Proceedings Paper:

Chudpooti, N, Duangrit, N, Akkaraekthalin, P et al. (2 more authors) (2021) Terahertz Free-Space Measurement System Using Low-Cost 3D-Printed Hemispherical Lens Antenna. In: 2021 Research, Invention, and Innovation Congress: Innovation Electricals and Electronics (RI2C). 2021 Research, Invention, and Innovation Congress: Innovation Electricals and Electronics (RI2C), 01-03 Sep 2021, Bangkok, Thailand. IEEE , pp. 110-114. ISBN 978-1-6654-0300-9

https://doi.org/10.1109/ri2c51727.2021.9559829

Terahertz Free-Space Measurement System Using Low-Cost 3D-Printed Hemispherical Lens Antenna

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***Abstract*—This paper presents a terahertz free-space (THz) measurement technique using a photopolymer-based additive manufactured hemispherical lens antenna directly fed by a WR-3 rectangular waveguide with an operating frequency range of 220 GHz to 320 GHz. The hemispherical lens antenna is fabricated by in-house custom-made low-cost photopolymer 3D printing using a digital light processing (DLP) technique to fabricate layer-by-layer using Monocure 3DR3582C printing material. An asymptotically single-mode all-dielectric Bragg fiber is used to investigate the performance of the developed free-space measurement setup. From the measurement results, the propagation loss in this work has an accuracy compared with an analytical calculation and conventional free-space measurement setup of 83.36% and 88.08%, respectively. Moreover, the use of a 3D-printed hemispherical lens antenna for the THz free-space measurement reduces the complexity of the measurement setup.**

Keywords*—*free-space measurement, 3D printing, lens antenna

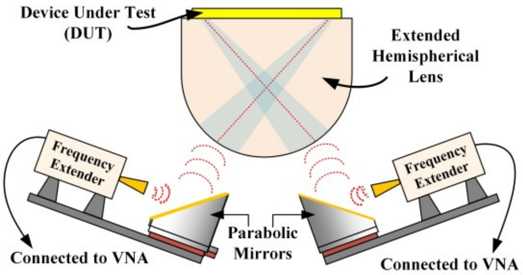
I. Introduction

The terahertz (THz) and sub-terahertz frequency range down to the region of 100 GHz has been of interest recently in many research fields and applications such as medical technology, material characterization, imaging and sensing technology, and high-speed circuits and systems, due to the various advantages compared with other technology [1]–[4]. To experiment and test a sample in the THz frequency range requires a complex measurement setup and a high degree of accuracy. A THz source, detector, and system are required to achieve THz measurements [5]–[8]. There are two major types of measurement system: contact and non-contact (or free-space) measurement [6]–[7].

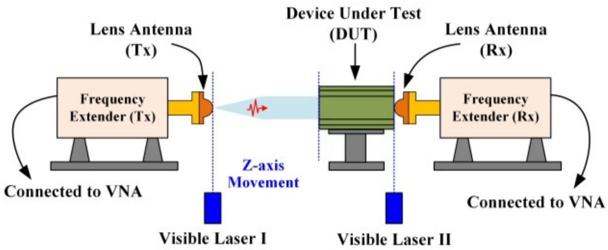
"Probe measurement", a standard contact measurement method in THz technology, is suitable for planar structures and on-chip measurement which can measure both passive and active devices [9]. For commonly planar structures, it is applied via microstrip and coplanar waveguide (CPW) structures to integrated circuit (IC) technology, such as monolithic microwave integrated circuits (MMICs), sub-millimeter-wave monolithic integrated circuits (S-MMICs), and THz monolithic integrated circuits (T-MMICs) [10]. However, probe technology is extremely constrained by high costs, physical contact force, and fragility. Presently, probe technology operates in frequencies of up to 1.1 THz frequency; it has been used in multiple high-frequency extenders covering the frequency band from 75 GHz to 1.1 THz [11]. Thus, probe technology is limited with respect to repeatability, contact cycle of the probe, and reliability of the measurement system, which is affected increases in contact–probe resistance, directly affecting measurement precision and contributing to degeneration of the measurement system [10].

