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THz Detectors and Emitters with On-Chip Antenna aligned on Hyper-Hemispherical Silicon Lenses

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***Abstract*— On-chip antennas with radiation towards the substrate are affected by modest coupling performance to a free-space path. (Hyper-)hemispherical silicon lenses can improve the efficiency of quasi-optical emission and detection even at THz frequencies. This approach requires an alignment accuracy in the µm-scale at THz frequencies. In this contribution, we report on the benefit of hyper-hemispherical silicon lenses in terms of relaxed alignment accuracy needs. We present the impact of alignment on quasi-optical measurements using indium phosphide resonant-tunneling diodes. The main components of the resulting setups are discussed while the effect of alignment is quantitatively evaluated for both, hemispherical and hyper-hemispherical silicon lenses. Moreover, design rules and concepts for a heterointegrated system are derived on consecutive observations.**

Keywords—THz detector, quasi-optical measurement setup, silicon lens, on-chip antenna

I. Introduction

Within the Terahertz frequency range (300 GHz – 3 THz), many promising applications are currently emerging, such as non-destructive imaging, material detection, high-resolution radar and localization, and extremely broadband wireless links [1]. However, efficient electronic devices are still lacking at these frequencies.

At THz frequencies, antenna and device form a codependency because of the short wavelength < 1 mm. There is high interest in realizing dense arrays of THz emitters for spatial power combining and beam steering an -forming, since the RF output power of single transmitters cannot be scaled further. In particular, power-efficient devices with small area $< \lambda^2/4$ are needed for such arrays. In that regard promising THz devices can be realized when integrating indium phosphide (InP) resonant tunneling diodes (RTD) with on-chip antennas, allowing for monostatic Tx- and Rx-operation from the same array [2],[3]. While patch antennas are top-firing into free space [4], alternative antenna types (e.g. slot-antenna or bowtie) radiate downwards through the substrate material. Due to the high permittivity of indium phosphide, most energy is pulled towards the substrate direction. Unless the substrate is thinned well below 100 µm thickness, substrate modes, which laterally dissipate the THz energy, may appear due to reflection at the substrate-air interface. Furthermore, the refraction at the substrate-air interface leads to poor beam quality. Silicon-based hemispherical lenses are attached to the InP substrate to increase the power extraction and beam focusing of the THz component. The alignment of these two components is not straightforward because of the small chip dimensions compared to the available lenses. Further design rules and concepts are needed to enable reproducible and solid measurement conditions with the components mentioned before. Additional heterointegration of such detector or transmitter chips into silicon-germanium (SiGe) circuits will result in similar alignment issues of a silicon lens.

II. Measurement Setup

A. Quasi-optical measurement setup for detectors

The basis of the development of a measurement system for the characterization of THz detectors is a far-field measurement approach. This approach is based on the coupling of a wave quantity from a THz source to the detector in free space. Due to the high frequencies in the THz regime and hence wavelength near the optical regime, such a setup can be described as quasi-optical. The usage of optical components like lenses is covered by this theory [5]. Fig. 1 presents the measurement setup used in this work. We subdivide the setup into three elements:

1. THz source: mm-Wave Converter
2. Free space beam path
3. Si-lens with the device under test (DUT)

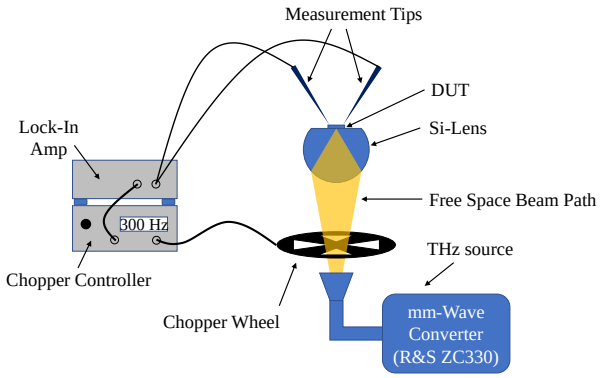

Fig. 1: Schematic setup of the presented quasi-optical measurement setup for detector characterization in THz frequency regime

