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Design of a Lens Based Quasi-Optical System with 26x26 Scanned Beams for Wireless Communication Links at 300GHz

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Abstract— This work presents a multi lens Quasi-Optical (QO) antenna for energy efficient backhaul/fronthaul links at 300GHz. By operating in the radiative near-field region, the proposed antenna system achieves power spreading loss of only 1dB for a point-to-point (PtP) link of 100m. The simulated antenna directivity is 62dBi and the half-power beamwidth is 0.15 degrees. To satisfy the tight alignment requirements of the envisioned scenario, scanning capability is included through the rotation of a lightweight free-standing silicon (Si) lens. This allows correction for misalignment of ± 2 degrees (or ± 13 beams) with a penalty of 1.8dB in the link's performance.

I. INTRODUCTION

To meet the ever increasing demand for capacity in high-traffic areas, 5G and future 6G network architectures favor the deployment of small cells for localized coverage. The scalable implementation of this approach requires low cost and efficient backhaul/fronthaul connections (i.e., line of sight links of about 50-200m). While optical fibers are a reliable solution, their deployment is costly and requires urban disruptions. A high-performance alternative can be wireless links in the THz band, which also enable rapid and cost-effective deployment.

The main challenge for reaching high-efficient wireless links is the low radiation energy efficiency of systems operating in the far field. Indicatively, the free space path loss for a 100m link at 300GHz can be as much as -120dB. A promising solution to alleviate this issue is operating a link in the radiative near-field region [1], [2]. This way the active energy can be focalized resulting to propagation spreading losses in the order of only a few dB. However, to maintain link distances in the hundreds of meters in the radiative near-field, electrically large antennas with ultra-high gain (> 50 dB) are needed. One significant impairment of such antennas systems, associated with their very narrow beamwidth, is the sensitivity to beam misalignment which can be caused by several factors in a point-to-point (PtP) link [3]. To compensate for these adverse effects, steering capabilities need to be incorporated in the antenna design, with typical specifications requiring scanning of ± 2 degrees [4].

This work presents a lens-based Quasi Optical (QO) antenna system for a radiative near-field link of 100m, operating at 290GHz. To reach power transfer levels over the wireless link of about 1dB, a primary aperture with 0.5m diameter is used. In addition, scanning capability is included in the system by rotating a lightweight free-standing lens. The proposed system can operate in a point-to-point link under scanning conditions of ± 2 degrees (or ± 13 beam), featuring a performance degradation of only 1.8dB with respect to the broadside case. The QO antenna's directivity is 62dBi and its half-power beamwidth is 0.15 degrees. The overall size is 0.5m x 0.67m, while the loss associated with the materials of the dielectric lenses is 1.15dB, and the combined spillover and reflections losses are 1dB.

II. LENS BASED QUASI-OPTICAL SYSTEM DESIGN

The proposed lens architecture is shown in Fig. 1 and consists of four lenses (L_{1-4}). L_1 is a silicon (Si) hyper hemispherical lens with a diameter of 2cm and truncation angle of 73.8deg. This lens is illuminated by a double slot antenna designed on a 90nm SiGe-BiCMOS process to facilitate integration with electronic frontends [5]. Then, a 10cm diameter free standing Si lens (L_2) is used to provide efficient illumination of the subsequent components and realize the beam scanning via its mechanical rotation. Following L_2 , a second free standing Si lens (L_3) with a diameter of 18.5cm is included to increase the magnification of the system, enabling a reasonable system size while featuring a primary aperture with an average $f_{\#}$ (i.e., focal distance to diameter ratio). Lenses L_{1-3} are made of high resistivity Si due to its negligible loss, while a $\lambda_d/4$ Parylene ($\epsilon_r=2.6$) layer is considered in the silicon-air interfaces to minimize reflections. Finally, a 0.5m diameter plano-hyperbolic HDPE ($\epsilon_r=2.3$ and $\tan\delta=3.9\times 10^{-4}$ at 300GHz [6]) lens is used as a primary aperture. The $f_{\#}$ chosen for this lens is 1.45, providing a good tradeoff between the lens thickness and the system's size.

The required beam scanning in the Quasi-Optical system can be realized through several lens rotations or displacements. The simplest approach would be to displace either the primary (L_4) or the integrated (L_1) lens. However, a big dielectric lens will be heavy (e.g., for $f_{\#}=1.45$, L_4 is heavier than 7kg), making the mechanical implementation challenging, whereas the integrated lens is sensitive given its connections with the electronics. To avoid these issues in the proposed multi-lens design, the scanning is performed by rotating L_2 which has a weight of only 0.3kg. To enhance the scanning performance, this rotation is performed from an offset position 6cm below the center of its lower surface, as shown in the inset of Fig. 1. Following this

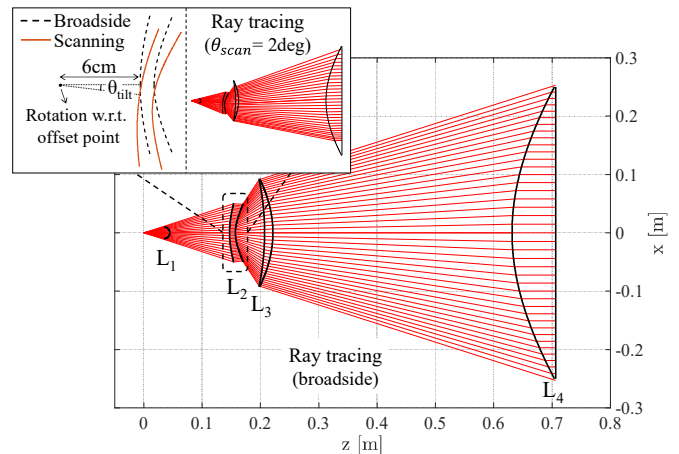


Fig. 1. Geometry of multi-lens QO system. The offset lens rotation considered for the scanning is illustrated in the inset together with the ray tracing for scanning at 2 degrees.

design choice, the surfaces of L_2 and L_3 are optimized with the aim of maintaining good performance for scanning up to 2 degrees. All lenses are rotationally symmetric.

