Spot Focusing Coma Correction by Linearly Polarized Dual-Transmitarray Antenna in the Terahertz Region

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Abstract—Focus scanning is critically important in many terahertz (THz) imaging and sensing applications. A traditional single focusing transmitarray can achieve a good focus when the source is on-axis, but moving the source off-axis produces a significant aberration. This article presents a novel approach to reducing coma for transmitarray off-axis scanning in the THz region. Here, a dual transmitarray solution is proposed, in which a transmitarray with an optimized phase profile is placed behind a regular phase profile transmitarray. A linearly polarized, dual-transmitarray antenna was fabricated for validation, and the focusing performances were experimentally characterized. The measured results are in good agreement with the theoretical ones. The generated spot of the dual-transmitarray antenna remains focused on an angle up to 50°, with a 3 dB spot size of less than 4 mm at 290 GHz. The measured near-field sidelobes are all below ~10 dB within the whole scanning range.

Index Terms—Focus scanning, near-field focus, terahertz (THz), transmitting antennas.

I. INTRODUCTION

TeraHertz (THz) waves are increasingly popular for their numerous applications, ranging from wireless communications [1] to medical scanning [2], [3]. It has a shorter wavelength than microwaves, allowing scanning applications involving THz waves to have a far greater resolution while being far less harmful to biological substances than X-ray [4]. One of the most exciting developments is using THz waves for scanning applications, such as in standoff personnel detection at security checkpoints [5], [6]. The unique absorption frequencies of substances also allow THz waves to be used in medical scanning applications [4]. In both cases, THz waves would have to be focused on tiny sections of a sample. As such, a near-field focus point can be raster-scanned to gather information about the structure of a medical sample. As a result, it is paramount to have a tight and scanning focus spot that can be used to “pinpoint” features in the sample [7].

Scanning with the use of THz waves necessitates near-field focus steering. While electrical scan techniques have been devised at much lower microwave frequencies, traditional mechanical scan techniques remain popular in the THz band due to their simplicity, low cost, and ease of fabrication [8]. While many spot-focusing antennas have been designed to achieve a focusing effect, traditional designs often lead to defocusing when achieving off-axis focus [9]. Designs involving reflectors or dielectric lenses often employ a parabolic phase profile. While this succeeds a tight focus in producing a focus spot on-axis, the off-axis focus often introduces coma into the resulting focus spot. Typically, when the off-axis scanning angle exceeds 30°, artefacts such as the broadening of intensity peaks, pattern degradation, and comatic aberrations would be presented. A broadened focus spot would reduce resolution and accuracy as the resolution depends on the diffraction-limited focus spot [10]. The presence of high-intensity sidelobes or pattern degradation would be undesirable in most scanning applications.

Comatic aberrations, or coma, are common forms of aberration arising from a lens’s imperfection [10], [11]. As off-axis rays have varying focal lengths, they cannot converge to a tight focus. Consequently, point sources that are located off-axis appear distorted. Antenna design involving parabolic phase profiles includes transmitarray [12] and reflectarrays [13]. Transmitarrays are antennas with a feed source illuminating a thin, transmitting surface, which can be constructed with metasurfaces or a similarly phase-shifting surface [14], [15]. The feed source would be located at the equivalent of the focal point [12]. Similarly, a reflectarray operates on the same principle but instead reflects the waves from a feed source. Open literature has reported some near-field focusing transmitarrays [16], and reflectarrays [17]. As transmitarray and reflectarray antennas with a parabolic phase profile are functionally identical to spherical lenses in classical optics, they share the common

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problem of introducing comatic aberration when performing off-axis focusing.

Traditional approaches generally only utilize one reflectarray or transmitarray to perform focusing, and suffer from off-axis aberration [16, 17, 18]. In classical lens optics, a solution to rectify such a problem utilizes methods such as introducing an aperture stop or passing the beam through several lenses, each correcting for different aberrations [19]. Inspired by such an approach, this article introduces a ‘doublet’ setup to reduce comatic aberration in off-axis scanning. The first transmitarray would have a phase profile optimized to minimize the coma via altering the off-axis rays’ focal length. The beam from the first transmitarray is then passed through an additional focusing transmitarray which refocuses the beam, allowing for a focus with a significantly reduced coma at the imaging plane.

