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Editorial mini-Review

Terahertz Radiation – the Dawn of a New Information Era

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Abstract - This mini-review article explores the evolution of wireless communication technologies, emphasizing the crucial role played by advancements in information transfer over long distances with minimal errors. Tracing developments from submergible cables to the current 5G technology, the review discusses the potential of 6G, offering insights into the transformative applications it could enable, such as holographic real-time communication and autonomous transport infrastructure. Exploring the applications of Terahertz (THz) frequencies, the article presents the limitations of current wireless speeds and proposes solutions, including the use of spintronic terahertz emitters (STEs) and antiferromagnetic materials, concluding on the challenges and prospects of integrating these technologies into practical applications.

Keywords - Terahertz radiation; 6G; Spintronic terahertz emitters, Antiferromagnets

1 Information (data) transfer – a brief histoy

The most important development of the last century which pushed the technological advancement of humanity is undoubtably the ability to transfer information over long distances in a short amount of time with a low error rate. With humble beginnings and reliance on submergible cables, human operators and a simple encryption mechanism, physicists and engineers worked tirelessly towards improving the efficiency of information transfer. It is easy to throw a few specialist terms in the conversation such as latency, jitter, throughput, speed, bandwidth; call them key metrics and complain about any one of them when the ubiquitous wireless network fails to deliver in terms of reliability or response time.

A substantial leap was taken in the last 150 years although the core concept and requirements remain the same: we need more information transferred faster and over longer distances, wirelessly and efficiently. What have we missed? A lifetime of development in material and computer science together with the associated engineering demands if we start the clock at the discovery of the transistor. It is however comforting to realise that the driving technology available to humans is still tool making and this will never change. The tool however is rather small, soon to measure about 10 atoms across and be densely packed on a piece of silicon. It has also become one of the most protected pieces of intellectual property as of recently at a global level despite its negligible size.

2 The state of the art and glancing at the future

The newest technological trend when it comes to wireless data transfer has reached the fifth generation of development (5G) and it already has a noticeable impact on our daily lives boasting an impressive peak transfer rate of 10 Gbit (1.25 Gbyte)/s. This sounds especially impressive when compared to the technology available at the turn of the 21st century. The development continues and by simply adding 1 to the acronym we should gain two orders of magnitude in peak data rate and obtain 6G $\sim$ 125 Gbyte/s.

This would allow for the implementation of novel emerging technologies such as true holographic real time projection communication or self-driving autonomous mass transport infrastructure. The current needs can be met by increasing the operational frequency of wireless systems to Terahertz (THz) [1]. Considering the recent advancement and increasing popularity of cloud-based computing, the current limited wireless transfer speeds are seen as a bottleneck.

The other option would be to develop significantly superior processing units (cheap, fast and efficient) which can be integrated in most (semi)autonomous applications for real time processing. The issue with this is slightly more fundamental and involves circumventing the laws of quantum mechanics. Not to worry, we have already done the impossible and there are plenty more ways of doing it again.

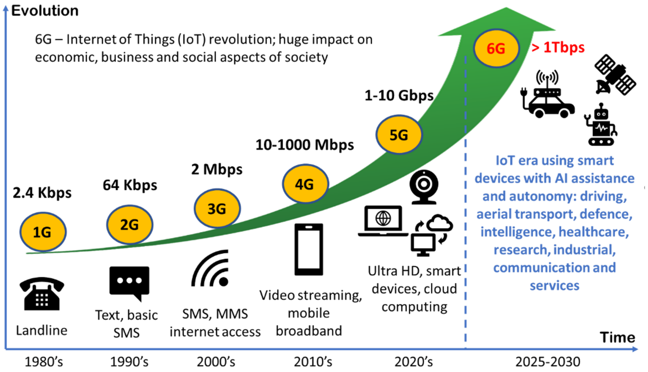

Figure 1: Historical trend and prediction of wireless communication technology with practical examples and associated data transfer rates.

3 Terahertz (THz) radiation – a promising alternative

The THz frequency band ranges between 100 GHz and 10 THz (generally accepted) although for the purpose of this discussion we will refer to research on true THz frequencies with corresponding wavelengths as low as 30µm. When compared to infrared (IR) and microwave radiation, the slow development for THz technologies is evident and the corresponding band has not yet been allocated [1]. The curious among us will demand an update on discoveries in the field and as a result of increasing interest from the scientific community and industry. A recent report presents and demonstrates the concept of optical fiber tip spintronics based THz emitters capable of spatial resolutions of 30µm when used for non-destructive imaging [2].

Spintronic terahertz emitters (STEs) are solid state nanodevices which convert an ultrashort laser pulse into a broadband THz pulse via: spin-current generation, spin to charge-current conversion and current-to-field conversion; all in a thin film stack comprised of a ferromagnetic metal and a normal (heavy) metal. The mechanism is based on spin-dependent super diffusive transport of optically excited electrons which contribute to spin injection aided by the inverse spin Hall effect.

The integration and results obtained of this device are impressive and will pave the way towards fully fiber-coupled spintronic THz systems as shown in Figure 2. There are however some aspects which can be improved such as the choice of spin pumping material – currently CoFeB, a well-known ferromagnet which requires an external bias field (the paper offers an alternative) and the lifetime of the device which suffers from degradation as a result of local heating [2].

