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Design of a Scannable Multi-Lens Quasi-Optical System for THz Near-Field Backhaul Communication

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***Abstract* — Radiative near-field links have gained noticeable interests recently for high-data-rate wireless communication. Unlike far-field links, near-field links can have negligible path loss within hundreds of meters for electrically large antennas at high frequencies. In this work, we propose a multi-lens quasi-optical (QO) system for 100-m near-field backhaul communication at H-band. The QO system is designed with compact size (aspect ratio of 1.3:1) and high coupling efficiency of 82%. Moreover, the rotation of an auxiliary lens realizes beam scanning for the link alignment. The scan range is in the order of 1 m with less than 2 dB scanning coupling loss and scanning magnification of 14.5:1.**

***Keywords* — Backhaul communication, terahertz frequencies, lens antennas, quasi-optical systems, radiative near-field links.**

I. Introduction

Nowadays, as 5G systems become more and more mature, 6G systems are being widely explored for achieving higher data rate [1]. However, it is challenging to achieve highly efficient wireless links at high frequencies due to inefficient electronic devices and significant path loss of far-field links. The latter can be solved by exploring radiative near-field links [2], [3], [4]. For electrically large antennas, their radiative near fields can reach hundreds of meters, and within this range, the near fields can be focalized with negligible path loss. In this work, we consider a radiative near-field link of 100 m for backhaul applications at H-band around 290 GHz. The quasi-optical (QO) systems of the transmitter and the receiver are required to be compact, with high power coupling efficiency and scanning capability for fine alignment.

To fulfill the requirements, we propose to use free-standing dielectric lenses as QO antennas rather than commonly used reflectors. This is because the lenses are more flexible to achieve scanning with easier alignment. Although lenses suffer from additional intrinsic dielectric and reflection losses, these losses can be mitigated to achieve similar performance as a reflector-based system [5]. In this work, we present a design of a multi-lens QO system with a low aspect ratio of 1.3:1, high power coupling efficiency of 82%, and certain scanning capability. Specifically, one of the auxiliary lenses is rotated by 10° to achieve 1.2 m scan range with less than 2 dB scanning coupling loss and scanning magnification of 14.5:1.

II. Coupling of a Radiative Near-field Link

Let us consider a simplified wireless communication link with the single-input single-output (SISO) setup depicted in Fig. 1. The transmitter and the receiver are identical. On the

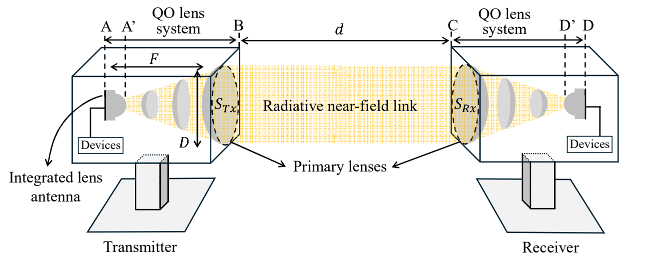

Fig. 1. Illustration of a SISO radiative near-field link. The transmitter and the receiver are identical. Each contains an integrated lens antenna and multiple free-standing lenses. An illustrative ray propagation is shown.

transmission (Tx) side, an integrated lens antenna is coupled with multiple free-standing lenses. The primary lens in Tx then focuses the EM fields on the receiver's aperture. This link has a near-field distance of d between the radiating apertures of the transmitter (S_{Tx}) and the receiver (S_{Rx}).

The coupling between the transmitter and the receiver is analyzed in reception (Rx) using the field correlation technique discussed in [3] combined with geometrical optics (GO) and physical optics (PO) approaches. Specifically, the coupling is calculated as the correlation between two sets of fields. One is the field radiated by the transmitter on the receiver aperture (S_{Rx}); the other is that radiated by the receiver when it operates in the Tx mode on the same surface. The maximum coupling can be achieved when these two sets of fields are conjugately matched over S_{Rx}. Therefore, the QO system is designed to optimize the aperture fields in Tx to fulfill the conjugate field-matching condition.

For the near-field link in Fig. 1, it was discussed in [6] that the optimal field distribution was the angular prolate spheroidal wave function. Therefore, by using this field distribution, the ideal coupling can be determined for different primary lens diameters D. Fig. 2(a) shows the link coupling efficiency when $D = 40$ cm, 50 cm and 60 cm at 290 GHz; while Fig. 2(b) presents the corresponding edge amplitude levels of the aperture fields. Note that Fig. 2 describes the ideal cases which are optimal for each link distance d. This means that the aperture field changes for different d. We can notice that as the diameter increases, the coupling becomes better, and the edge field level becomes lower. However, bigger diameter means larger size of the QO system and more expensive fabrication. We select 50 cm as the diameter for the primary lens for high achievable coupling efficiency and low edge field level at 100 m.