This article considers a system fed with a linearly polarized source in which only the source would be mechanically steered. Transmitarrays would be used to focus the waves from the source. This is a setup that has been established [20] and is also used in some of this group’s work [8], [21] but for one-transmitarray and far-field applications. While it is possible to steer the transmitarray or whole antenna systems instead [13], [22], source steering is preferred because applications, such as standoff personnel screening, using bulky reflectors/transmitarrays/lenses focus a source, in which mechanically steering the reflectors/transmitarrays/lenses or whole antenna system are quite difficult and cumbersome. Furthermore, such applications require a rapid scan to be performed in one second [6], [23]. This requires the focusing aperture to be mechanically steered at high speeds, which can be quite difficult for heavy and cumbersome reflectors/transmitarrays/lenses. Furthermore, medical applications such as in vivo disease diagnosis demand handheld and fast-scan portable THz imaging systems [3]. This leads to considering a movable source, as THz sources are increasingly miniaturized. There have been many promising developments in making small THz sources through the use of IC technology [24], [25]. This system considers a 1-D scanning system that can be used to construct portable THz scanning apparatus that can be easily carried to various venues to provide medical scanning or safety scans [5].

II. THEORETICAL MODEL

This section describes a theoretical model constructed to calculate the resultant field radiated by the transmitarray at the imaging plane given a source distribution. The transmitarray would simply be treated as a component that can alter the incoming electromagnetic (EM) wave phase, and its specific construction would not be considered. This will be subsequently used in Section III which optimizes transmitarray designs.

Angular spectrum method (ASM) [10], a subset of scalar diffraction theory [26], has been widely utilized for calculating the near-field distributions for various aperture antennas, including near-field planes [27], and lenses [10, 26]. This article uses ASM to calculate, optimize, and design the transmitarrays. The scalar wave equation that governs the propagation of EM waves in free space is given in the form of the Helmholtz equation

$$\nabla^2 \psi + k_0^2 \psi = 0$$  \hspace{1cm} (1)

where $k_0 = \frac{2\pi}{\lambda}$, and $\lambda$ is the free-space wavelength at the operating frequency. The solution in the form of a scalar complex potential, is then expressed as a product of a complex amplitude and a phase function

$$\psi = A(x, y) e^{j\phi(x, y)}.$$  \hspace{1cm} (2)

A plane wave solution is used to model the propagating EM wave. A Fourier transform of the equation can be taken, and a solution for how the wave propagates can be written as a function of the wave’s initial profile. Suppressing the temporal dependence of $e^{-j\omega t}$, the field in the imaging plane $E$ and source plane $E_0$ are related by

$$FT [E] = FT [E_0] e^{j(\sqrt{k_0^2 - k_z^2} - \sqrt{k_0^2 - k_y^2})z}$$  \hspace{1cm} (3)

where $k_0$ is the free-space wavenumber at the operating frequency of 290 GHz, and $k_x$ and $k_y$ are the transversal wavenumbers along the x- and y-axis, respectively. The Fourier transform of initial field distribution in the source plane is represented by $FT [E_0]$, and $e^{j(\sqrt{k_0^2 - k_z^2} - \sqrt{k_0^2 - k_y^2})z}$ represents the spatial transfer function. The transmitarray is expressed as a transparency function, which is a combination of an amplitude function and phase function, which modifies the EM wave’s amplitude and phase distribution

$$t(x, y) = A(x, y) e^{j\phi(x, y)}.$$  \hspace{1cm} (4)

The EM field distribution originating from the source would be propagated through free space in the form of (3) and then the transparency functions in the form of (4) [26].

One distinctive advantage of the ASM is computationally efficient due to the utilization of the fast Fourier transform algorithms. Most other methods of calculating wave propagation, such as finite-element methods and finite-difference time-domain method, require a large amount of computation time. This is not practical for the optimization in this article, as the design process involves performing slight modifications to the antenna and calculating the resultant field on the imaging plane.

On any setup, the theoretical model proceeds as follows. First, the initial field distribution would be defined, as shown in Fig. 1. This could be the amplitude and the phase information of a horn source, taken at the correct operating resolution and size. Then, this would be propagated through $z = z_1$ to reach the transmitarray, which is performed via taking the Fourier transform of the field at $z = 0$, multiplying it with the spatial transfer function, and then taking the inverse Fourier transform of it using (1) [27]. Subsequently, the propagation is simulated by multiplying the field distribution with the transparency function $t(x, y)$ in (2), before propagating through $z = z_2$ to the imaging or focal plane. Such a setup can easily be extended to calculate the field after propagating it through multiple transmitarrays or across different distances. Note that coupling between the two transmitarrays can be ignored as they are separated by 5
mm. This is a relatively large distance of about five free-space wavelengths at 290 GHz.

