Architecture and Component Characterization of a High-Resolution Free-Space Vector Network Analyzer for the Terahertz Range

A.D.J. Fernandez Olvera#1, A.F. Betancour*2,
C. de Dios*3, P. Acedo*4, and S. Preu#5
#Terahertz Devices and Systems, Dept. of Electrical Engineering and Information Technology,
Technische Universitt Darmstadt, Merckstr. 25, 64283 Darmstadt, Germany
*Sensors and Instrumentation Techniques, Electronic Technology Department,
Universidad Carlos III de Madrid
Av. de la Universidad 30, 28911 Leganes, Spain
{1fernandez, 5preu}@imp.tu-darmstadt.de, {2abetancu, 3cdios, 4pag, }@ing.uc3m.es

***Abstract* — The design of a free-space vector network analyzer (FS-VNA) to extract the electrical properties of materials for frequencies up to 2.7 THz is presented. It is based on 1.55 μm laser-driven photomixers, that serve as terahertz signal generators and coherent receivers. We describe the system architecture and the component performance supported by preliminary results.**

***Keywords* — VNA, THz, frequency combs, photomixers, photoconductive antennas**

I. INTRODUCTION

Designing photonic or electronic terahertz (THz) components requires precise knowledge of the electrical and dielectric properties of the component's materials. The two most common approaches to determine such properties in the THz range are

- a purely electronic approach that uses the local oscillator of a gigahertz (GHz) VNA and a chain of frequency multipliers to up convert/down convert the RF signal to a THz signal and back,
- an optoelectronic/photonic approach that uses lasers and photomixers to down convert an optical signal into a THz signal.

Although the electronic approach produces higher output power, a single system is limited in frequency coverage and maximum achievable frequency, as multiplier chains require metallic hollow core waveguides with limited single mode bandwidth (typically <50% of the center frequency). For covering a frequency range from 75 GHz (WR10) to 1.5 THz (WR0.65), typically 5 to 8 extender subsystems are required. To date, there are no commercial extender subsystems available for frequencies above 1.5 THz [1].

The optoelectronic approach, in contrast, does not require any waveguides and the only bandwidth limitation comes from the carrier dynamics in the photoconductive material of the photomixer and its antenna [2], typically allowing for 3-4 THz frequency coverage in continuous wave (CW) operation [3], [4]. Under pulsed operation, photonic FS-VNAs can easily reach 3 THz [5], with a hard limit around 6.5 THz [6], [7] due to signal-to-noise limitations of the photocondutors. Pulsed systems, however, only provide a resolution on the order of 1-10 GHz, which might not be enough for characterizing components with high quality factors.

Here, we present a design based on the generation of a high-resolution THz signal, with the the potential to reach Hz level, by mixing two optical modes of a frequency comb in a photomixer. This work focuses on the design aspects and the individual component performance of such photonically-enabled CW FS-VNA.

II. VNA ARCHITECTURE

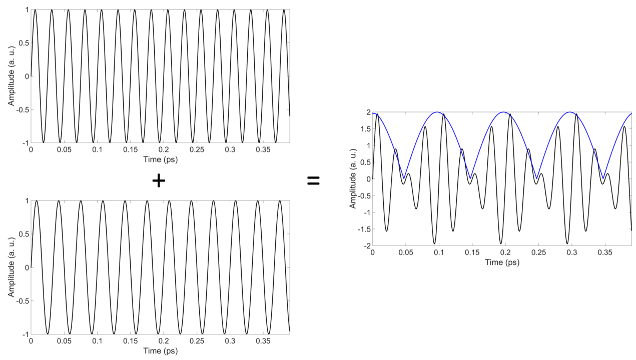

Fig. 1. The photomixing process. Two laser signals that differ by their THz frequency are mixed, resulting in a THz beat note. The blue line, proportional to the incoming laser power from both lasers, is down converted by the photomixer, yielding a THz current subsequently radiated by an antenna.

