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Designing optical system with off-axis parabolic mirrors for THz communication setup

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Abstract. The terahertz (THz) range of an electromagnetic spectrum is considered to use for data transfer at low and high frequencies, including the 6G wireless network. The current study aims at modeling and analyzing the efficiency of a THz optical system using off-axis parabolic mirrors (OAPMs) to collimate and focus radiation from a 140 GHz IMPATT (impact ionization avalanche transit-time) diode with a waveguide horn antenna. Directivity patterns of the THz source were measured experimentally and the radiation profile was approximated with a Gaussian distribution. The modeled source was implemented in ANSYS OpticStudio and combined with two identical aluminum OAPMs to simulate beam collimation and focusing on a detector. A full optical system was simulated using 10^8 rays to calculate radiant flux and spatial energy distribution at the detector plane. The results showed that the system with both collimating and focusing mirrors achieved nearly 85% power transfer efficiency, while the experiment achieved 40%. The collimated beam had a reduced divergence angle and significantly increased the peak radiant intensity. It is found out that a system comprising two OAPMs effectively improves delivery of radiation from a compact THz source to a small-area detector, substantially increasing usable transmission range without increasing the source power. However, it requires an additional tracing system to keep high efficiency value.

Keywords: terahertz (THz) range, wireless data transfer, 6G network, off-axis parabolic mirrors.

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1. Introduction

Realization of sixth-generation (6G) wireless communication systems is expected to heavily rely on exploitation of terahertz (THz) frequency bands to enable ultra-high data rates, extremely low latency, and high spatial resolution [1]. Owing to significant free-space path loss and atmospheric attenuation at the THz frequencies, efficient beam shaping and high-gain quasi-optical components become essential. In this context, off-axis parabolic mirrors (OAPMs) are promising quasi-optical elements for a number of targeted 6G THz communication applications.

One of the most prominent application areas for OAPMs is point-to-point THz backhaul and fronthaul links. Future 6G networks are expected to require high-capacity wireless backhaul capable of supporting terabit-per-second data rates. OAPMs can provide highly directive, low-loss collimation and focusing, enabling narrow beams that partially mitigate the high free-space loss at THz frequencies. The reflective and achromatic nature of the OAPMs is especially beneficial for ultra-wideband operation needed in terabit-scale backhaul scenarios [2].

Another important domain for OAPMs application is indoor THz communication, including data-center interconnects and ultra-high-capacity wireless local area networks. In controlled indoor environments, OAPMs can form stable high-gain beams with low distortion, supporting efficient spatial reuse and reduced interference. These properties are crucial for dense 6G deployments operating at THz frequencies. The OAPMs are also suitable for hybrid quasi-optical and electronic beamforming architectures. In experimental THz platforms, the OAPMs may be combined with phased arrays or reconfigurable intelligent surfaces to separate coarse optical beam shaping from fine electronic beam steering. This approach can reduce hardware complexity and power consumption, while maintaining broadband and high-efficiency beam control. Moreover, the OAPMs are valuable components in THz channel sounding systems and 6G research testbeds. Accurate characterization of THz beam propagation, blockage, scattering, and reflection is essential for realistic channel modeling. The broadband and low-dispersion properties of the OAPMs enable precise time- and frequency-domain measurements over wide THz bandwidths [3].

Finally, OAPMs may contribute to integrated sensing and communication (ISAC) systems, which represent a key technological pillar of 6G. Highly directive THz beams formed by the OAPMs can simultaneously support high-data-rate communication and high-resolution sensing or localization. This dual functionality is particularly attractive for industrial automation, robotics, and autonomous systems [4].

A primary advantage of OAPMs in a THz 6G communication context is their broadband, low-loss performance, which enables consistent focusing and collimation across large portions of the THz band. This wideband behavior is essential for THz systems targeting multi-gigahertz or terahertz-wide signal bandwidths for high-speed data transmission. Furthermore, the off-axis geometry eliminates central apertural obstruction, enabling higher effective aperture and increased gain for point-to-point free-space THz links, improving link budget and spatial resolution without introducing wavelength-dependent refractive effects [5].