III. SIMULATED PERFORMANCE

To showcase the performance of the proposed design, the scenario of Fig. 2(a) is considered, with two identical QO antenna systems (Tx and Rx) at a distance of 100m. Subsequently, considering a certain misalignment angle between the two systems (θ_{scan}), both beams are scanned such that the alignment is preserved. The scanned beams of a single QO antenna over a plane at 100m are plotted in Fig. 2(b), indicating very good scanning performance. The modelling of the described multi-lens system is performed through a combination of Physical Optics and sequential Geometrical Optics techniques [7] while the optimization of L_2 and L_3 is performed using Ansys Zemax OpticStudio [8].

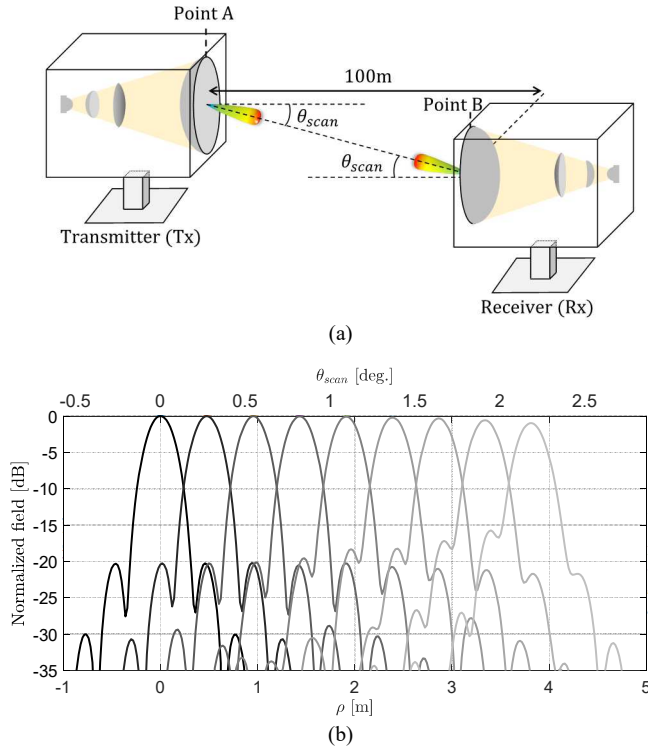


Fig. 2. (a) Illustration of a point-to-point (PtP) radiative near-field 100m link. The QO antenna systems at the side of the transmitter and receiver are identical to that of Fig. 1. (b) Scanned beams at 100m considering a 1-degree step in the tilt angle of L_2 (see inset of Fig. 1).

To assess the overall system, the coupling (power at point B / power at point A in Fig. 2(a)) together with the spillover and reflections for both Tx/Rx units, are computed and illustrated in Fig. 3 versus with the scan angle. For the derivation of the coupling over the wireless link, the employed procedure is detailed in [2]. For reference, the performance of a simpler system featuring only L_1 and L_4 is also plotted in Fig. 3. In this case, the $f_{\#}$ of L_4 is optimized considering an identical L_1 . The optimal value is 1.8 and results in a system with an overall size of 0.5m x 0.95m. The scanning in this configuration is performed by displacing the primary lens (L_4), the weight of which is 5.5kg.

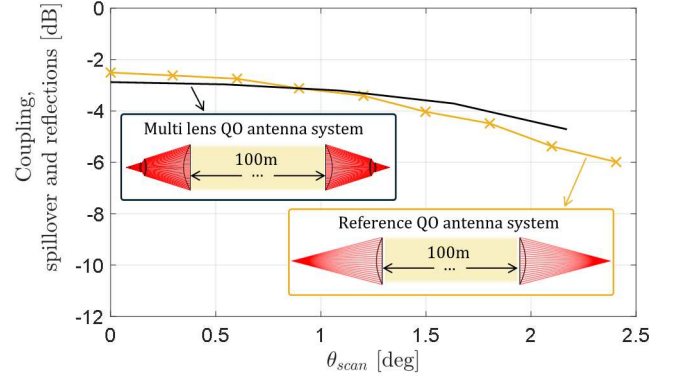


Fig. 3. Coupling together with spillover and reflection loss (for both QO systems) versus the scan angle for the scenario illustrated in Fig.2(a). For reference, the performance of an optimized simplified lens system ($f_{\#}=1.8$) is also plotted.

Fig. 2(b) and Fig. 3 indicate the good scanning capability of the proposed QO antenna design. In fact, its performance is very close to that of the reference case (optimal system with L_1 and L_4). However, the scanned lens in the proposed multi-lens approach is much lighter (only 0.3kg compared to 5.5kg), facilitating the mechanical implementation, while the size in one dimension is reduced by about 30cm. Overall, the proposed multi-lens QO antenna system can be a suitable candidate for fronthaul/backhaul radiative near field links at 300GHz.

IV. ACKNOWLEDGMENT

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