As the THz source, we use a mm-Wave converter (ZC330 for J-band measurements) which is controlled by a vector network analyzer (VNA) ZVA67 by Rohde and Schwarz. This source setup can deliver THz radiation within the converter's frequency band. The setup is designed with a vertical beam path since the DUT has to be placed on a horizontal surface (see Fig.1). THz radiation is generated at the underside by the source, followed by the free space beam path, and the DUT with Si-lens. To initially translate the signal in vertical free-space radiation out of the source, a 90° waveguide bend followed by a horn antenna is utilized. Since

the expected detector voltage is very low compared to the noise floor, the lock-in measurement technique is applied. To this end, a chopper wheel is inserted into the propagation path to modulate the signal radiated from the source. The signal is then collected by the Si-lens and focused onto the detector chip. Owing to the huge difference in the refraction indices of an substrate-air surface, the Si-lens is paramount to couple a significant part of the incoming radiation into the substrate of the detector chip. Another advantage of using the lens is to have a surface for placing the small InP chip with an on-chip antenna and RTD. For measuring the detector voltage, a MFLI lock-in amplifier (see Fig.1) of Zurich Instruments is utilized. This LIA covers the frequency range from DC up to 500 kHz with 60 MSa/s. This measurement technique is common for detector characterization since it reduces the influence of 1/f noise observable at low output voltages from the detector [6]. The limiting factor in our setup is a chopper frequency of 300 Hz for the chopper wheel (see Fig. 1 and Fig. 2). To shift the measured voltage out of the 1/f-noise, a chopper frequency of around 10 kHz would be preferable. The setup's aluminum frame is covered with absorbing material to avoid unwanted reflections in the free space propagation path (see Fig. 2). The DUT is manually contacted with standard tungsten measurement tips by use of a light microscope.

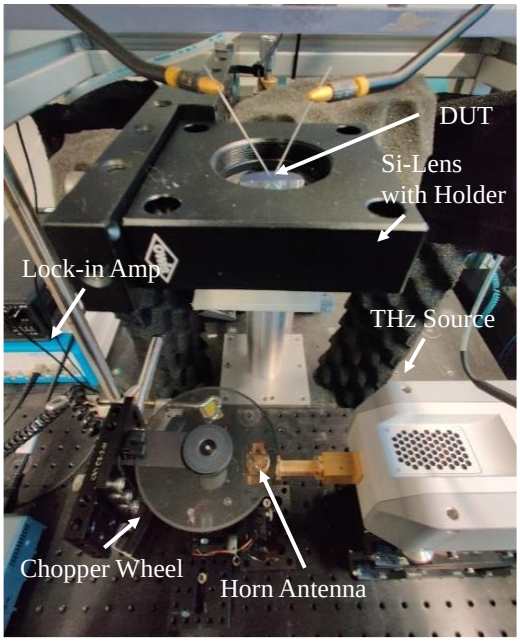

Fig 2.: Quasi-optical measurement setup with THz source, chopper wheel, and housed hyper-hemispherical silicon lens: the InP chip is placed onto the silicon lens with contact pads facing upward, the THz radiation emits vertically upward from the horn through the chopper wheel. The horn is mounted onto the mm-wave extender by means of a 90° waveguide bend

B. *Calibration procedure*

For estimation of the detector responsivity, it is necessary to know precisely the power which is radiated by source. In our setup, the source power is set in the VNA. The received power needs to be calibrated before measuring. For this purpose, a power meter Erickson PM5 from VDI is used. This power meter is connected to the mm-wave converter via a rectangular waveguide connection. Furthermore, a computer is used for the communication link between the power meter and the VNA. The calibration is then performed with a power leveling software tool from Rohde and Schwarz. After power calibration of the source, incident power at the DUT can be derived by means of the Friis transmission equation with knowledge of the antenna systems gain. EM simulation of the lens arrangement is performed to derive the total gain of the system.

C. *Hyper-hemispherical silicon lens*

To reduce substrate modes and improve coupling at the substrate-air interface, an optical lens is recommendable. We use a hyper-hemispherical lens made from high-resistivity float zone silicon (HRFZ-Si) in our setup [7]. The HRFZ-Si material exhibits sufficiently low loss in the THz range for our desired setup performance. Since the change of refractive index at the lens/air interface is still relatively high, an anti-reflective coating could further reduce the losses. HRFZ-Si lenses were often used for irradiation and collimation of THz waves for various antenna types [8][9]. While a hemispherical lens can be constructed geometrically as a half-sphere, a hyper-hemispherical (HHS) lens is obtained by cutting a sphere above the center plane. To define the geometrical dimension of such a lens, a height is specified next to the lens diameter. The HHS lenses generally show a higher collimation effect as compared to the hemispherical type.