A free-space measurement system can be divided into two major types depending on the emission mode: 1) the pulse mode (or time–domain) and 2) the continuous-wave (CW) [7]. The pulse mode, or terahertz time-domain spectroscopy (THz-TDS) system, provides the broadband operating frequency than another measurement setup in the THz band. For the THz-TDS measurement system, the measured information is collected many times for one experiment setup, then the mathematical model/function is used to synthesize the collected information as a post-process. It requires more data processing to be completely utilized. This measurement system can process precise information for applications such as material characterization, thickness measurement, imaging system, and THz waveguide characterization [5]–[8]. Additionally, the THz-TDS measurement system is an expensive component to set up because it requires a femtosecond laser source together with a time delay scan [5]. Moreover, in the THz-TDS measurement setup, it has been used a splitter mirror, off-axis ellipsoidal, and parabolic mirror, resulting in measurement cost and difficult measurement setup in each case of study [11]–[12].

Secondly, CW spectroscopy systems are capable of operating with narrow-frequency sources such as backward wave oscillators (BWOs), quantum cascade lasers (QCLs), and harmonic multiplying which can operate in continuous mode. The key advantage of such sources is that they provide high output power (~100mW) and are more suitable for imaging applications [7]–[8], [14]. Due to the narrow bandwidth of a CW source, multiple sources are required to cover the THz frequency band. Additionally, the CW system can be measured using a frequency extender in combination with a conventional vector network analyzer (VNA) as is used with probe measurement technology. Frequency extenders can operate to 1.1THz [13]. In the past few years, non-conventional non-contact THz measurement systems



(a)



(b)

Figure 1. Illustration of the THz free-space measurement experiment setup: (a) non-conventional non-contact measurement setup; and (b) the proposed measurement setup based on the lens using 3D printing.

have been developed which use a hemispherical lens to focus the signal onto the device under test (DUT) [15]–[17].

This paper presents a novel non-conventional THz free-space measurement system using a 3D-printed hemispherical lens antenna as presented in [18]. The hemispherical lens was designed to operate at 0.22 THz – 0.32 THz of the WR-3 waveguide band. To investigate the performance of the proposed measurement system, it was applied to measure the propagation loss of an asymptotically single-mode hollow-core THz Bragg fiber structure which has an operating frequency between 0.246 THz and 0.276 THz [19]. The measurement results were compared with the obtained propagation loss of the proposed measurement system and the measured results of the experimental setup in previous work [19]. The key advantages of the system were eliminating the use of a parabolic mirror and simplifying the experimental setup. The proposed measurement system in this paper has provided a cost-effective and more flexible method of measuring the non-planar structures of a DUT.

II. THz Free-Space Measurement Setup

A. *Non-Conventional THz Free-Space Measurement*

The non-conventional non-contact measurement system was presented in [15]–[17], where the electromagnetic (EM) wave was transmitted and received by a horn antenna connected to a rectangular waveguide and a frequency extender, as shown in Figure 1(a). The parabolic mirror was then used to collect and collimate the EM wave onto the hemispherical lens, which was fabricated with high-resistivity silicon [16]. By using a hemispherical lens antenna in the conventional probe measurement system, a non-contact probe measurement system was achieved. The hemispherical lens is a key advantage because it is used to couple the EM wave from the frequency extender and focus it onto the DUT. To receive and transmit the radiation wave of the DUT, an on-chip antenna was used to measure the reflection and transmission coefficients of the system. To measure the EM wave after travel through the DUT, the second antenna on the DUT re-radiates the EM wave back to the second of parabolic mirror, which collects and focuses the EM wave onto the horn antenna at the receiver.

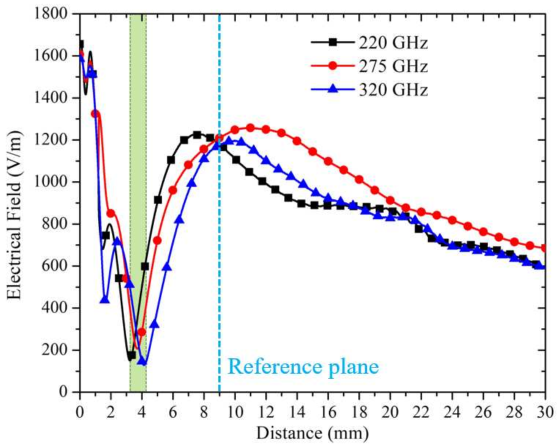


Figure 2. Simulated electric field of 3D printed hemispherical lens antenna on the propagation direction (*z*-axis).