III. TRANSMITARRAY DOUBLET DESIGN

A. Double Transmitarray

A single lens setup is unable to achieve a diffraction-limited spot when the incident angle is large [19]. Optical systems must conserve radiant flux, resulting in the Abbe Sine condition (ASC) [31] which states that image size increases as the incident ray angle increases. A double transmitarray system has a less stringent ASC, so the image size can remain small even as the incident angle increases. This gives a better improvement over coma correction when compared to a single transmitarray setup. This necessitates the use of a double-transmitarray setup.

The configuration of the proposed doublet transmitarray is shown in Fig. 2, which consists of an aperture transmitarray and a focusing transmitarray, illuminated by a feed source moving in a circular arc. In this case, the focusing transmitarray has a phase profile given by [28]

$$\phi_f = k_0 \left(R_1 + R_2\right) \quad (5)$$

where $R_1$ and $R_2$ are the spatial distances from the feed source to the focusing transmitarray element, and the spatial distance from the element to the focal point for the ON-axis focusing scenario, respectively.

The aperture transmitarray has a phase profile which can be expressed as a polynomial up to a particular order [19]

$$\phi_a = \sum_{n=1}^{N} a_n \left(\frac{r}{\rho}\right)^{2n} \quad (6)$$

Here, $a_n$ are coefficients to be determined through an optimization algorithm. The variable $r$ represents the radial distance from the center of the aperture transmitarray, and $\rho$ represents the total radial length of the aperture transmitarray. An optimized transmitarray of the following phase profile allows for the correction of coma via adjusting the “focal length” of the wave that passes through each part of the transmitarray. Such an adjustment results in a more uniform focal length on the area of focus, achieving a diffraction-limited focus. As mentioned above, the source moves in a circular arc located at a constant radius of $z_1$ behind the aperture transmitarray. The location of the source can be identified with the angle subtended by the arc from the axis $\theta$, as shown in Fig. 2. While a setup with regular transmitarray produces significant coma, the doublet setup can reduce the coma dramatically. This setup has been tested with $z_f$ being 56 mm and $z_2$ being 40 mm. Such a setup can correct for coma up to an angle of 50°.

In general, the transmitarray design is principally similar to lenses. Like lenses, it is defined to be a radially symmetric thickness profile. As such, any thickness profile can be described by a polynomial function of $r$, in which $r$ is the radial distance from the center of the lens as given in (6). The transmitarrays constructed here will be circular and has a radius of $\rho = 10$ mm, corresponding to 9.3 $\lambda$ at 290 GHz. While the polynomial can be in any order, it must only contain even-number order terms to maintain a radially symmetric profile. Furthermore, an arbitrary cut-off of 5 terms, or up to the order of 10, is being considered, as this allows for more efficient optimization.

B. Optimization

The goal of the optimization procedure is to produce an aperture transmitarray which can best reduce the effects of comatic aberration. The performance of an aperture transmitarray is governed by its phase profile, which is in turn governed by (6). The phase profile can be adjusted to improve the transmitarray’s performance by changing each coefficient. An iterative procedure can be performed in which the coefficients can be adjusted and then evaluating the performance that results from this adjustment. These coefficients are referred to as aperture coefficients in this article.

The procedure for optimization is as follows. First, an initial set of aperture coefficients is defined. These coefficients would be used to “construct” an aperture transmitarray by generating a transparency function (4) from the coefficients. Then, the resultant field on the imaging plane can be calculated. This is performed by utilizing (3) and (4) to calculate how a wave changes...
as it propagates from a source through the transmitarrays, as described in Section II.