One of the major problems for THz remains the power limitation for conventional, compact, affordable and suitable for room temperature transmitters/sources. Fig. 1 presents a good overview of the output powers for THz sources and its comparison to the output powers of neighborhood radio frequencies and infrared range devices. The figure clearly shows a lack of the sources with the output power exceeding 1 mW in the THz range.

While sources with higher power have not yet been developed, the problem can be worked around using additional optical elements, such as polymer lenses or metallic mirrors, to collimate radiation emitted by a source and to collect it on a detector. Although polymer lenses are widely used in THz systems [7, 8], they do not work in a wide spectral range and their finite Fresnel losses and absorption reduce optical throughput. Also, considering that THz radiation tends to diverge rapidly, large numerical aperture optics are required for longer wavelengths, which means that the lenses have to become large and heavy. Moreover, it is hard to design an optical lens system with diffractive quality, *i.e.*, low optical aberrations. Usually, doing so requires a large number of lenses.

So, referring to D.M. Mittleman and others in [9], OAPMs can be used as an alternative to optical elements, like lenses, for THz systems, due to their broadband, low-loss operation and high numerical apertures. The OAPM arrangement is primarily dictated by spatial requirements. For an object point placed at the OAPM focus, the image is always a perfect collimated beam. The imaging properties of off-axis field points have become important with the development of linear and planar detectors. As shown in [5, 10], the OAPM arrangement has a large influence on the resulting geometric optical aberrations. The astigmatism and coma are inherent aberrations due to the off-axis geometry, and the resulting aberrations for different OAPM arrangements are important to be estimated for optimal arrangement of 90° OAPMs in THz setups.

Given the inherent limitations of low-power, compact THz sources, this study specifically aims to design, model, and quantitatively assess the performance of a practical reflective optical module to enhance the THz source usability in data transmission links. The core technical challenge was to overcome the high divergence (22° at 0.1 level) of radiation from a 140 GHz IMPATT diode source and efficiently deliver the radiation energy to a small-area pyroelectric detector.

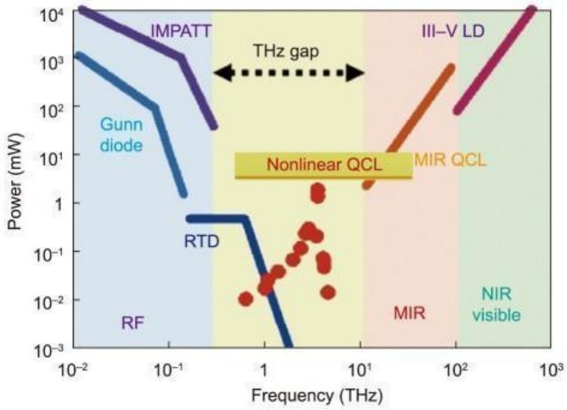


Fig. 1. THz output powers of different sources *versus* frequency [6]. IMPATT: impact ionization avalanche transit-time; RTD: resonant tunneling diode; NIR: near-infrared; MIR: mid-infrared; LD: laser diode.

The purpose of the current study pursues the following objectives: 1) to experimentally characterize the radiation pattern of the source and translate it into a Gaussian beam model compatible with optical design software; 2) to implement and optimize a system comprising two commercial off-axis parabolic mirrors in ANSYS OpticStudio for collimation and subsequent focusing; 3) to rigorously evaluate both geometric aberrations and the system efficiency by calculating key metrics such as spot diagram distributions, total power transfer efficiency, collimated beam divergence and peak radiant intensity at the detector; and 4) to assemble a stand and perform an experiment to validate the evaluations. The ultimate goal is to demonstrate significant extension of the effective operational range for a THz communication link without increasing the source power. As the main instrument for the study, ANSYS OpticStudio software was used.