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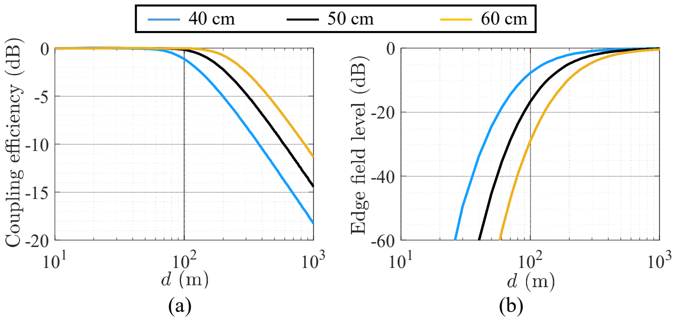

Fig. 2 (a) Coupling efficiency between two circular apertures with different diameters when using the ideal field distribution in [6]. (b) Corresponding edge field levels.

III. Proposed Multi-lens QO System

To achieve high coupling efficiency with compact system size, we propose the multi-lens QO system shown in Fig. 3. Here, L4 is the primary lens; L1 is the integrated lens antenna which feeds the QO system; and L2 and L3 are auxiliary lenses used to reduce the system size. In the following, the geometry and the performance of the system are discussed.

Since the primary lens L4 is large, we consider low-weight and low-cost HDPE as the lens material which has relative permittivity of $\varepsilon_r = 2.32$ and loss tangent of $\tan\delta \approx 3.9 \times 10^{-4}$ at 290 GHz [7]. The lens diameter is 50 cm and the thickness is about 7.5 cm, which leads to about 1.2 dB dielectric loss. The antenna feed of the QO system is a double-slot antenna integrated with a silicon hemispherical lens, L1. A quarter-wavelength matching layer made of parylene ($\varepsilon_r = 2.62$) is implemented on the lens surface to reduce the reflection at the lens surface. The lens diameter is 2 cm and the truncation angle is 73.8°. The resulting lens radiation efficiency is $\eta_{rad}^{int} \approx 95.1\%$ and its radiated field is shown in Fig. 3(b). Between L1 and L4, two auxiliary silicon lenses (with matching layers) L2 (6 cm) and L3 (19 cm) are added to reduce the system size to 65 cm which leads to an aspect ratio of 1.3:1.

The f-number of each lens, $f_\#$, is defined as the lens focal distance over the diameter, and is optimized to maximize the radiation efficiency of the QO system while maintaining a high link coupling efficiency. The resulting f-number of L4 is $f_\#^{L4} = 1.45$ and the aperture field of L4 is shown in Fig. 3(c). The field is symmetric with the edge field level of about -20 dB. In the figure, the near field radiated by the transmitter on the receiver's aperture is also shown by the black dashed curve. By performing the field correlation between these two sets of fields, the resulting link coupling efficiency (including the link spillover efficiency) is 82% which is about 0.7 dB lower than the ideal coupling shown in Fig. 2(a).

IV. Scanning Performance

In practice, the transmitter and the receiver will be installed at a certain distance to have clear line-of-sight. However, due to the installation tolerance and the wind turbulence, there can be significant beam misalignment which will lead to very low coupling efficiency. Therefore, the proposed multi-lens QO system should have scanning capabilities to a certain extend.

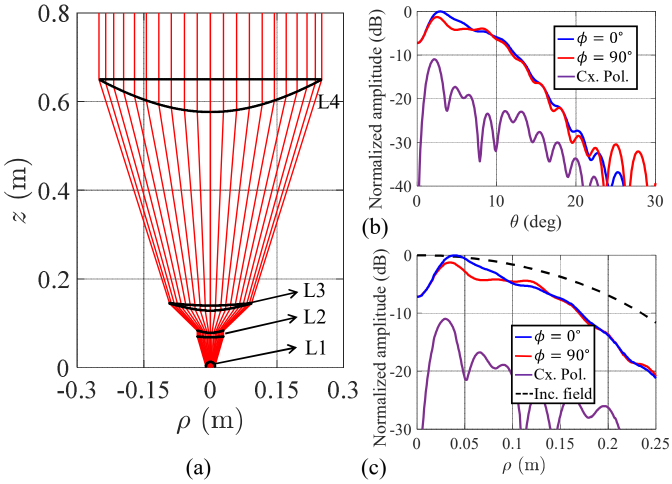

Fig. 3 (a) Geometry of the proposed multi-lens QO system. The primary lens L4 is made of HDPE while L1, L2, and L3 are silicon lenses. The ray tracing from L1 to L4 is shown. (b) Radiation pattern of the integrated lens antenna radiated on L2. (c) Aperture field of the primary lens. The near field radiated by the transmitter and incident on the receiver's aperture is also shown.

