A Comparison of Continuous-Wave and Pulsed Free Space 2-Port Photonic Vector Network Analyzers for Terahertz Characterization

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***Abstract*— Photonic Vector Network Analyzers (PVNA) provide a viable solution to the rising demand for efficient, accurate, and affordable characterization instruments for benchmarking terahertz devices and components. This paper compares continuous-wave and pulsed versions of the free space 2-port PVNA and their aptitudes for THz characterization using a distributed Bragg reflector as an application example.**

I. Introduction

THE vector network analyzer (VNA) is to date the most robust and sophisticated commercially available system for characterization and development of devices in the microwave, millimeter-wave band and lower end of the THz range. However, due to their limited frequency coverage (up to 1.5 THz [1]) and narrow bandwidth of their frequency extenders, there is a strong need for alternatives to characterize devices and components operating in the higher THz range across a larger frequency span. THz sources and receivers based on photonic approaches have improved immensely in recent times, which has been the basis of constructing exceptional THz characterization systems for both pulsed and continuous-wave (CW) varieties, making them excellent candidates for PVNA concepts. THz systems under pulsed operation have been reported to reach a bandwidth of 6.5 THz [2], [3], and for CW operation till 4 THz [4].

Recently, we have reported two free space 2-port PVNAs: a pulsed version with 0.2 – 2 THz frequency coverage and 7.14 GHz spectral resolution [5] and a CW version with a bandwidth of 0.1 – 1 THz and a spectral resolution of 20 MHz [6]. The systems' performances have been validated separately in multiple versatile applications ranging from material parameter extraction to device characterization. In this paper, we discuss the characteristics of these systems and compare the measurement results of a distributed Bragg reflector (DBR) to assess their distinctive capabilities better.

II. System Architecture and Calibration:

Fig.1 depicts a simple schematic of the free space 2-port PVNA architecture. It contains a set of two transmitters (Tx1 and Tx2) and two receivers (Rx1 and Rx2) to generate and detect the THz signal, an optical unit that drives these devices, and four wire grid polarizers (WGP1-4) working as frequency-independent directional couplers to guide the THz signals toward the receivers. The optical unit for the CW case consists of a pair of telecom-wavelength DFB lasers from TOPTICA photonics [7]. A fiber coupler combines the two laser signals, which an Erbium Doped Fiber Amplifier (EDFA) then amplifies, and finally, a 1:4 splitter is used to distribute the laser signals to the two photomixing transmitters (commercial telecom-wavelength PIN photodiodes with an integrated bowtie antenna [7] ($Tx_{cw,1}$ and $Tx_{cw,2}$)) and the two photomixing receivers (ErAs:InGaAs photoconductors [8] ($Rx_{cw,1}$ and $Rx_{cw,2}$)). For the pulsed case, all devices are driven with a modified Menlo C-fiber laser system operating at a center frequency of around 1560 nm with 90 fs pulse duration and a repetition rate of 100 MHz, containing two fiber ports and a phase-locked free space port. The laser pulses from the fiber ports drive the receivers (ErAs:InGaAs based photoconductive H-dipole antenna ($Rx_{p,1}$ and $Rx_{p,2}$)), whereas the laser pulse from the free-space port goes through an optical delay unit (ODU), is split into two and then drives the transmitters (ErAs:In(Al)GaAs based photoconductive slotline antenna ($Tx_{p,1}$ and $Tx_{p,2}$) [2]). The applied biases to Tx1 and Tx2 are modulated at different frequencies (f_{mod1} and f_{mod2}), and the received signals are first amplified using a trans-impedance amplifier (TIA) and then demodulated at those frequencies using two lock-in amplifiers (LIA) encompassing two demodulators each.

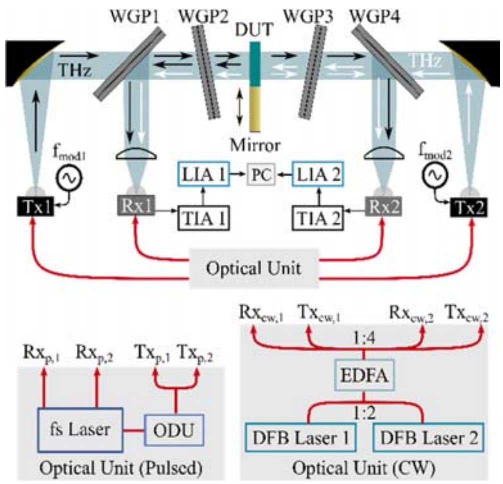

Fig. 1. Schematic diagram of the system architecture of a free space 2-port PVNA.

For the free space PVNA, the calibration procedure using a 'Through' or 'Line' (measurement of the empty setup) and a 'Reflect' (measurement with a metal mirror in the position of the device under test (DUT)) standard is performed. These readings serve as the reference data for S-parameter calculations, eliminating the need for additional measurements [5], [6].