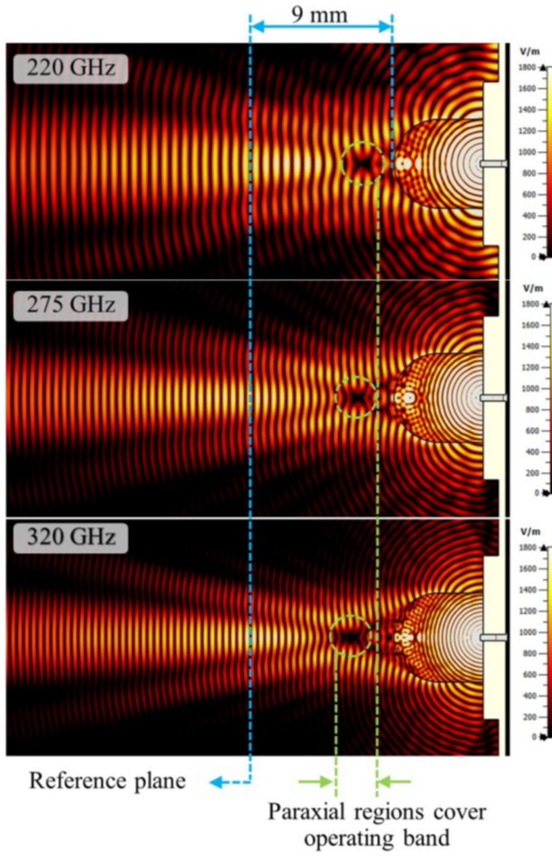
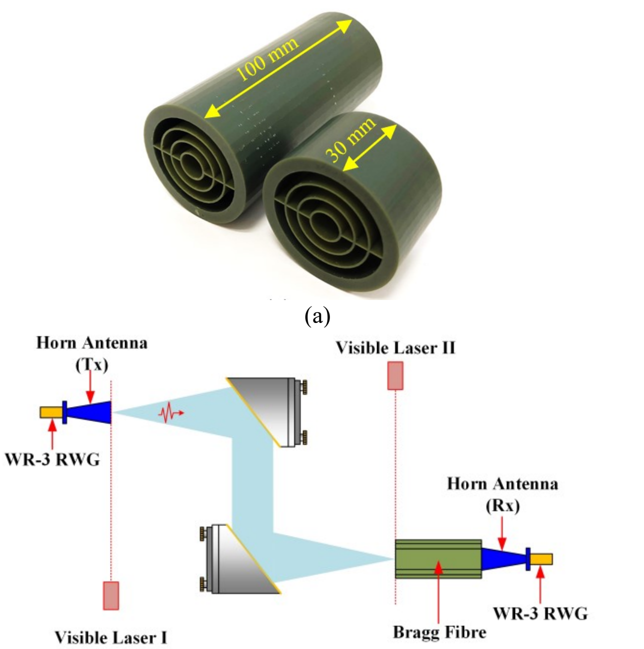


Figure 3. Simulated electric field of 3D-printed hemispherical lens antenna at 220 GHz, 275 GHz, and 320 GHz on the *yz*-plane.

B. *THz Free-Space Measurement Using 3D Printed Hemispherical Lens Antenna*

The proposed free space measurement system is based on a lens antenna using 3D printing technology whist proposed system is reduced the use of a parabolic mirror, as conventional free-space measurement in [5]. Figure 1(b) for a 3D-printed hemispherical lens antenna is an area to be avoided when implemented in the proposed measurement system, as represented by the green area in Figure 2. Figure 3 shows the levels of the electric field for the paraxial points: they are clearly presented on the *yz*-plane (region on green dash line), showing that the paraxial points at 220 GHz, 275 GHz, and 320 GHz were 3.2 mm, 4.0 mm, and 4.6 mm, respectively. Thus, a distance more than 8 mm in the *z*-direction was required to avoid the paraxial region of the W-band and the near-field region of the lens antenna. In this work, the distance of 9 mm in the *z*-direction of the 3D-printed hemispherical lens antenna was selected for demonstrating the proposed measurement system. Thereafter, the EM waves were transmitted through the DUT and measured by the second lens antenna. It was mounted onto the second set of frequency extenders placed at the output of the DUT.