The central idea behind the design is to use the tuning capabilities of 1.55 μm lasers to generate a THz tone that inherits such properties. This is achieved by ultra-fast photoconductors coupled to a THz antenna. The generated photocurrent $I_{phot}(t)$ is proportional to the total optical power from both lasers with fields $E_1 e^{j\omega_1 t}$ and $E_2 e^{j\omega_2 t}$, respectively

$$I_{phot}(t) \sim \left|E_1 e^{j\omega_1 t} + E_2 e^{j\omega_2 t}\right|^2 = 1 + cos(\omega_1 - \omega_2)t. \quad (1)$$

The frequency of the CW component is exactly the difference in frequency between the lasers, that can be easily

Published at: https://ieeexplore.ieee.org/document/8874811

chosen to be within the THz range, as shown in Fig 1. This THz signal is then emitted by an antenna (e.g. spiral, log-periodic or bow-tie) attached to the photoconductive material. The same principle is used for the detection, but in this case, the laser-generated THz charge modulation is used as local oscillator that is mixed with the incoming THz radiation that biases the device. If the same pair of laser signals is used for generation and detection, the signals are phase-locked. This homodyne detection technique is able to measure the amplitude and the phase of the incoming THz signal [8]. For noise reduction, the source signal is usually electrically (by using a CW biasing signal) or optically (by using a pair of acousto-optical modulators) modulated for implementation of the lock-in technique. Further details of the process can be found in [2].

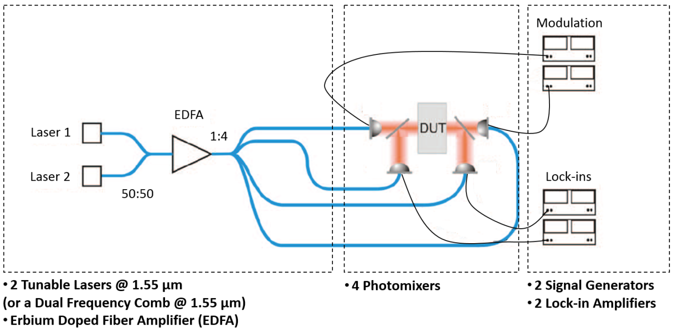

Fig. 2. Schematic of one realization of a photonically enabled FS-VNA with its respective components.

The proposed FS-VNA, shown in Fig. 2, can be divided into three sub-systems:

- Optical subsystem: includes the laser system required for generating the two optical tones for photomixing and an erbium-doped fiber amplifer (EDFA).
- Optoelectronic subsystem: includes four photomixers, i.e. two transmitters (T1 and T2), and two receivers (R1 and R2). In this manner, both transmission and reflection coefficients can be obtained simultaneously.
- Electronic subsystem: includes two signal generators and two lock-in amplifiers, required to reduce the noise floor and detect the THz signal with a large dynamic range.

There are several options for realization of each subsystem. In the following, we present the alternatives that we have already researched and implemented.

III. VNA COMPONENTS

A. *Optical subsystem*

The optical subsystem provides the optical beat note. We investigated two possible versions: 1) two free-running lasers, and 2) a dual frequency comb.

1) *Free-running lasers*

The simplest version uses two free-running distributed feedback (DFB) lasers working in the C-band (around 1.55 μm). For driving four photomixers, usually an EDFA is further required. Although two lasers are sufficient for THz generation, the THz frequency coverage of the system can be extended by replacing one of the two DFB lasers by a third DFB laser with a larger difference frequency, achieving a tuning range from DC to 2.7 THz [9]. The three lasers and their control system in [9] were developed by TOPTICA Photonics AG.

The linewidth of the free-running DFB lasers, and hence the best resolution of this version of the FS-VNA, is about 1 MHz.

2) *Dual frequency comb*

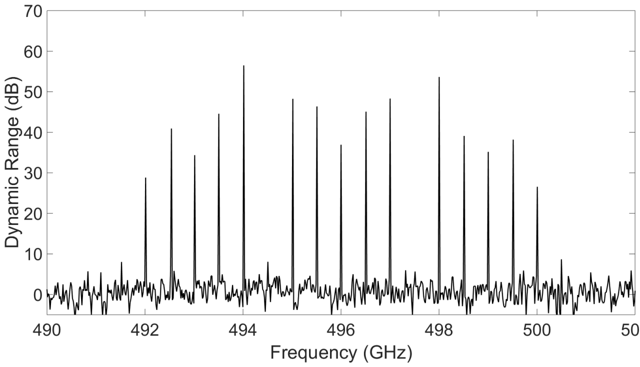

Fig. 3. Reconstructed THz spectrum performed with the dual-comb version of the optical subsystem. The measurement corresponds to the signal-to-noise ratio of transmitted THz comb centered at 496 GHz, with no sample present.