The beam scanning is achieved by rotating the lenses in the QO system. Specifically, we compare the scanning performance when rotating the primary lens L4 and the auxiliary lens L2. First, the radiated near fields of the transmitter at 100 m for different scanning cases are compared, as shown in Fig. 4(a). Here the maximum lens rotation angle is determined by the side lobe levels of the near fields which are set as -10 dB. The primary lens L4 is rotated up to 2° and the scan range of the main beam is about 0.24 m (0.14° for 100 m). In fact, this scan range is lower than half lens diameter (25 cm) so it is impractical. Moreover, it would be difficult to use a motor to move such a large-diameter primary lens considering the power consumption and the size limitation. On the other hand, L2 allows for a rotation until 10°. The resulting main beam is scanned to 1.2 m (0.69°). Note that the lens size is much smaller (6 cm) so it is more flexible to achieve the lens rotation. For this case, we can also calculate the scanning magnification as the lens rotation angle versus the beam scanning angle: $10°/0.69° \approx 14.5:1$.

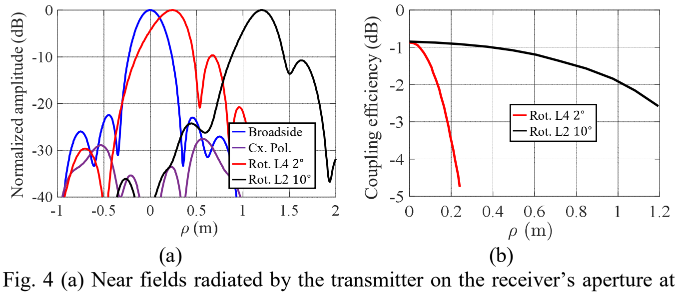

Fig. 4 (a) Near fields radiated by the transmitter on the receiver's aperture at 100 m for different scanning cases. The primary lens L4 is rotated by 2° and the auxiliary lens L2 is rotated by 10°. (b) Comparison of the link coupling efficiency for the mentioned scanning cases versus the scan range.

The link coupling efficiency is then calculated using the mentioned field correlation technique and is shown in Fig. 4(b) versus different scan ranges. Apparently, the rotation of the auxiliary lens L2 presents much larger scan range than rotating L4. The scanning coupling loss is about 1 dB when scanning to 1 m and less than 2 dB for 1.2 m. Therefore, the proposed multi-lens setup is very suitable for realizing the beam alignment within 1.2 m, with low scan loss.

V. Conclusion

In this work, we propose to use a multi-lens QO system to realize a radiative near-field link of 100 m at H-band for backhaul applications. The QO system is analyzed using a field correlation technique combined with GO/PO methods. To reduce the size of the system, two auxiliary silicon lenses are added. The resulting setup has a low aspect ratio of 1.3:1 with high coupling efficiency of 82%.

Scanning capabilities have been implemented in the QO system to allow for link alignment capabilities. By rotating the auxiliary lens up to 10°, the system can achieve a scan range of 1.2 m with the scanning coupling loss less than 2 dB and the scanning magnification of 14.5:1. Therefore, the proposed multi-lens QO system is a very promising candidate for realizing the required near-field backhaul communication link, with compact size, high coupling efficiency, and good scanning capability.

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References

[1] G. Singh, I. Verma, S. Bhardwaj, R. Sharma and W. Ahmed, "Requirements, Technologies, Applications and Challenges of 6G Communication: A Review," *2024 IEEE Int. Conf. on Comput., Power and Commun. Technologies* (IC2PCT), India, 2024.

[2] V. R. Gowda, *et al.*, "Wireless Power Transfer in the Radiative Near Field," *IEEE Antennas Wireless Propag. Lett.*, vol. 15, pp. 1865-1868, 2016.

[3] N . Llombart and S. O. Dabironezare, "Feasibility Study of Quasi-Optical MIMO Antennas for Radiative Near-Field Links," *IEEE Trans. Antennas Propag.*, vol. 70, no. 8, pp. 7073-7083, 2022.

[4] N. B. Plug, S. O. Dabironezare and N. Llombart, "MIMO Antennas for Radiative Near-Field Links: A Comparative Study at 300 GHz," *in 47th Int. Conf. on Infrared, Milli., and Terahertz Waves (IRMMW-THz)*, Delft, Netherlands, 2022.

[5] E. Gandini, A. Tamminen, A. Luukanen and N. Llombart, "Wide Field of View Inversely Magnified Dual-Lens for Near-Field Submillimeter Wavelength Imagers," *IEEE Trans. Antennas Propag.*, vol. 66, no. 2, pp. 541-549, Feb. 2018.

[6] G. Borgiotti, "Maximum Power Transfer Between Two Planar Apertures in the Fresnel Zone," *IEEE Trans. Antennas Propag.,* vol. 14, no. 2, pp. 158-163, March 1966.

[7] J. W. Lamb, "Miscellaneous Data on Materials for Millimetre and Submillimetre Optics," *Int. J. Infrared Milli.*, vol. 17, no. 12, pp. 1997-2034, 1996.