(b)

Figure 4. (a) Asymptotically single-mode Bragg fiber with length of 30 mm and 100 mm; (b) Free-space measurement setup used in [19].

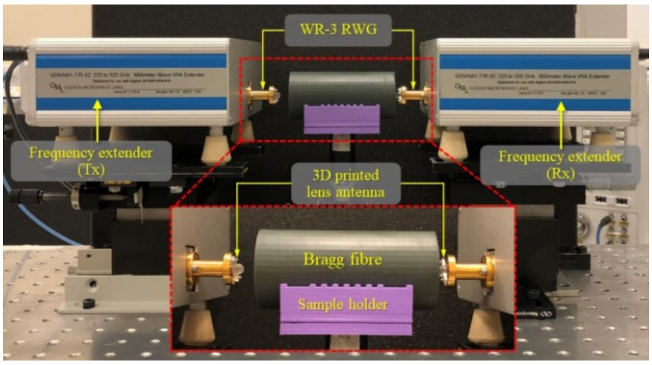


Figure 5. The proposed free-space THz measurement setup.

III. Laboratory Measurement Setup

A. Example Device Under Test

The DUT for testing the performance of the proposed measurement system was an asymptotically single-mode all-dielectric Bragg fiber with two different lengths of 30 mm and 100 mm to measure both transmission coefficient and the extracted propagation loss that was previously reported in [19]. It had an operating frequency band from 0.246 to 0.276 THz. The Bragg fiber used a HTM140-V2 photopolymer material with the EnvisionTEC Perfectory 3 mini multi lens 3D printer that used DLP rapid prototyping technology for fabrication. Figure 4(a) shows the fabricated prototype of the Bragg fiber at two different lengths (30 mm and 100 mm).

B. Previous Free-Space Measurement Setup

The previous measurement setup for measuring the transmission coefficient and propagation loss of the Bragg fiber structure is shown in Figure 4(b). The WR-3 rectangular waveguides at both ends were connected to the frequency extender from Oleson Microwave Labs (OML), which had an operating frequency range from 220 GHz to 325 GHz. Then, the frequency extender was connected to a Keysight Technologies PNA-X N524A network analyzer. A standard Line-Reflect-Line (LRL) calibration was used to shift the reference plane to the end of the WR-3 rectangular waveguide (RWGs). Two standard conical horn antennas, mounted on the open ends of the WR-3 RWGs were used to transmit and then receive the propagated EM wave. Two visible lasers were used to determine the focal points of the parabolic mirrors and assist in aligning the measurement system. To measure the transmission coefficient, the transmitter horn antenna on the left in Figure 3(b) radiated the EM wave, then the propagated wave was focused onto the core of the Bragg fiber structure by a pair of parabolic mirrors. The second conical horn antenna placed at the end of the DUT collected the EM wave which propagated through the DUT. Subsequently, the cut-back method was used to calculate the propagation loss based on the transmission coefficient of the two different lengths of Bragg fiber [21].

C. Free-Space Measurement Setup Using 3D-Printed Hemispherical Lens Antenna

The proposed free-space measurement setup using a 3D-printed lens antenna is shown in Figure 5. The 3D-printed

shows a diagram of the proposed measurement setup. The frequency extender with a rectangular waveguide at both ends generated the EM wave while connected to a VNA. The EM wave was radiated using the 3D-printed hemispherical lens antenna presented in [18], fabricated using a Monocure 3DR3582C rapid photocurable resin-based polymer. It provided an antenna gain of 16.1dBi with transmitted beam angles lower than 15 degrees. To demonstrate the radiation wave of the hemispherical lens antenna, the simulated electric field distribution in the propagation direction is plotted in Figure 2. Points have been plotted from 0 mm to 30 mm in the z-direction to represent the electric field in the propagation direction at each of the three frequencies (i.e., 220 GHz, 275 GHz, and 320 GHz). At 220 GHz (black line with solid square symbol), the lowest point of the electric field was 196 V/m at 3.2 mm in the *z*-direction. The lowest point of the electric field was referred to as the paraxial point from caustic rays of the spherical surface of the lens antenna [20]. When considering the electric field intensity of the three frequencies, the level of electric field increased after the paraxial regions, then the radiation wave formed into a plane wave. Thus, the paraxial region of the whole operating band