In our setup, an HHS silicon lens with a diameter of 10 mm was selected, while the height of the lens is 6.19 mm. These lens dimensions have been selected by evaluation of 3D-EM simulations of available lens types combined with the anticipated antenna structure. For all following simulations, a refractive index $\varepsilon_r = 11.67$ and a dissipation factor of $\tan\delta = 5 \cdot 10^{-5}$ at 300 GHz are considered, which is close to the literature InP material properties [10].

III. Test System Alignment

In the first order, the alignment of the transmitting horn-antenna of the frequency-extender and the lens with a chip on top is a two-dimensional translation problem. Assuming a perfectly vertical mounting both for the transmitting horn antenna and the detecting THz DUT, the complete system can be aligned to one common optical axis. By means of a commercial visible light laser, an initial mechanical alignment is carried out. The final alignment is realized by moving the transmitting horn antenna while searching for the maximum detector voltage. The detector chip cannot be moved, because of the sensitive contacting scheme of tungsten wafer probes touching the microscopic antenna structure. Under these circumstances, only the transmitting mm-wave converter with the mounted horn can be moved to seek the optimum alignment. This matter will result in another critical alignment issue presented in the following section.

A. *Displacement of the chip to lens center*

The sub-system consisting of an InP chip and a silicon lens cannot be implied as perfectly aligned. Since antennas are reciprocal, we consider simulation and theory of a transmitting element to analyze the detector setup, which is easier to implement and calculate. If the antenna on the InP chip is perfectly centered with respect to the silicon lens, the system will have its main beam direction in the z-direction. Due to the collimation effect of the HHS lens, all rays will be refracted rotationally even towards the central axis. If,

however, the antenna center is not aligned with the lens center, the resulting beam will have an angular tilt [11]. In the detector scenario, the system would detect incoming waves from a direction off the optical axis. As shown in [12], a hemispherical lens with a chip on top can be approximated as an extended hemispherical lens. Even if the InP chip on top of the lens does not cover the full lens surface, it extends the optical path for most outgoing waves. The extension L is then interpreted as the wafer thickness, in our case 350 µm.

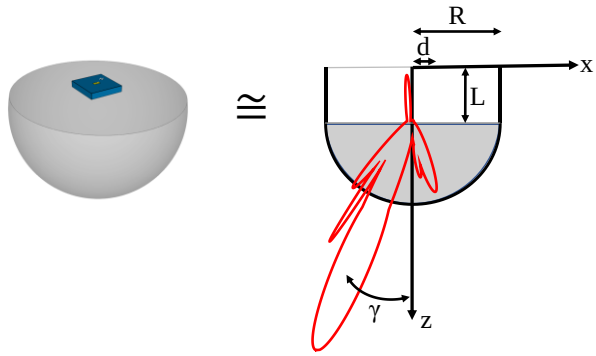

Fig. 3: Approximation of silicon lens as extended hemispherical lens and influence to the main lobe of a 1-dimensional displacement of d from the center. A resulting angular tilt of the pattern by the angle γ occurs.

For an extended hemispherical lens, a 1-dimensional displacement of the lens' center results in an angular tilt γ in the according plane. The beam is tilted to the counter direction of the displacement. This effect is sketched in Fig. 3, where the exact angular tilt can be derived as:

$$y = \tan^{-1}\left(\frac{d}{L}\right) \qquad (1)$$

This analytical formula is only valid for an extended hemispherical lens. Nevertheless, a hyper-hemispherical lens can be approximated to an extended hemispherical-type, if the extension L is interpreted as the combination of wafer thickness and sphere extension. To prove this behavior, we utilize full 3D-EM simulations in Empire XPU. Fig. 4 presents a simulated radiation pattern of a displaced slot antenna versus an aligned one. A slot antenna has been designed for resonance at 300 GHz, and the previously described lens dimensions were considered. By comparing both maximum gain angles, we observe an angular tilt of 6.7° in the opposite direction from the initial lateral shift of 200 µm. This value is indeed much smaller than the value expected from (1) for a hemispherical lens. This can be explained by the higher lens extension of a hyper-hemispherical lens in comparison to a hemispherical one [13]. Simulations of hemispherical lens types with the same slot antenna are following the curve described by (1).