III. System Characteristics:

In Fig. 2, we compare the reference measurements of the two systems for all four S-parameters, which provide a good indication of the characteristics of the systems. For S_{21} and S_{12}, the reference is an empty setup measurement, whereas, for S_{11} and S_{22}, a metal mirror is placed in the sample holder in place of the DUT. In terms of bandwidth, pulsed PVNA is definitely superior, reaching up to 3 THz (3^{rd} order low pass filter, TC = 10 ms, equivalent noise bandwidth (ENBW) = 9.196 Hz) compared to 1 THz (8^{th} order low pass filter, TC = 100 ms,

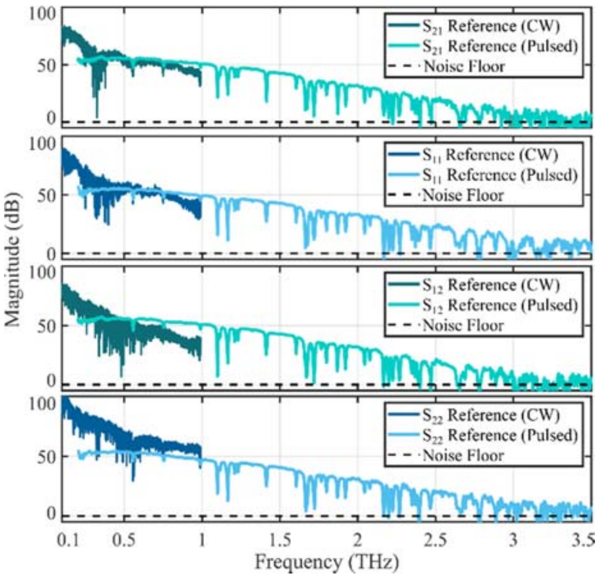

Fig. 2. Comparison of reference measurements for the calculation of S-parameters for CW and pulsed free-space 2-port PVNA.

ENBW = 0.5 Hz) of the CW system. In terms of dynamic range (DNR), the peak DNR for the CW can reach up to 90 dB at 0.1 THz, compared to the peak DNR of 55 dB at 0.5 THz of the pulsed case. However, above the 0.5 THz range, the DNR of both CW and pulsed cases are similar. Fig. 2 further shows that the CW measurement comprises a large number of unwanted reflections originating from the DUT, the WGPs, and other quasi-optical elements, which strongly influence the DNR of characterization measurements. However, proper post-processing methods can significantly reduce the effects of these reflections [6]. The other advantage of the CW PVNA is that it

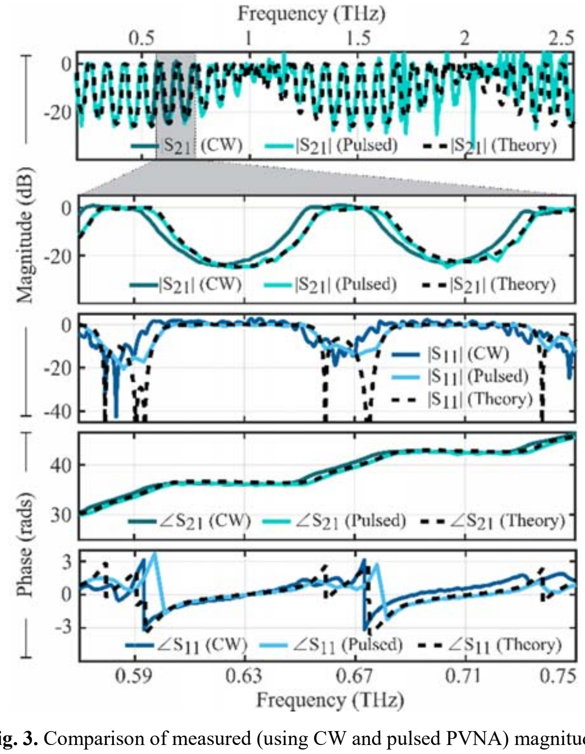

Fig. 3. Comparison of measured (using CW and pulsed PVNA) magnitude and phase of the S-parameters of a DBR with theoretical values.

has a very high frequency resolution of 20 MHz compared to 6 GHz of pulsed PVNA in this case.

IV. Terahertz Characterization:

To compare the THz characterization performance of the CW and pulsed PVNA, we inspect a distributed Bragg reflector (DBR) comprised of three 520 µm thick highly resistive Silicon layers separated by air gaps of 150 µm. Fig. 3 compares the measured magnitude and phase of the S-parameters using CW and Pulsed PVNA with the theoretically determined values. Although the pulsed PVNA can measure up to 2.5 THz, the comparison is limited to 0.57 - 0.75 THz, where data from both systems are available. Also, due to the reciprocal nature of the DBR, the comparison for S_{21} and S_{11} is sufficient. Both the PVNAs show an excellent match with the theoretical data. Because of its higher spectral resolution, the CW measurements reproduce the narrow resonances better (as evident from the S_{11} magnitude and phase data) compared to the pulsed case. However, the CW data has a frequency shift compared to the pulsed and theoretical data. This is mainly due to the thermal inertia and a miscalibration of the look-up table of the DFB diodes, which can lead to a frequency shift of 1-2 GHz [7].

V. Conclusion

We compared CW and pulsed free space 2-port PVNA in terms of system architecture, characteristics, and THz characterization performance. The pulsed PVNA is better suited for broadband investigation, whereas CW PVNA for precise characterization of narrow spectral features.

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