2. System design, modeling, and characterization

We started with sequential mode of the software, defining source points as shown in Fig. 2, which corresponds to the inner source size of 1.65×0.83 mm. Then, models of two similar off-the-shelf MPD249-G01 OAPMs from Thorlab were added to the system. After optimizing their mutual position and the positions of the source points and image plane, spot diagrams and ray aberrations were calculated.

Fig. 3 shows spot diagrams of different fields and provides a clear understanding of the system quality. As may be seen from the table in Fig. 3, geometrical aberrations have 0 root mean square (RMS) spot radius and 0 geometric (GEO) spot radius for the center point.

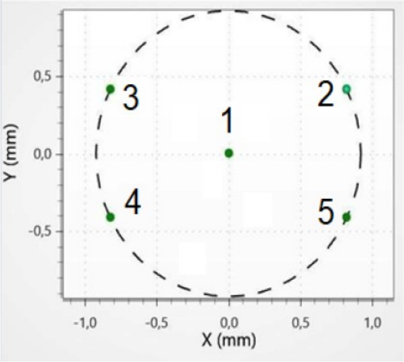
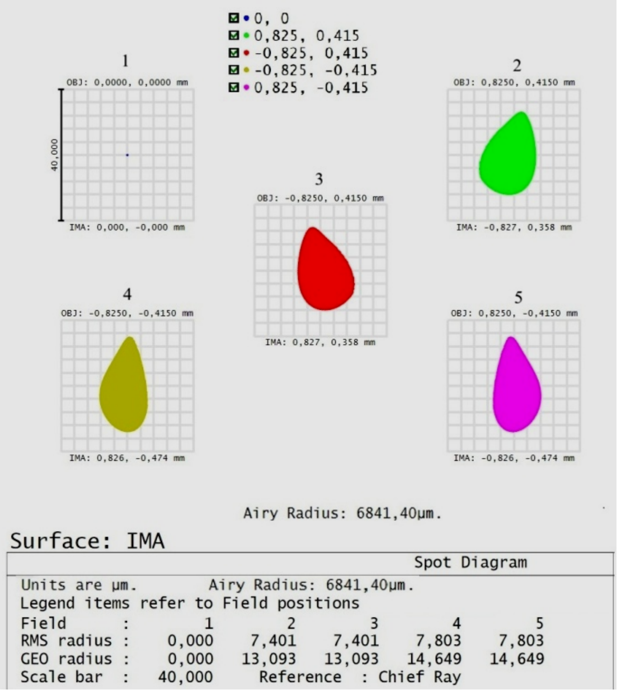


Fig. 2. Source points definition.



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Units are μm.          Airy Radius: 6841,40μm.
Legend items refer to Field positions
Field       :        1        2        3        4        5
RMS radius  :    0,000    7,401    7,401    7,803    7,803
GEO radius  :    0,000   13,093   13,093   14,649   14,649
Scale bar   :   40,000     Reference    : Chief Ray
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Fig. 3. Spot diagrams of the system for the field points specified in Fig. 2.

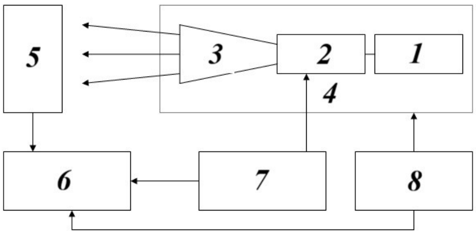

Fig. 4. Schematic stand for measuring THz source directivity diagrams: *1* – 140 GHz generator, *2* – electrical signal modulator, *3* – horn antenna, *4* – rotating stand, *5* – pyroelectric detector, *6* – Lock-In Amplifier SR-830, *7* – signal generator Agilent 33250A, and *8* – PC.