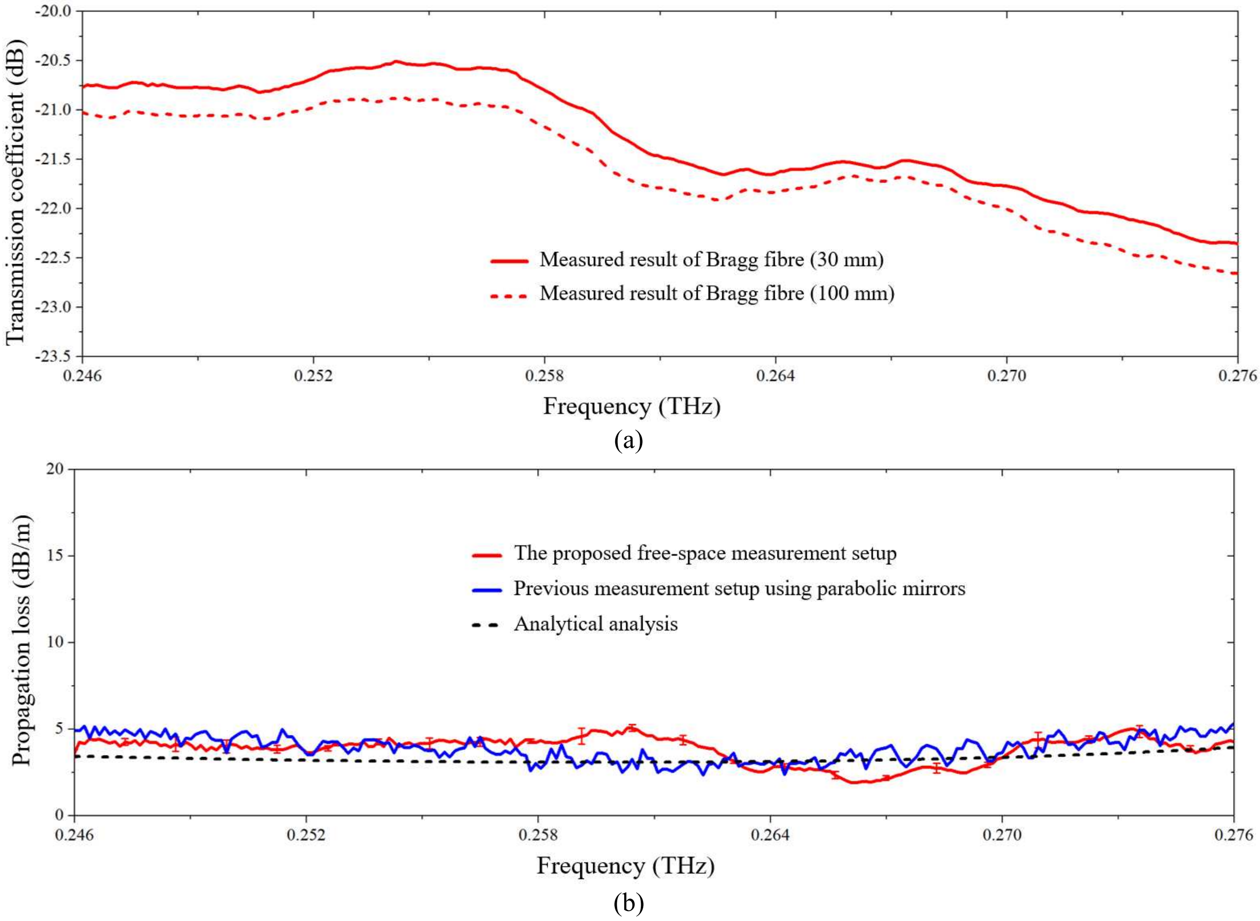


Figure 6. (a) Measured transmission coefficient of 30 mm and 100 mm lengths of Bragg fiber, measured with a distance between transmitted lens antenna and Bragg fiber of 9 mm; (b) Measured propagation loss of the proposed measurement setup (red line), the conventional measurement setup using horn antennas and parabolic mirror (blue line), and the simulation result of the desired HE_{11} mode (black dashed line).