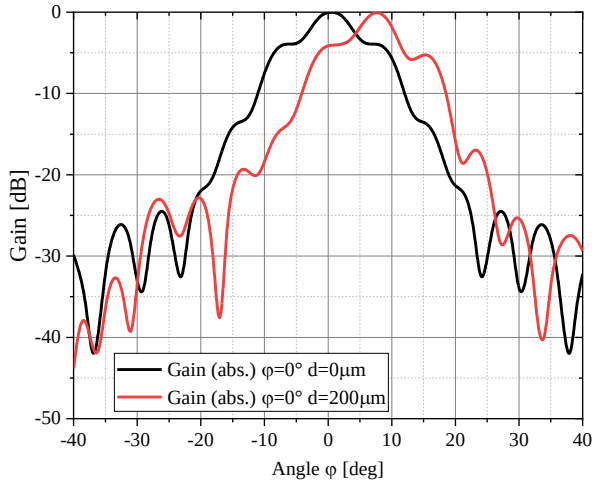

Fig. 4: Simulated normalized radiation patterns ($\varphi = 0°$) at 300 GHz of a generic slot antenna combined with a 10 mm hyper-hemispherical silicon lens with and without a displacement of 200 µm

A comparison of resulting angular tilt from different lateral displacements for both lens types in combination with the same on-chip antennas is presented in Fig. 5. For any lateral displacement, the tilt is much lower when using a hyper-hemispherical lens. There is also good agreement between simulation and the extended analytical model for the hyper-hemispherical lens. For small displacements, we can approximate this behavior to be linear. The hemispherical lens shows an angular tilt of 0.15°/µm compared to 0.04°/µm for the hyper-hemispherical one at 300 GHz. Nevertheless, precise placement of the antenna chip on the lens becomes important. Since the considered antenna structures for THz frequencies are quite microscopic, a manual placement will consistently result in a displacement from the center. Moreover, since for now it is not possible to mechanically attach the chip on the lens (e.g., by vacuum or adhesive), any modification of the system will lead to an additional movement. For the detector characterization, this leads to an error in the calculation of the responsivity, since the incoming power to the antenna structure is not precisely known.

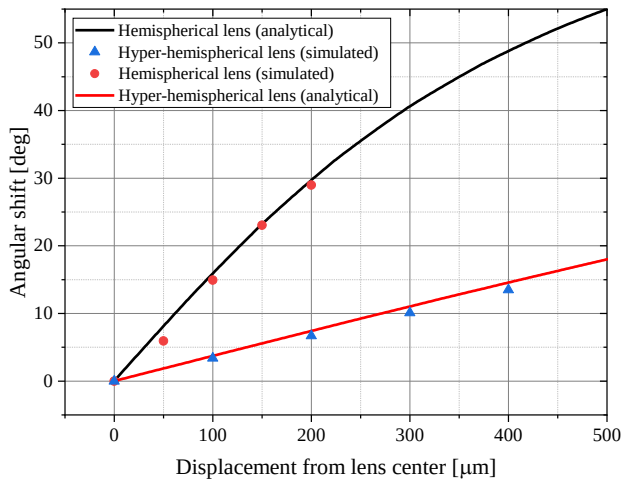

Fig. 5: Simulated beam angle of (hyper)-hemispherical silicon lenses with a diameter of 10 mm for different lateral displacements compared to analytical expressions

