conditions, the measured signal exhibits a dynamic range of approximately 75 dB while extending to nearly 30 THz.

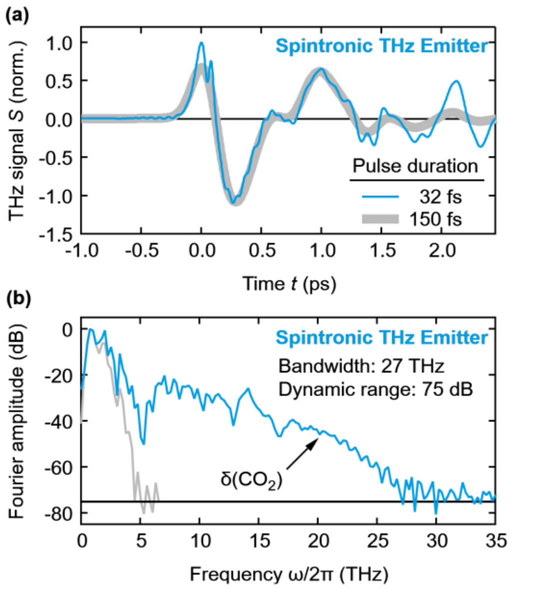

Figure 4: THz emission signal from a spintronic THz emitter. (a) Measured THz signal as a function of time t from a spintronic THz emitter (blue), normalized to its maximum value. In this case a laser power of 2.3 W and a pulse duration of 32 fs was used. For comparison, the gray waveform is a low-pass-filtered version of the blue signal, assuming pump pulses with a duration of 150 fs. (b) Fourier-transform spectra of the THz waveforms shown in panel (a) using the same color code. The horizontal black line indicates the noise level, which gives a dynamic range of 75 dB after five minutes of measurement time and an overall bandwidth of 27 THz (blue) and 4.5 THz (gray) for incident pump pulse duration of 32 fs and 150 fs, respectively.

These measurements demonstrate that compact femtosecond laser technology can support THz bandwidths that were previously associated with significantly larger and more complex laser infrastructures. More importantly, they confirm that broadband THz spectroscopy is moving beyond the traditional few-THz regime that has defined many commercial THz systems over the past decades.

The importance of pulse duration becomes even clearer when the optical excitation conditions are varied as shown in Figure 4(a)-(b) as a gray solid line. For an excitation with laser pulses of commonly used 150 fs, the bandwidth is significantly reduced to 4.5 THz. Moreover, Figure 5 compares the underlying charge-current dynamics inside the spintronic THz emitter for an additional pulse duration of 100 fs. In general, as optical pulses become shorter, the underlying dynamics become increasingly clearer, which enables access to valuable insights into ultrafast processes operating in the few to tens of femtoseconds regime.

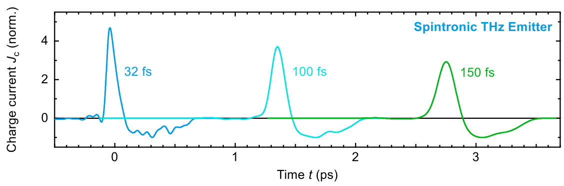

Figure 5: Charge-current dynamics $J_c(t)$ retrieved from the measured THz signals from a spintronic THz emitter for three different pump pulse durations: 32 fs (blue), 100 fs (turquoise) and 150 fs (green), all normalized to their respective minimum.

In addition, a high THz bandwidth offers the opportunity of detecting material-specific fingerprints, such as the dip at 5 THz (Figure 4(b)), which represents a lattice vibration (phonon) in the crystalline ZnTe detector used, or the features between 12 and 17 THz, which provide clear evidence of the sapphire substrate material of the spintronic THz emitter (Figure 4(b)). Additionally, Figure 4(b) provides clear evidence of a vibrational mode of the CO_2 molecule $\delta(CO_2)$ at 20 THz present in the laboratory air [5].

The full potential of THz sensing becomes more apparent when ultrashort optical excitation is combined with advanced THz emitter architectures as demonstrated in Ref. [6]. Here, merging of a broadband, gapless THz source and a semiconductor-based crystalline emitter, such as GaSe, unlocks even more broadband spectra for a given pulse duration. Figure 6 illustrates the achievable bandwidth of 30 THz with only a 90 µm-thick GaSe crystal, so no hybrid emitter design yet. However, using next-generation emitter architectures, measurable THz bandwidths extending beyond 30 THz can be easily achieved.