The cost function quantifies the error of a set of aperture coefficients. This is defined as the discrepancy between the simulated image and an ideal distribution \( M(x, y) \). The ideal distribution is a perfectly ON-axis focused spot shifted to the point on the imaging plane in which the OFF-axis beam should be on. The ideal distribution’s near-field sidelobe level (SLL) is set as \( L \). When the realized SLL is smaller than this value, it does not contribute to the cost function. As the performance for all angles must be accounted for, the cost function adds the error resulting from each scanning angle. Thus, the cost function can be written as

\[
\text{Cost} = \sum_{\text{angles}} \left[ \sum_{(x,y) \in \text{focus zone}} (F(x, y) - M(x, y))^2 + P \sum_{(x,y) \notin \text{focus zone} \text{ and } |F(u,v)| > L} (F(x, y) - L)^2 \right].
\]

The cost function thus balances two things: the size of the spot as well as its position on the imaging plane. This is important in lowering the most significant comatic aberration contribution, known as the third-order coma [29]. Coma is an aberration dependent on the product of the lens radius squared and the perpendicular distance (to the optical axis) of the OFF-axis incidence. An aspherical profile is required as it allows for OFF-axis incident rays to be deflected differently and hit the imaging plane at the same spot. Equation (6) which adjusts the phase profile of the aperture transmitarray gives us direct access to control the sphericity of the lens. Thus, the cost function measures how the phase profile affects the size of the coma.

Moreover, while the coma can also be quantified in other metrics, the cost function in (7) remains the most cost-effective. For example, the coma can be quantified by its eccentricity, which measures the ellipticity of a shape and is defined as

\[
e = \sqrt{1 - \frac{b^2}{a^2}},
\]

where \( a \) and \( b \) are the semimajor and semiminor axis respectively. If the spot is perfectly spherical, it would have an eccentricity of zero, and any ellipsoidal spot would have an eccentricity of greater than zero but less than 1. Initial attempts at optimizing the coefficients via reducing eccentricity have been successful in making the focus spot more circular. However, it fails to account for both keeping the spot at the right location on the imaging plane and keeping it at a size comparable to a diffraction-limited spot. While higher order correction terms can be added to the cost function, the increased complexity reduces the probability of achieving convergence in the solution. Thus, this form of the cost function gives the most direct way of fulfilling all the requirements required for a good focus spot for different angles of incidence.

Upon calculating the cost or the error that results from this set of aperture coefficients, a simulated annealing algorithm can be used to decide whether to adopt this set of aperture coefficients. If the error is less than that of the previous iteration, this set of coefficients will be adopted. If the error increases, there remains a probability that the coefficients will be accepted [30]. This probability is a function of a temperature that is determined by the iteration step the optimization process is on. At every step, a temperature is calculated by \( T = \text{steps} - k \), with \( k \) being the current step. The probability of accepting an adjustment is then

\[
P(T, \Delta E) = \exp\left(\frac{-\Delta E}{T}\right),
\]

where \( \Delta E \) is the error. Thus, there is a nonzero probability of accepting an adjustment even if it increases the error. The next coefficient is then adjusted. The rate at which the coefficient change can be modified by a “learning rate.” If the learning rate is small, then each iteration changes the coefficient by a smaller value, allowing the exploration of the solution space to be taken in finer steps at the cost of lowering the rate of solution convergence.

When all the aperture coefficients have been adjusted, the optimization process iterates onto the next step, in which the temperature reduces, and each of the aperture coefficients is adjusted again. This is iterated over the predefined number of steps, and the aperture transmitarray is optimized for that specific angle. The source field shifts to one that represents moving the incident beam to the next incident angle. The temperature is reset to the starting temperature, and the optimization continues to fit the aperture coefficients to minimize the aberrations caused by the new source. Note that the aperture coefficients do not reset, and the results from optimizing the source at another angle are used directly. A flowchart demonstrating the algorithm is summarized in Fig. 3.

In the actual implementation of the optimization for this setup, a simulation area, or the field area that is to be simulated, is 200 mm \( \times \) 200 mm. The unit cell of the grid is one-third of the wavelength which is 0.33 mm. The plane has 601 \( \times \) 601, with the transmitarray aperture spanning 2808 out of the total of 361 201 unit-cell of the grid. The source field distribution is given by the measured field from a horn antenna at a radius of 56 mm away from the aperture transmitarray and offsets at 0°, 30°, 40°.
and 50°. Angles smaller than 30° were omitted because a source displacement at those angles would only have minor comatic aberrations. Testing it at 0° ensures that the transmitarray’s efficacy remains comparable to traditional transmitarrays. The number of steps iterated is determined to be 100 steps, as the simulation plateaus at a level of error after iterating for such many steps. On average, this requires a computational time of 550 seconds using a computer with 16-GB memory and an Intel Core i7 CPU @1.80 GHz.