lens antennas were mounted on the open end of the WR-3 RWG of the frequency extender which connected to a Keysight Technologies PNA-X N5242A network analyzer with an operating range from 220 GHz to 325 GHz. The standard LRL calibration method was used to shift the reference plane to the open end of the WR-3 RWG to eliminate systematic errors. This was done by connecting a cable from the PNA-X through to the open-ended WR-3 RWG of the frequency extender. Both frequency extenders were placed on a 3-axis movable stage for measurements of the 30 mm and 100 mm Bragg fibers. The measurement setup process consisted of the following steps: 1) align both frequency extenders and Bragg fiber using the visible laser along the *z*-axis; 2) align the frequency extender to the core of the input and output of the Bragg fiber with the visible laser on the *x*-axis; 3) move the transmitted frequency extender along the *z*-axis away from the core of the Bragg fiber to 9 mm and measure the transmission coefficient. For measurement of the transmission coefficient, the second 3D printed lens antenna was mounted on the WR-3 open-ended RWG of the second set of the frequency extender, which was placed at the output end of the Bragg fiber. This measurement setup is similar to the previous work in [19]. The intermediate frequency (IF) bandwidth for the proposed measurement setup was set to 10 Hz, the smoothing factor was 3% with the 10 nearest points, and 230 frequency points were used to record the data in the frequency range from 0.246 THz to 0.276 THz.

IV. Measurement Results

The measurement results of the proposed system are shown in Figure 6, showing operating frequencies from 0.246 THz to 0.276 THz. The distance between the transmitted lens antenna and the Bragg fibers was 9mm. Figure 6(a) shows the measured transmission coefficients of the 30mm and 100mm Bragg fibers. The propagation loss was calculated using the cut-back calibration method together with the transmission coefficient, as shown in Figure 6(b). In Figure 6(b), the red line shows the propagation loss of the proposed measurement setup, as compared to the propagation loss of the previous measurement setup and the analytical analysis of the simulation, as depicted by the blue line and black dashed line, respectively. The proposed measurement setup was mechanically remounted three times to calculate the standard deviation, giving a maximum of 0.491 at 0.259 THz. For measurement results over the frequency band from 0.246 THz to 0.255 THz, the extracted propagation loss of the proposed measurement setup was in good agreement with the conventional measurement result and the analysis technique, which have an average similarity data within 88.08% and 83.36%, respectively.

V. Conclusion

The proposed free-space measurement setup used 3D-printed hemispherical lens antennas to eliminate the use of parabolic mirrors for collimating and focusing the radiation wave, as had been used in the previous measurement setup. The transmission coefficient and propagation loss of the Bragg fiber were used to demonstrate the performance of the proposed measurement setup. The proposed measurement setup reduced the component setup time and the complexity of the measurement system. The repeatability of the proposed measurement system was demonstrated via mechanically remounting the measurement setup three times, which depicted a maximum standard deviation of 0.491 at 0.259 THz. The measured results demonstrated good agreement with respect to accuracy and repeatability compared to the previous measurement setup and analytical results. The free-space THz measurement setup developed in this work can be applied to use in the THz free-space measurement setup for the measurement of planar circuits or on-chip/on-wafer free-space THz measurement as reported in [22]–[24].

AKNOWLEDGMENT

This work was supported in part by the Thailand Science Research and Innovation Fund, and King Mongkut's University of Technology North Bangkok with contract no. KMUTNB-FF-65-42, and in part by the Engineering and Physical Science Research Council under Grant EP/S016813/1 and Grant EP/N010523/1.

REFERENCES

[1] M. Tonouchi, "Cutting-edge terahertz technology," *Nature Photonics*, vol. 1, pp. 97-105, 2007.

[2] J. H. Choi, Ed., *High-Speed Devices and Circuits With THz Applications*. Boca Raton, FL, USA: CRC Press, 2014.

[3] N. B. Lawler, D. Ho, C. W. Evans, V. P. Wallace, and K. S. Iyer, "Convergence of terahertz radiation and nanotechnology," *Journal of Materials Chemistry C*, vol. 8, no. 32, pp. 10942-10955, 2020.

[4] H. Cheon, J. H. Paik, M. Choi, H.-J. Yang, and J.-H. Son, "Detection and manipulation of methylation in blood cancer DNA using terahertz radiation," *Scientific reports*, vol. 9, pp. 1-10, 2019.

[5] N. Duangrit *et al.*, "Terahertz dielectric property characterization of photopolymers for additive manufacturing," in *IEEE Access*, vol. 7, pp. 12339-12347, 2019.