For the field points, the RMS spot radii are <8 um and the geometric radii are <15 um. Accordingly, it could be stated that the achieved system is a diffractive limited one since the Airy radius of the system provided by OpticStudio is 6.84 mm. To calculate energy transfer of the system, a new model in non-sequentional mode of OpticStudio was generated. To start with, we transferred the measured radiation data from a 140 THz IMPATT diode with attached waveguide horn antenna (WR-6), to one of the ANSYS OpticsStudio standard source models. For this, we started with measurements of directivity diagrams in the planes of the electric (E) and magnetic (H) field vectors according to the power flux density of the horn antennas. To do that, we placed the horn antenna connected with the IMPATT diode on a rotating platform and rotated it at a certain angle relative to the detector. Next, we measured voltage on the detector, which is proportional to the density of the power flux. The angle between the antenna and the receiver varied from –90° to +90° with a step of 0.9°. In this manner, we obtained density of the power flux dependence on an angle. Fig. 4 displays a schematic of the stand for measuring THz source directivity diagrams.

Fig. 5 presents the measured directivity diagram of the IMPATT diode with the horn antenna. The received beam has a shape of a Gaussian function with the divergence angle of 22° at 0.1 level.

Next, we approximate the results with a Gaussian distribution of the form (1) to use in the ANSYS OpticStudio software for distribution modeling:

$$I(l,m)=I_0 e^{-\left(G_x l^2+G_y m^2\right)}, \tag{1}$$

where I_0 is the power flux density at the peak intensity, l and m are the direction cosines of the ray in the directions of the x and y axes, and G_x and G_y are constants, respectively. The best match of the experimental data was obtained for $G_x = G_y = 54.5$. Fig. 6 shows the approximation result for an IMPATT diode with a horn antenna, featuring a Gaussian distribution. This model, with a total power of 5.3 mW and a peak irradiance of 91.5 mW/sr, is suitable for use in ANSYS OpticStudio.

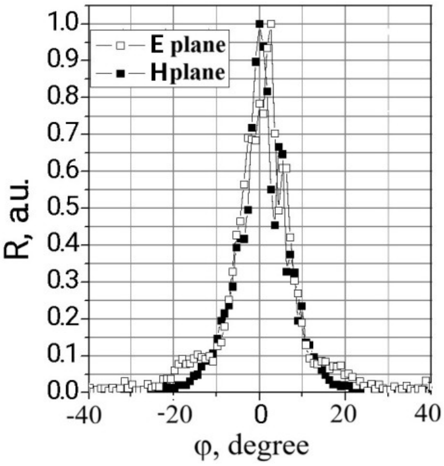

Fig. 5. Normalized radiation patterns of horn antenna in E- and H-plane.

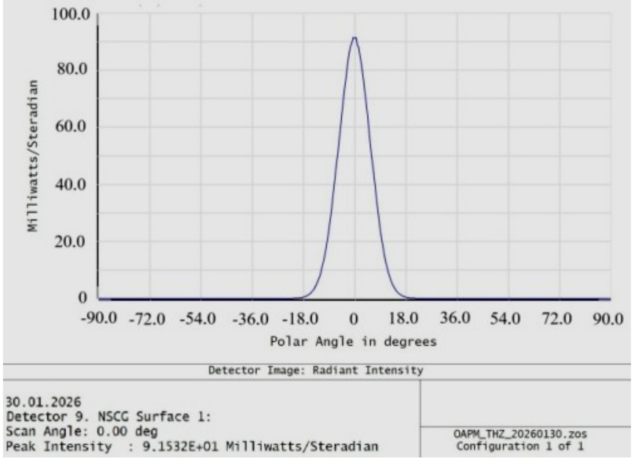

Fig. 6. Approximated spatial propagation pattern of the IMPATT diode integrated with the horn antenna.