The use of a doublet lens configuration is a well-established method in classical lens optics to correct spherical aberrations. Historically, a Schmidt plate has been used to correct spherical aberrations in optical applications, leading to the Schmidt telescope and Schmidt camera [31]. A spherical lens causes principal rays to bend less than marginal rays, resulting in misalignment that is too great for a single lens to correct [32]. A Schmidt plate corrects for that by making the marginal rays diverge while making the principal rays converge. This compensates for the unbalanced amount of bending experienced by the rays when it passes through the spherical lens. The optimized aperture transmitarray has a phase profile resembling the Schmidt plate. As such, it corrects for the aberrations introduced by the traditional focusing transmitarray, which has a phase profile akin to that of a spherical lens. The aperture transmitarray itself is also unable to operate independently, as it exists to introduce divergence and convergence that is to be “corrected” by the focusing transmitarray. Without the focusing transmitarray, the focus spot produced by the aperture transmitarray alone would also appear defocused. While our design shares similarities with such optical elements, our transmitarrays are nevertheless more compact and lightweight than conventional optical components.

C. Results

The distance of 5 mm between the aperture and focusing transmitarray is selected after testing with various interplane distances. It is found that an interplane distance of 5 mm yields the smallest accumulated error. The optimized phase profiles for the two transmitarrays are shown in Fig. 4. Fig. 5 shows the theoretical intensity distributions on the image plane calculated by the model developed in Section II for the conventional transmitarray with parabolic phase profile and the proposed doublet transmitarray architecture. Furthermore, the 1-D cross section of the focal spot intensity is shown in Fig. 6 for different feed rotation angles. Fig. 6(a) clearly shows the focal spots’ elongation in conventional parabolic phase-shifting transmitarrays, displaying the coma effects. For conventional parabolic phase-shifting transmitarray, with a feed displacement angle of 0°, the −3 dB spot size is 2λ. However, at larger angles such as 40° and 50°, the spot size spreads out to be more than 10λ, which is unacceptable in scanning applications. Using the doublet rectifies the situation as shown in Fig. 6(b) for doublet transmitarray, the intensity peak is far narrower and has a width of 4λ even for an incident angle as large as 50°. It demonstrates that the system has effectively corrected the effects of focusing a source with large oblique incident angles. This article aims to overcome the THz focusing coma problem using an optimized dual-transmitarray architecture. Therefore, bandwidth enhancement is not considered in the optimization process, as indicated in the cost function in (7). The optimization process has been performed with a single frequency (290 GHz). Future investigations can be undertaken to improve the optimization process to increase the bandwidth.

IV. TRANSMITARRAY ELEMENT DESIGN

Fig. 7 shows the configurations of the polarization-conversion element used for the building block of the two transmitarrays. The element consists of a 45°-tilted C-shaped metallic layer sandwiched by two orthogonal wire gratings [33]. The lattice size of the unit cell is $P = 0.33$ mm, corresponding to 0.32λ at 290 GHz. The 0.127 mm-thick Rogers 5880 with a measured relative dielectric constant $\varepsilon_r = 2.3$ and loss tangent tanδ = 0.004 at 290 GHz [34] is adopted as the substrate of the element.
Fig. 6. One dimensional cross section of the intensity distribution generated by the theoretical model across the $yz$ plane with different feed source rotation angles, for (a) the conventional parabolic phase-shifting transmitarray, and (b) the proposed doublet transmitarray.

Fig. 7. Configuration of the C-shaped polarization-conversion transmitarray element. (a) 3-D perspective view of the transmitarray element. (b) Top view of the middle C-shaped pattern; (c) Top view of the bottom wire grating. The dimensions are $R_1 = 0.07 \text{ mm}$, $R_2 = 0.15 \text{ mm}$, $w = 0.04 \text{ mm}$, and $h = 0.127 \text{ mm}$.

The transmitarray element can convert the incident $x$-polarized ($x$-pol) waves into the transmitted orthogonal $y$-polarized ($y$-pol) waves with high efficiency. This is enabled by the multireflections between the two orthogonally-polarized wire gratings and the middle C-shaped polarization-conversion component [35].