All shown experiments provide direct evidence of the relationship between optical pulse duration and achievable THz bandwidth. While the exact spectral response depends on the emitter material and system configuration, the broader implication is clear. Compact femtosecond laser technology is no longer the limiting factor. Instead, it is becoming the enabling technology that allows increasingly sophisticated THz emitters and system architectures to unlock previously inaccessible regions of the THz spectrum with a single THz source.

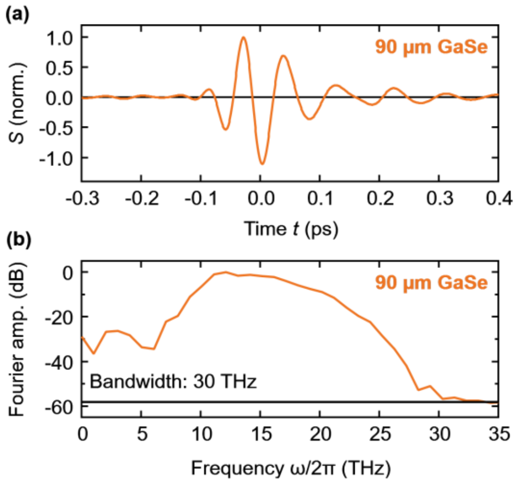

Figure 6: THz emission signal from a GaSe crystal. (a) Normalized THz signal S(t) (orange) of a z-cut GaSe crystal with a thickness of 90 μm. (b) Fourier spectrum of the waveform from panel (a). The black line indicates the average noise floor, from which a bandwidth of 30 THz and a dynamic range of 58 dB can be determined.

From Spectroscopy to Material Intelligence

At first glance, the difference between a 6 THz and a 30 THz time-domain spectroscopy system may appear to be a simple increase in bandwidth. In practice, the impact is far greater. Extending the accessible spectrum dramatically increases the amount of information that can be extracted from materials in all states of matter: solid, liquid or gaseous. Additional molecular signatures become accessible, material fingerprints become more distinct as shown in Figure 4(b), and ultrafast dynamics can be observed with greater temporal resolution. In many aspects, the transition resembles the evolution from a conventional single-parameter material characterization to multiparameter material sensing in a hard-to-access but very important frequency region. The objective is no longer simply to detect an object or observe a signal. The objective is to obtain a richer and more meaningful understanding of the underlying material system and its femtosecond dynamics.

The significance of ultra-broadband THz technology extends far beyond spectroscopy itself. As bandwidth increases and system architectures become more practical, THz technology could begin to evolve from a specialized measurement technique into a broader material sensing platform. The common thread across many emerging applications is not the acquisition of more data, but the acquisition of better information.

In semiconductor manufacturing, broadband THz systems may provide new ways of inspecting structures that are invisible to conventional optical methods. In battery production, they may help monitor material changes and degradation processes long before they become visible to traditional inspection techniques. In pharmaceutical manufacturing, they may provide new methods for identifying chemical composition and product integrity without opening a package. Similar opportunities exist in advanced manufacturing, non-destructive testing, quality assurance and materials development. The connection of these applications is the growing need to understand materials deeply rather than to simply observe or test them.

Over the past decades, digital technologies have transformed the way information is generated, processed and exchanged. Artificial intelligence (AI) is now transforming how meaning is extracted from this information. As digital systems become increasingly intelligent, the demand for richer information about the physical world will continue to grow. Future industrial systems, autonomous machines and AI-driven infrastructure will require more than images and sensor readings. But many of the physical properties that govern the behavior of materials, devices and industrial processes remain largely inaccessible to today's digital systems.

Broadband THz technology provides a pathway toward this future. By providing direct access to the material composition, structural state and dynamic behavior of matter, ultra-broadband THz technologies may help close this gap. In this sense, the significance of broadband THz spectroscopy extends far beyond a new measurement capability. It represents an important step toward a future in which digital systems can interact with the physical world not only through observation, but through a deeper understanding of the materials and processes that define it.

References

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Authors

Dr. Oliver Gueckstock
Postdoctoral Researcher - Freie Universität Berlin, Department of Physics, Berlin, Germany
Dr. Quentin Remy
Postdoctoral Researcher - Freie Universität Berlin, Department of Physics, Berlin, Germany
Dr. Tom S. Seifert
Senior Research Scientist - Freie Universität Berlin, Department of Physics, Berlin, Germany
Prof. Dr. Tobias Kampfrath
Professor - Freie Universität Berlin, Department of Physics, Berlin, Germany
Francisco van Riel Neto
Product Manager - VALO Innovations GmbH – A Part of HÜBNER Photonics, Hannover, Germany
Dr. Oliver Prochnow
CEO - VALO Innovations GmbH – A Part of HÜBNER Photonics, Hannover, Germany