In this version, the DFB lasers are substituted by a dual frequency comb system. This system consists of two optical frequency combs (slave combs) with a mode spacing in the GHz range, but with a difference of 50 Hz between them. Both combs are then frequency shifted with respect to each other by 275.5 kHz, using two acousto-optic modulators. The combs are generated by electro-optical modulation of one filtered mode of a wider comb (master comb) spawned from single mode laser (master laser). The mode filtering for the slave-comb generation is performed using optical injection locking, as explained in [10]. Further details about the architecture to implement the dual frequency comb can be found [11].

For the THz comb generation, the first of the slave combs is mixed with another filtered mode from the master comb, which is separated several hundreds of GHz from the central frequency of the slave comb. The mixing occurs in the photomixer acting as THz generator. Due to the coherence between the optical combs and the master laser, the frequency of the resulting THz comb is extremely stable and precise. This frequency stability and precision gives the Hz-level linewidth and an absolute frequency capability to the FS-VNA.

For the THz comb detection, the second of the slave combs is mixed with the same previously filtered mode from the master comb. The mixing occurs in the photomixer acting as coherent THz receiver. Due to the 50 Hz difference in the mode spacing, and the frequency shift of 275.5 kHz between the two slave combs, the comb gets down converted to an intermediate frequency (IF) of 275.5 kHz but now with a mode separation of 50 Hz. Thus, besides the absolute frequency capability and

Hz-level linewidth, this version has the additional advantage of sampling several frequency points at the same time.

A first measurement with this version of the optical subsystem is shown in Fig. 3. The master comb featured a mode spacing of 16 GHz and total span of 496 GHz. For the measurement shown in Fig. 3, we selected two modes of the master comb spaced by the total span: 496 GHz; one of those modes was further modulated to generate the two slave combs. The slave combs have a mode spacing of 0.5 GHz and 0.5 GHz + 50 Hz, and a total span of 8 GHz. The result shown in Fig. 3 is the reconstructed spectrum from the measured IF signal.

B. Optoelectronic subsystem

1) Photoconductive mixers as Tx and Rx

The photomixers used for THz generation and detection are in-house built ErAs:In(Al)GaAs photoconductive antennas (PCAs). The specific details of the PCAs used as the transmitters T1 and T2 and receivers R1 and R2 can be found in [3].

2) PIN-diode photomixer as Tx, photoconductive mixer as Rx

Although the ErAs:In(Al)GaAs PCAs provide enough dynamic range for most measurements, commercial PIN-diode photomixer sources (Heinrich Hertz Institute, Berlin) can provide higher THz power levels [12]. Replacement of T1 and T2 by PIN diode-based photomixers increases the dynamic range by about 30 dB, reaching up to 100 dB, as shown in Fig. 4.

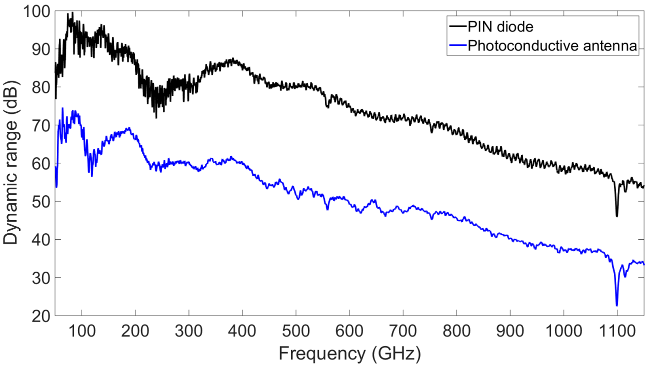

Fig. 4. Dynamic ranges in transmission mode with a commercial PIN diode THz signal generator (black line) and an in-house ErAs:In(Al)GaAs PCA as THz generator (blue line). In both cases, the receiver was an ErAs:InGaAs PCA. The integration time per frequency point was 300 ms.

C. Electronic subsystem

The electronic subsystem consists of 2 MFLI lock-in amplifiers from Zürich Instruments supporting a maximum IF of 500 kHz. For the case of electrical CW modulation of the photoconductive sources T1 and T2, the modulating singal is provided by the built-in signal generators in the MLFI lock-in amplifier.

IV. CONCLUSIONS AND OUTLOOK

The performance of each of the subsystems shown here suggests that the proposed photonic FS-VNA will offer competitive or even better performance (in terms of frequency coverage, resolution and dynamic range) as compared to available electronic solutions.