The split angle of the middle $C$-shaped pattern $\theta$ is tuned to change the transmission phase while other parameters are fixed. The simulated transmission coefficient as a function of the split angle at 290 GHz is shown in Fig. 8. A $180^\circ$ transmission phase range can be observed as $\theta$ varies from $30^\circ$ to $190^\circ$, with insertion loss better than $-2 \text{ dB}$. Another $180^\circ$ phase range can be achieved by simply rotating the $C$-shaped pattern along its geometric centre by $90^\circ$, as shown in Fig. 8. Compared to the $C$-shaped element in [33], our unit cell can provide a continuous $360^\circ$ phase range by simply tuning just one geometric parameter ($\theta$) of the element. The transmission coefficients’ amplitude being lower than $-2 \text{ dB}$ for all transmitarray elements also shows that the multireflection between the two transmitarray panels can be ignored.

While conventional PCB process may offer acceptable fabrication accuracy for transmitarray fabrication at H-band, micromachining technology can provide a much higher accuracy of 0.5 $\mu\text{m}$, resulting in a much smaller fabrication error. The metal used for the transmitarrays is aluminium with a thickness of around 0.6 $\mu\text{m}$. The detailed micromachining process can be found in [14]. But different from using the transparent Benzocyclobutene dielectric in [14], opaque commercial Rogers 5880 is adopted as the substrate in this article, making the alignment of different metallic layers challenging during the fabrication process. To investigate the misalignment effects on the performance of the transmitarray, Fig. 9(a) shows the unit cell surrounded by PBCs with different kinds of offsets. Model A presents the perfectly aligned case, while B and C show the element structures after performing offsets along the $y$- and $x$-directions to the middle $C$-shaped pattern. Model D further introduces an $x$-direction offset to the bottom wire grating pattern. These different models are simulated in ANSYS HFSS. The simulated transmission coefficients as a function of the split angle of the $C$-shaped pattern are shown in Fig. 9(b). It can be observed that model A-D share almost identical transmission curves. As a result, the introduced $C$-shaped polarization-conversion element is free of alignment problems among different metallic layers, making the microfabrication of the transmitarray straightforward. This unique and appealing property is enabled by the multireflection working principle of the polarization conversion element. In addition, PBCs have been adopted, which take into account...
the coupling effects between the unit cells. Fig. 9(c) shows the simulated transmission coefficients of the element under different incident angles. The maximum phase deviation is about 30° for large incident angles of 50°. As a result, the effects of oblique incidences are not considered in the optimization process in Section III for simplicity. We then modeled the whole antenna system, including the transmitarray doublet and the feed horn in ANSYS HFSS to perform the full-wave simulation. The simulated total efficiency, defined as the ratio of the radiated power to the input power of the whole antenna system, is 89%.

Fig. 9. (a) Configurations of the unit cell under PBCs with different types of metallic layer offsets. The offset values are $\Delta y_1 = 0.1$ mm for model B, $(\Delta x_1, \Delta y_1) = (0.1$ mm, $0.1$ mm) for model C, and $(\Delta x_1, \Delta y_1, \Delta z_1) = (0.1$ mm, $0.1$ mm, $0.02$ mm) for Model C, respectively. (b). Simulated reflection coefficients as a function of split angle with different offsets. (c). Simulated transmission coefficients of the unit cell under different oblique incidences at 290 GHz.

V. EXPERIMENTAL DEMONSTRATION

The dual-transmitarray introduced in the above sections was fabricated and measured to demonstrate the proposed approach and design. Fig. 10 shows the micro-machining transmitarray under the microscope. A picture of the experimental setup is shown in Fig. 11. A horn source is placed on a platform that traces an arc that is always 56 mm away from the transmitarray unit. Specifically, a circular ring-shaped high-precision servo motor is used to move the horn source. The transmitarray is placed at the centre of the rotary table. The ring can be rotated, allowing the horn source to be moved in a circular arc at a constant radius of $z_1 = 56$ mm away from the transmitarray. A receiver is placed $z_2 = 40$ mm away from the transmitarray. The alignment between the source and the transmitarray has been carefully implemented by a laser in the experiment. It is important to point out that a bulky THz diagonal horn (VDI WR-3.4) was used as the feed source of the transmitarray for ease of measurement, as shown in Fig. 11. However, in practical applications, lightweight and small-footprint THz IC sources with mm-scale size [24], [25] are available to work as the feed source of the transmitarray.