[6] A.J.L. Adam, "Review of near-field terahertz measurement methods and their applications," *J Infrared Milli Terahz* Waves, vol. 32, pp. 976-1019, 2011.

[7] L. Angrisani, G. Cavallo, A. Liccardo, G. P. Papari, and A. Andreone, "THz measurement systems. New trends and developments in metrology," *IntechOpen*, pp. 21-48, Jul. 2016.

[8] B. Khani *et al.*, "Compact optoelectronic continuous wave terahertz spectroscopy system (230-400 GHz) for paper sorting and characterization," in *In The European Conference on Lasers and Electro-Optics; Optical Society of America: Washington, DC, USA, 2017.*

[9] L. Chen *et al.*, "Terahertz micromachined on-wafer probes: repeatability and reliability," in *IEEE Transactions on Microwave Theory and Techniques*, vol. 60, no. 9, pp. 2894-2902, Sept. 2012.

[10] S. L. Rumyantsev *et al.*, "Terahertz beam testing of millimeter wave monolithic integrated circuits," in *IEEE Sensors Journal*, vol. 17, no. 17, pp. 5487-5491, 1 Sept.1, 2017.

[11] C. Brücknerab, G. Notnia, and A. Tünnermannab, "Optimal arrangement of 90° off-axis parabolic mirrors in THz setups," Optik, vol. 121, no. 1, pp. 113-119, Jan. 2010.

[12] A. Steiger, M. Kehrt, C. Monte, and R. Müller, "Traceable terahertz power measurement from 1 THz to 5 THz," Optics express, vol. 21, no. 12, pp. 14466-14473, 2013

[13] M. F. Bauwens, N. Alijabbari, A. W. Lichtenberger, N. Barker, and R. M. Weikle, "A 1.1 THz micromachined on-wafer probe," *in Proc. IEEE MTT-S Int. Microw. Symp.*, 2014, pp. 1–4.

[14] P. Dean *et al.*, "Terahertz imaging using quantum cascade lasers—a review of systems and applications," *Journal of Physics D: Applied Physics*, vol. 47, no. 37, Aug.2014.

[15] C. Caglayan, G. C. Trichopoulos and K. Sertel, "Non-contact probes for on-wafer characterization of sub-millimeter-wave devices and integrated circuits," in *IEEE Transactions on Microwave Theory and Techniques*, vol. 62, no. 11, pp. 2791-2801, Nov. 2014.

[16] C. Caglayan and K. Sertel, "Noncontact on-wafer Characterization of differential-mode millimeter- and submillimeter-wave devices and integrated circuits," in *IEEE Transactions on Microwave Theory and Techniques*, vol. 64, no. 11, pp. 3911-3917, Nov. 2016.

[17] C. Caglayan and K. Sertel, "Experimental analysis of repeatability and calibration residuals in on-wafer non-contact probing," in *IEEE Transactions on Microwave Theory and Techniques*, vol. 65, no. 6, pp. 2185-2191, Jun. 2017.

[18] N. Chudpooti *et al.*, "220-320 GHz hemispherical lens antennas using digital light processed photopolymers," in *IEEE Access*, vol. 7, pp. 12283-12290, 2019.

[19] B. Hong *et al.,* "Low-loss asymptotically single-mode THz Bragg fibre fabricated by digital light processing rapid prototyping," *IEEE Trans. Terahertz Sci. Technol.*, vol. 8, pp. 90-99, 2018.

[20] L. Novotny and B. Hecht, "*Propagation and focusing of optical fields,"* in Principles of Nano-optics, 2nd ed. New York, Cambridge University, 2012, pp. 47–52.

[21] J. C. Daly, Fiber Optics. Boca Raton, FL, USA: CRC Press, 2000.

[22] T. Takan *et al.*, "Detection of far-infrared radiation using glow discharge detectors," *Opt Quant Electron*, vol. 48, no. 292, Apr. 2016.

[23] T. Ozturk *et al.*, "Comparison of free space measurement using a vector network analyzer and low-cost-type THz-TDS Measurement methods between 75 and 325 GHz," *J Infrared Milli Terahz Waves*, vol. 38, pp. 1241–1251, Jun. 2017.

[24] Y. Salamin *et al.*, "Compact and ultra-efficient broadband plasmonic terahertz field detector," *Nature Communications*, vol. 10, 2019.