B. *Concepts for exact positioning*

To improve the positioning of the chip to the lens center, we propose to include a second interposer substrate in the structure (see Fig. 6). Moving the InP chip on the lens surface while having the antenna connected with the measurement tips is a major problem. If the chip is glued on a second substrate, which is mounted in a suitable holder, movement of the lens against the chip becomes possible [14]. Best RF performance can be realized when either utilizing the same wafer material as the lens (HRFZ-Si) or the chip substrate (InP) because the number of material interfaces does not increase. The second substrate thickness additionally contributes to the extension length L, which decreases the angular tilt for a given displacement. Moreover, the much wider interposer with the rigidly mounted InP chip leads to a decrease in mechanical tilt when contacting the antenna with tungsten probes, thus resulting in a more repeatable electrical contact. As a glue between InP chip and interposer, an adhesive with low shrinkage and low THz loss tangent must be selected. The interface between lens and interposer substrate also needs to be considered. Since the interposer substrate shows comparable optical characteristics to either chip or lens, the overall system is still acting as a hyper-hemispherical lens with minor additional losses. The fine adjustment is then conducted as an active alignment procedure, monitoring the detector voltage while moving the lens under the chip/interposer structure (see Fig. 6).

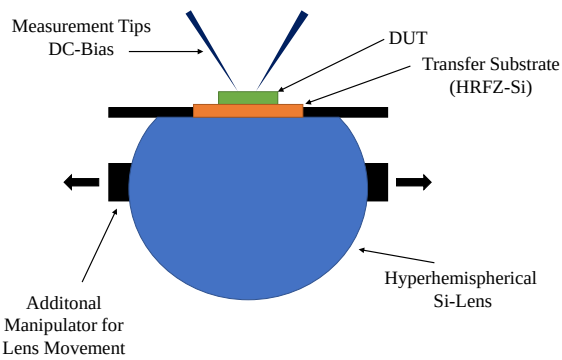

Fig. 6: Schematic of the method to align the lens under the chip with a transfer or interposer substrate.

IV. Extensions and Improvements

A. *Setup for transmitter characterization*

Since the overall path between the transmitting element and receiver is bidirectional, the measurement setup can also be modified for transmitter characterization. In this case, we monitor the outcoming power of the lens produced by the transmitting element. Now instead of measuring a voltage at the DUT, a DC bias is applied at the same terminals. As shown in [15][16], resonant-tunneling diodes act as an oscillator when applying a DC bias in the negative differential region of the diode's IV curve. In this case, we detect a narrowband signal governed by the LC resonant circuit formed by the RTD and the integrated antenna, emanating in the z direction. Since the exact frequency is not known (depending on technological deviations), the vector network analyzer with mm-Wave converter is not well suited for the characterization of the free running oscillator. Total output power can always be measured with a bolometer, integrating over all frequencies in the band [17]. A spectrum analyzer with high sensitivity is used to measure the frequency and power level of the transmitted signal. An external mixer is utilized to convert the signal down to the analyzer band. The setup is schematically shown in Fig. 7. Adding a parabolic mirror instead of a waveguide bend can improve the concept [18] but increases the number of free-space calculations needed to obtain the power budget.

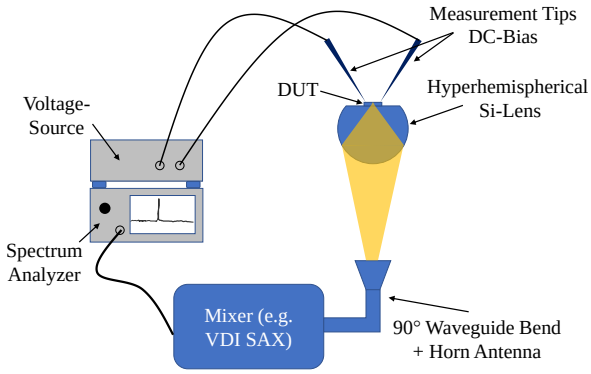

Fig. 7: Schematic setup of the modified quasi-optical measurement setup for oscillator characterization in THz frequency regime