The measured power densities on the imaging plane for different incident beam angles at 290 GHz are shown in Fig. 12. It is observed that a small scanning focusing spot can be achieved for the designed transmitarray antenna. It is noted that although only five discrete incident cases are given in Fig. 12 for brevity, the transmitarray antenna can realize continuous near-field focus scanning by continuously moving the feed horn along the designed arc. Moreover, 2-D near-field focusing is also feasible by moving the feed source across a 2-D area, as the transmitarrays have radial symmetry.

Fig. 10. Picture taken under a microscope of (a) the C-shaped polarization-conversion transmitarray element and (b) the wire grating.

Fig. 11. Photograph of the measurement setup.
Fig. 12. Measurement results of transmitarray performance at 290 GHz.

Fig. 13. Measured intensity distributions in cross section at (a) 260 GHz, (b) 280 GHz, and (c) 300 GHz.

Fig. 14. Comparing the measured intensity cross sections with the theoretically calculated intensity cross sections. The measurement is performed at 290 GHz. The dotted lines are the simulated intensities while the solid lines are the measured intensities.

Fig. 13 shows the measured 1-D intensity distributions at different frequencies. The measured scan loss is 6 dB up to 45° incidence at 300 GHz. The measured correction at 50° incidence is not as significant as that presented in the simulation results as shown in Fig. 5. A reason for this is that the theoretical model presented in the earlier section does not account for the diffraction effect which occurs at the edges of the transmitarray, especially for large incident angles. However, the double transmitarray can mitigate the off-axis aberration up to 45° incidence with measured near-field SLL better than -13.3 dB in the yz-plane.

A comparison with the theoretical results is shown in Fig. 14. The theoretical intensities are overlayed on the measured results. Optimization was performed at 290 GHz. In particular, the profile of the spot has a similar shape and size to the theoretical profiles. The spots’ positions in the measured and theoretical results also align. There are a few reasons why the discrepancy between simulated and measured results arises. First, the theoretical model simply assumes that the transmitarray is a surface covered with phase-shifting elements. Therefore, the theoretical model does not consider the diffraction effects as the wave hits on the edges of the transmitarray. Second, the effects of the incident angles are not taken into account in the theoretical model. This is consistent with how the discrepancies become more prominent as the incident angle increases. The fabrication tolerances and nonideal measurement environment also contribute to the discrepancy.

Furthermore, the experimental results can also be compared with other techniques used to achieve wide-angle near field focusing. Our technique has been able to achieve a large scanning area coverage, comparable to that proposed in [9]. Our technique also achieved a similar diffraction limited focus spot size and lower SLLs as compared to the frequency scanning focus solutions [36], [37].

VI. CONCLUSION

This article presents a novel dual-transmitarray antenna to correct for coma aberration introduced by traditional THz focusing systems. A propagation model was constructed and used in conjunction with an optimization algorithm to produce a design that could minimize the comatic aberration introduced by a traditional focusing method. This article considered a setup involving a horn source that can move in a circular arc at r = 56 mm away from the transmitarray unit and images onto a plane
located 40 mm away. The resultant design was subsequently constructed and experimentally demonstrated. The measured results verify that the focus spots remain tight with minimum sidelobe levels up to an off-axis angle of 45°. This makes the method extremely valuable in improving the focusing aspect of THz scanning systems and can be applied to create a more robust and portable system. Focus steering in this article is achieved by rotating the feed source in this article, unlike the in-plane rotation of the two transmitarrays [38] for achieving near-field focus steering. The dual-transmitarray solution in this article overcomes the coma problem and improves the focus scanning performance.

This article has only considered a direct system with transmitarrays, and the measurement was only performed by 1-D scanning. As a proof of concept, it demonstrates that it is possible to design antenna systems that minimize comatic aberrations for off-axis scanning beams operating in the THz region. Such a method can easily be generalized to 2-D focus scanning. The devised system and strategy work with transmitarrays; it can be generalized with similar setups in applications involving reflectarrays, lens antennas, and reflectors. In general, such a method can be used in systems that require tight focus spots in off-axis sources. It can also be easily modified to be used with higher or lower frequencies, such as the regime of microwave and millimeter-wave, thus making it widely applicable across various other problems. Future work can be done to apply the same strategy and methodology to improve other scanning antenna systems.

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