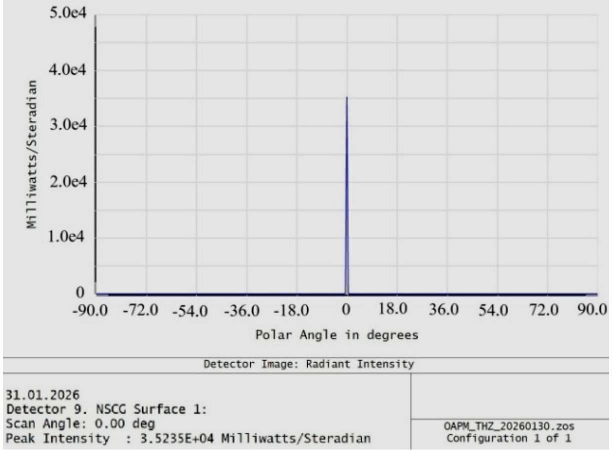

Fig. 7. Modulated collimation radiation after the first OAMs mirror.

Further, we inserted a model of two similar off-the-shelf MPD249-G01 OAPMs of Thorlab according to sequential mode positions. Each mirror had a diameter of 50.8 mm and a focal length of 101.6 mm and was covered with a protective aluminum coating with the reflectivity exceeding 95% in the THz range. Moving forward, we ran a simulation with 10^8 rays and obtained a collimated beam with the distribution shown in Fig. 7.

Next, a second identical OAPM was placed 0.8 m from the first mirror to collect the collimated beam at the image plane (Fig. 8). The total distance between the radiation source and the detector was approximately 1 m. Subsequent simulation of this complete setup determined the overall radiant flux at the detector. The result of the simulation showed a total radiant power of 4.5 mW, corresponding to a total system efficiency of 85%.

Cumulatively, this work enabled development of a wireless THz communication setup, which is conceptually similar to the one described in [11] but implemented with proprietary components for comprehensive investigation.

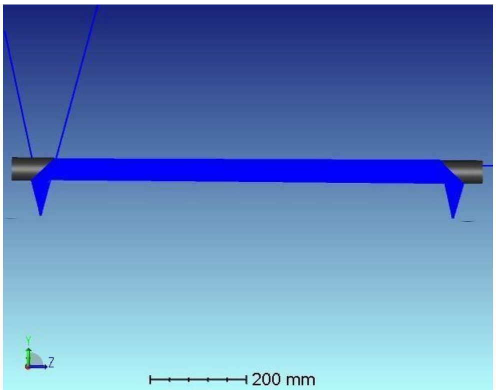

Fig. 8. Optical system with two OAPMs for collimation and focusing of 140 GHz radiation.

3. Experiment setup

Fig. 9 shows an assembled setup for measuring radiant power emitted by the THz source, collimated by the first OAPM and collected in the detector plane by the second OAPM identical to the first one. The system comprises a 140 GHz IMPATT diode source, two Thorlabs MPD249-G01 off-the-shelf OAPMs, and a Gentec THZ12D-35-VP pyroelectric power meter with the sensitive area 12 mm in diameter. Coarse adjustment of the element positions was achieved using a laser level and precise tuning was performed by aligning a white LED with the source and making fine adjustments of each element to receive the smallest possible spot on the detector. As a result, we achieved radiant power on the detector equal to 2.1 mW, which corresponds to approximately 40% of the 5.3 mW power emitted by the source. The total radiant power emitted by the source was determined in a prior measurement by placing the detector closely in front of the source to collect all its power.

4. Results & discussion

An optical system with two OAPMs for collimation and focusing of 140 THz radiation on the pyroelectric detector surface was considered. With the help of ANSYS OpticStudio software, such a system was modeled in sequential and non-sequential modes. The model in the sequential mode helped to optimize elements

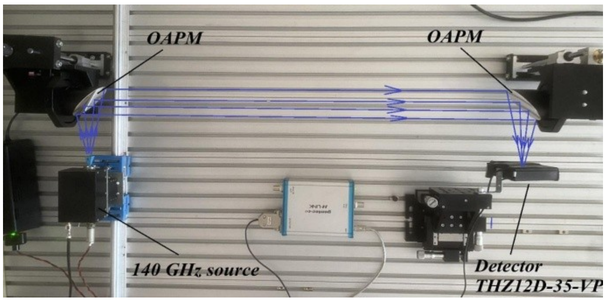

Fig. 9. Experimental setup with two OAPMs for collimation and focusing of 140 THz radiation.