B. *Setup for heterointegrated chips*

In ongoing work, oscillator circuits will be fabricated including a flip-chip process. Here the RTD oscillator chips are stacked on another oscillator chip fabricated in SiGe technology for injection locking purposes. SiGe technology is utilized to generate a subharmonic injection locking signal, to control the phase and frequency of the single oscillator element [19]. In this chip package, the oscillator (DUT) is now in a face-down orientation with respect to the second oscillator chip. The biasing of the DUT is done through the CMOS chip (see Fig. 8). The InP RTD oscillator is again radiating through its substrate. Therefore, the measurement setup needs to be modified to accommodate the upward firing THz source. One of the biggest challenges in building this setup is again the perfect alignment of the Si-lens onto the upper chip. Misalignment will again lead to an angular tilt of the outcoupled beam at the silicon lens. The lens is here necessary to improve the outcoupling of the radiation from the substrate and to avoid reflections at the substrate-air interface which could propagate sideways as substrate modes. Because the placement of the lens is always fraught with uncertainties, another possible approach is the use of a setup as shown in [20]: by use of a spherical positioner, a complete far-field pattern of an antenna chip can be recorded. With such a setup, the direction of the emanating beam can be found, and the measurement becomes independent of lens alignment. Another approach could be a microfabrication process including lens mounting in a glue step using a die bonder with sub-micron accuracy. To this effect, two possible process flows can be considered: one is to glue the processed RTD oscillator onto the Si-lens and flip-chip mount the SiGe-oscillator chip onto the InP chip/lens assembly. The other one is to mount the already heterointegrated InP and SiGe chip stack onto the Si-lens. The first-mentioned process flow would avoid mechanical stability issues since the flip-chip bump assembly appears last in the process.

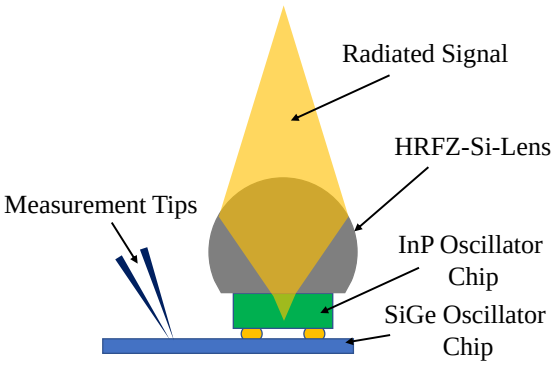

Fig. 8: Schematic of the heterointegrated assembly under investigation

V. Conclusion

In this publication, we presented a viable measurement concept for free-space measurements in the THz regime. We analyzed the robustness of the measurement setup using a silicon lens to different types of displacements resulting from fabrication or mounting issues. Compared to hemispherical lenses, we showed that the use of hyper-hemispherical silicon lenses reduces the resulting angular tilt when misplacing an antenna on the lens surface. The angular tilt for small displacements tends to be smaller by a factor of 3.75 (at 300 GHz). To solve the initial alignment problem, a µm-scale alignment must be realized. We presented several approaches to improve the current setup, which could be modified for the characterization of oscillators with on-chip antennas and even for heterointegrated InP oscillators.

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References

[1] P. Hillger *et al.*, "Toward Mobile Integrated Electronic Systems at THz Frequencies," *J Infrared Milli Terahz Waves*, vol. 41, no. 7, pp. 846–869, 2020, doi: 10.1007/s10762-020-00699-x.

[2] K. Arzi *et al.*, "Broadband Detection capability of a Triple Barrier Resonant Tunneling Diode," in *2019 Second International Workshop on Mobile Terahertz Systems (IWMTS)*, Bad Neuenahr, Germany, Jul. 2019 - Jul. 2019, pp. 1–4.

[3] R. Izumi, S. Suzuki, and M. Asada, "1.98 THz resonant-tunneling-diode oscillator with reduced conduction loss by thick antenna electrode," in *2017 42nd International Conference on Infrared Millimeter and Terahertz Waves: Cancun, Quintana Roo, Mexico, August 27-September 1, 2017*, Cancun, Mexico, 2017, pp. 1–2.

[4] Y. Koyama, R. Sekiguchi, and T. Ouchi, "Oscillations up to 1.40 THz from Resonant-Tunneling-Diode-Based Oscillators with Integrated Patch Antennas," *Appl. Phys. Express*, vol. 6, no. 6, p. 64102, 2013, doi: 10.7567/APEX.6.064102.

[5] Z. Zhao, M. E. Farage, Y. Yi, and C. Li, "A Quasi-optical THz Imaging System Using a One-port Vector Network Analyser," in *2020 International Conference on UK-China Emerging Technologies (UCET)*, 2020, pp. 1–4.