The cycle repeats and it appears like scientists have already found a way (in principle) to couple the existing fiber-optic network to a nanometric transducer which could facilitate ultrafast wireless information transfer with some limitations caused by the type of materials used. Material scientists tend to be convinced by their ability to solve most technological problems by mixing different atoms together towards achieving their objectives and the first issue identified in the previous study was the utilization of a ferromagnetic alloy which requires and can be easily perturbed by stray magnetic field. The solution is simple: non-magnetic and non-metal replacement.

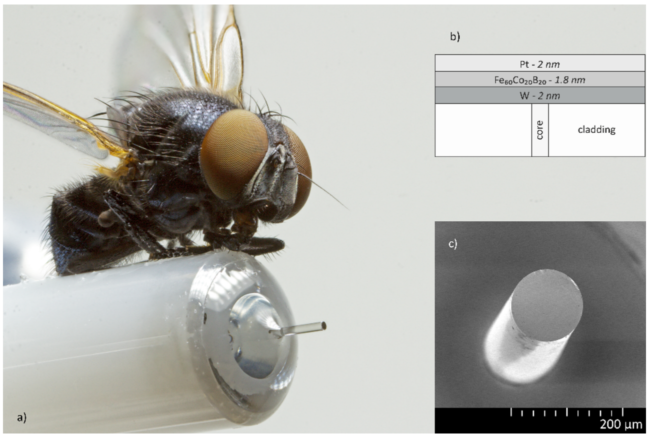

Figure 2: a) Fiber-tip spintronic THz emitter, Calyptratae for scale. b) Schematic diagram of the spintronic tri-layered structure. c) Scanning electron microscope image of the spintronic THz emitter which uses a 10 µm single mode laser waveguide [2].

4 Antiferromagnetic materials – from a passive to an active component

Antiferromagnets (AF) have been a mere curiosity for a long time until they became an integral part of spin valve structures (used in data storage) as pinning layers culminating with the integration in Magnetic Random Access Memories (MRAM). Recently however, the interest has shifted to the unique ability of these materials of emitting THz radiation as a result of intrinsic ultrafast spin dynamics.
Both broadband and narrowband corresponding THz signals corresponding to incoherent and coherent magnons were produced by NiO(AF)/Pt bilayers where the excitation process depends on the crystalline orientation of the antiferromagnetic NiO: (111) and (001). The paper shades light on the mechanisms behind the spin dynamics which are attributed to an off-resonant instantaneous optical spin torque and strain-wave-induced THz torque [3]; yet another way of coupling optical and high frequency wireless systems.

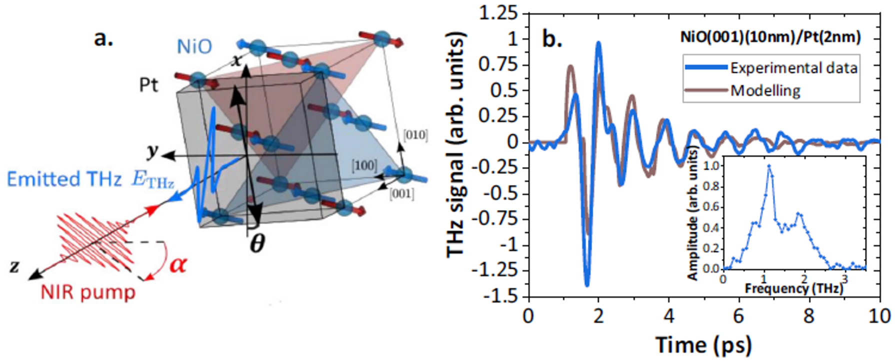

Figure 3: a) Schematic diagram of the experimental setup; crystal and magnetic structure of antiferromagnetic NiO. b) Time domain THz emission from NiO(001) (10nm)/Pt(2nm) bilayer modelled and measured; Inset: Fourier transform of time domain signal [3].

There seems to be no shortage of material-based solutions to the problem of generating THz radiation and we are now at the forefront of understanding the underlying physics behind emitting high frequency signals together with the associated material properties required for this process. There are plenty more avenues to be explored, one of which could be the integration of antiferromagnetic or compensated ferrimagnetic spin polarized Heusler alloys in bilayer structures as proposed previously [4].

5 Conclusions

The final question remains and it is always the same when it comes to predicted disruptive technology: when do we get to buy and use one? The answer is never an easy one and it always seems like the laws of physics go stubbornly against the inventor. THz radiation is high frequency, non-ionizing and already used in some security and quality control applications which require fast imaging. For wireless networks, the aim is to use the higher end of the spectrum and this comes with unique challenges such as very high spreading loss, frequency selective molecular absorption and very short penetration depth. On the flip side, the connection may only need to be sustained temporarily at high data rates for mobile applications.

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[2] Paries et al, Fiber-tip spintronic terahertz emitters, Opt. Express 31, 30884-30893 (2023) https://doi.org/10.1364/OE.494623. Fig. 2 was reproduced without modifications from the original manuscript cited above

[3] Rongione et al, Emission of coherent THz magnons in an antiferromagnetic insulator triggered by ultrafast spin–phonon interactions. Nature Communications 14, 1818 (2023) https://doi.org/10.1038/s41467-023-37509-6. Fig. 3 was reproduced without modifications from the original manuscript cited above following CC BY 4.0 Deed Attribution 4.0 International https://creativecommons.org/licenses/by/4.0/

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