positioning and proved diffraction behavior of the system. Using the model in the non-sequential mode, we evaluated the radiant power in the detector plane and calculated that the overall efficiency of the system was equal to 85%. Despite the fact that the experiment gave us about 40% of the system efficiency, the results are still considered as sufficient since the efficiency without any mirrors in this range (~1 m from the source to the detector) is less than 1%. As for the difference between the model and the experiment, there are several main contributors, such as mutual elements positioning, OAPMs manufacturing tolerances, modeling precision of the OAPMs reflectance coefficient, deviation of the source model, diffraction on the mirror edges *etc*.

Another point worth to be mentioned is that extending the distance of data transfer with the help of optical systems leads to the necessity of knowing exact mutual positions of the source and the detector together with the tracking system, if one of them is moving.

5. Conclusions

This study successfully designed, modeled, and experimentally validated an optical system utilizing two OAPMs to efficiently collimate and focus radiation from a low-power 140 GHz IMPATT diode. The Gaussian beam model, derived from experimental directivity measurements, enabled accurate simulation in ANSYS OpticStudio, predicting a high-power transfer efficiency of 85%.

The constructed prototype confirmed the system functionality, delivering 2.1 mW (40% of the source power) to the detector at a ~1 m distance – a major improvement over the <1% efficiency expected without beam shaping. The significant discrepancy between the simulated and the measured efficiencies is primarily attributed to practical alignment challenges, manufacturing tolerances, and model simplifications, underscoring the critical need for precise assembly and potential active tracking in future deployments.

In summary, this work demonstrates a practical and effective method to extend the operational range of compact, low-power THz sources using a simple OAPM-based optical system, highlighting the potential of such system for advancing short-range, high-directionality THz communication links.

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Zabudsky V.V.: conceptualization, methodology, investigation.

Lysiuk I.O.: methodology, investigation.

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Проєктування оптичної системи з позаосьовими параболічними дзеркалами для налаштування ТГц зв'язку

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Анотація. Розглянуто терагерцовий (ТГц) діапазон електромагнітного спектра, який використовується для передачі даних як на низьких, так і на високих частотах, включаючи бездротову мережу 6G. Метою дослідження було моделювання та аналіз ефективності ТГц оптичної системи з використанням позаосьових параболічних дзеркал для колімації та фокусування випромінювання від 140 ГГц лавинно-пролітного діода з рупорною антеною. Діаграми спрямованості ТГц джерела вимірювали експериментально, а профіль випромінювання було апроксимовано гауссовим розподілом. Змодельоване джерело реалізовано в ANSYS OpticStudio та поєднано з двома ідентичними алюмінієвими позаосьовими параболічними дзеркалами для моделювання колімації пучка променів та фокусування на детекторі. Повну оптичну систему змодульовано з використанням 10^8 променів для розрахунку потоку випромінювання в площині приймача випромінювання. Результати показали, що система з колімуючими та фокусуючими дзеркалами досягає майже 85% ефективності передачі потужності, тоді як експериментально було отримано ефективність 40%. Колімація випромінювання зменшує кут розбіжності та значно збільшує пікову інтенсивність випромінювання. Згідно з дослідженням, система, що включає два позаосьові параболічні дзеркала, ефективно покращила транспортування випромінювання від компактного ТГц джерела до детектора, суттєво збільшуючи дальність передачі без збільшення потужності джерела. Однак, для підтримки високої ефективності потрібна додаткова система трасування.

Ключові слова: терагерцовий (ТГц) діапазон, бездротова передача даних, мережа 6G, позаосьові параболічні дзеркала.