[6] L. Liu, J. L. Hesler, H. Xu, A. W. Lichtenberger, and R. M. Weikle, "A Broadband Quasi-Optical Terahertz Detector Utilizing a Zero Bias Schottky Diode," *IEEE Microw. Wireless Compon. Lett.*, vol. 20, no. 9, pp. 504–506, 2010, doi: 10.1109/LMWC.2010.2055553.

[7] Tydex LLC, *THz Materials*. [Online]. Available: http://www.tydexoptics.com/pdf/THz_Materials.pdf (accessed: Feb. 15 2021).

[8] P. Lu, V. Rymanov, S. Dülme, B. Sievert, A. Rennings, and A. Stöhr, "THz beam forming and beam switching using lens-assisted quasi-optical THz transmitter," in *2017 International Topical Meeting on Microwave Photonics (MWP)*, 2017, pp. 1–4.

[9] J. Liu, Q. Huang, and X. Shi, "A bow-tie antenna on the extended hemispherical lens for THz frequency," in *2016 IEEE International Conference on Microwave and Millimeter Wave Technology (ICMMT)*, 2016.

[10] J. A. Hejase, P. R. Paladhi, and P. P. Chahal, "Terahertz Characterization of Dielectric Substrates for Component Design and Nondestructive Evaluation of Packages," *IEEE Trans. Compon. Packag. Manuf. Technol.*, vol. 1, no. 11, pp. 1685–1694, 2011, doi: 10.1109/TCPMT.2011.2163632.

[11] D.F. Filipovic, G.P. Gauthier, S. Raman, and G.M. Rebeiz, "Off-axis properties of silicon and quartz dielectric lens antennas," *IEEE Trans. Antennas Propagat.*, vol. 45, no. 5, pp. 760–766, 1997, doi: 10.1109/8.575618.

[12] H. Frid, "Closed-Form Relation Between the Scan Angle and Feed Position for Extended Hemispherical Lenses Based on Ray Tracing," *IEEE Antennas Wireless Propag. Lett.*, vol. 15, pp. 1963–1966, 2016, doi: 10.1109/LAWP.2016.2545858.

[13] G. Guimaraes and P. Reynaert, "Analysis of Substrate Mounted Dielectric Lenses for Silicon-based THz Sources," in *2019 12th Global Symposium on Millimeter Waves (GSMM)*, 2019, pp. 78–80.

[14] M. Neshat, D. M. Hailu, M.-R. Nezhad-Ahmadi, G. Z. Rafi, and S. Safavi-Naeini, "Gain Measurement of Embedded On-Chip Antennas in mmW/THz Range," *IEEE Trans. Antennas Propagat.*, vol. 60, no. 5, pp. 2544–2549, 2012, doi: 10.1109/TAP.2012.2189772.

[15] M. Asada and S. Suzuki, "Terahertz oscillators using electron devices — an approach with Resonant tunneling diodes," *IEICE Electron. Express*, vol. 8, no. 14, pp. 1110–1126, 2011, doi: 10.1587/elex.8.1110.

[16] K. Arzi *et al.*, "Millimeter-wave Signal Generation and Detection via the same Triple Barrier RTD and on-chip Antenna," in *2018 First International Workshop on Mobile Terahertz Systems (IWMTS)*, 2018.

[17] J. Vrba, Ed., *Proceedings of European Microwave Conference in Central Europe (EuMCE 2019): 13th-15th May 2019, Prague, Czech Republic*. [Piscataway, NJ]: IEEE, 2019.

[18] S.-H. Shin, X. Shang, N. M. Ridler, and S. Lucyszyn, “Polymer-based 3-D Printed 140-220 GHz Low-cost Quasi-optical Components and Integrated Subsystem Assembly,” *IEEE Access*, p. 1, 2021, doi: 10.1109/ACCESS.2021.3057606.

[19] K. Arzi *et al.*, “Sub-harmonic injection locking for phase and frequency control of RTD-based THz oscillator,” *IEEE Trans. THz Sci. Technol.*, p. 1, 2020, doi: 10.1109/TTHZ.2019.2959411.

[20] B. Sievert, J. T. Svejda, D. Erni, and A. Rennings, “Spherical mm-Wave/THz Antenna Measurement System,” *IEEE Access*, vol. 8, pp. 89680–89691, 2020, doi: 10.1109/ACCESS.2020.2993698.

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