ACKNOWLEDGMENTS

This research was funded by the European Union Marie Curie Sklodowska Actions through the Innovative Training Network (ITN) with project number 675683 (CELTA), and by the European Research Council with the European Starting Grant (ERC-StG), grant agreement number 713780 (Pho-T-Lyze).

REFERENCES

[1] Virginia Diodes. (2019). Vector Network Analyzers Extension Modules [Online]. Available: https://www.vadiodes.com/en/products/vector-network-analyzer-extension-modules [Accessed Jan. 23 2019].

[2] G. Carpintero, L.E. Garcia Muoz, H. Hartnagel, S. Preu, and A.V. Risnen, Eds., Semicondutor Terahertz Technology: Devices and Systems at Room Temperature Operation. UK: Wiley, 2015, ch. 2.

[3] A. D. J. Fernandez Olvera, H. Lu, A.C. Gossard, and S. Preu, "Continuous-wave 1550 nm operated terahertz system using ErAs:In(Al)GaAs photo-conductors with 52 dB dynamic range at 1 THz," Optics Express, vol. 25, no. 23, pp. 29492-29500, 2017.

[4] T. Gobel, D. Stanze, R. J. B. Dietz, B. Globisch, H. Roehle, and M. Schell, "1.5μm CW THz photomixing system with 105 dB signal-to-noise ratio," 38th International Conference on Infrared, Milimeter and Terahertz Waves, Mainz, Germany, 2013.

[5] F. Faridi, U. Nandi, and S. Preu, "1.5 port vector Spectrometer for terahertz time Domain spectroscopy," 43rd International Conference on Infrared, Milimeter and Terahertz Waves, Nagoya, Japan, 2018.

[6] U. Nandi, J. C. Norman, A. C. Gossard, H. Lu, and S. Preu, "1550-nm driven ErAs:In(Al)GaAs photoconductor-based terahertz time domain system with 6.5 THz Bandwidth," Journal of Infrared, Millimeter, and Terahertz Waves, vol. 38, issue 4, pp. 340-348, 2018.

[7] R. B. Kohlhaas, R.J.B. Dietz, S. Breuer, S. Nellen, L. Liebermeister, M. Schell, and B. Globisch, "Improving the dynamic range of InGaAs-based THz detectors by localized beryllium doping: up to 70 dB at 3 THz," Optics Letters, vol. 43, no. 21, pp. 5423-5426, 2018.

[8] A. R. Criado, C. de Dios, P. Acedo, and Hans Hartnagel, "New concepts for a photonic vector network analyzer based on THz heterodyne phase-coherent techniques ," 7th European Microwave Integrated Circuits Conference, Amsterdam, Netherland, 2012.

[9] A. J. Deninger, A. Roggenbuck, S. Schindler, and S. Preu, "2.75 THz tuning with a triple-DFB laser system at 1550 nm and InGaAs photomixers," Journal of Infrared, Millimeter, and Terahertz Waves, vol. 36, issue 3, pp. 269-277, 2015.

[10] A.R. Criado, C. de Dios, G.H. Dohler, S. Preu, S. Malzer, S. Bauerschmidt, H. Lu, A.C. Gossard, and P. Acedo, "Continuous-wave sub-THz photonic generation with ultra-narrow linewidth, ultra-high Resolution, full frequency range coverage and high long-term Frequency stability," IEEE transaction on Terahertz Science and Technology, vol. 3, no. 4, 2013.

[11] B. Jerez, F. Walla, A. Betancur, P. Martin-Mateos, C. de Dios, and P. Acedo, "Electro-optic THz dual-comb architecture for high-resolution, absolute spectroscopy," Optics Letters, vol. 44, issue 2, pp. 415-418, 2019.

[12] S. Nellen, R. Kohlhaas, L. Liebermeister, S. Breuer, B. Globisch, and M. Schell, “Continuous wave terahertz generation from photodiode-based emitters with up to 200 μW terahertz power,” 43rd International Conference on Infrared, Milimeter and Terahertz Waves, Nagoya, Japan, 2018.

Published version: A.D.J. Fernandez Olvera, A.F. Betancur, C. de Dios, P. Acedo. and Sa. Preu, “Architecture and Component Characterization of a High-Resolution Free-Space Vector Network Analyzer for the Terahertz Range,” In the European Microwave Conference in Central Europe (EuMCE), 2019, pp. 257-260.
ISBN: 978-2-87487-067-5