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A Shaped Quartz Lens Antenna for Wide Scanning Sub-millimeter Imaging Systems

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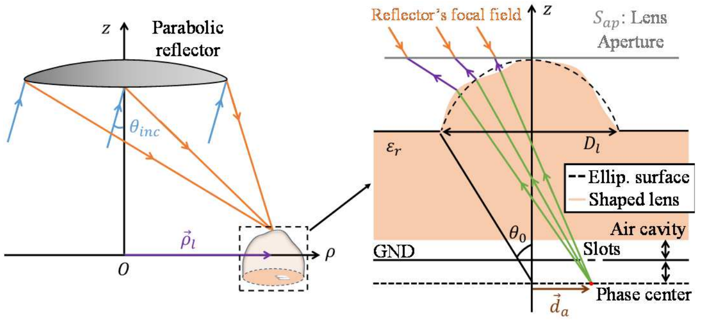
Abstract—**Lens based focal plane arrays (FPAs) with thousand elements are promising candidates for wide scanning sub-millimeter security imaging systems. To analyze such arrays, a field correlation approach is employed to design an FPA of quartz lenses coupled to a reflector. We consider quartz as the lens material due to its lower cost compared to silicon lenses. Here we focus on the design of the lens element at the edge of the FPA. The reflector's scanning angle at the edge of its FPA is $\mathbf{20.3^{\circ}}$, and the lens surface is shaped to couple better to the reflector. The far-field performance of the optimized shaped lens is validated by full-wave simulations with excellent agreement. The simulated scan loss of the system is 2.6 dB. A prototype was fabricated and will be measured to validate the simulation.**

I. INTRODUCTION

Large format focal plane arrays (FPA) are promising candidates for sub-millimeter imaging applications due to their fast image acquisition speed [1], [2]. They are commonly designed as horn or dielectric lens arrays and coupled to a reflector to achieve imaging. Horn-based FPAs are easier to be implemented; however, they suffer from high scan loss since the radiation patterns of horn antennas cannot be easily shaped, e.g. [3]. To improve the scanning performance of FPAs, i.e. field of view, we can use dielectric lenses as array elements. Recently, a coherent Fourier optics methodology has been proposed to analyze and design silicon lens based FPA coupled to a reflector [4]. In this method, the lenses near the edge of the FPA are shaped to couple better to the reflector. An example silicon lens array was designed and it achieved less than 2 dB scan loss when scanning 50 reflector's beam (20.3°). However, the fabrication of shaped silicon lenses is complex and expensive. In this work, we propose to use shaped quartz lens as a substitute which is cheaper and easier to fabricate. As will be discussed, it can achieve 2.6 dB scan loss under the same wide scanning conditions.

II. IMAGING SCENARIO

Here we consider a shaped quartz lens placed on the focal plane of an on-axis parabolic reflector operating at 180 GHz. The relative permittivity and loss tangent of the quartz material at 180 GHz are 3.75 and 4.2×10^{-4}, respectively. The reflector has the diameter of $D_r = 141.4\lambda_0$ and the focal distance of $F_r = 242.8\lambda_0$, where λ_0 is the free-space wavelength. This on-axis reflector models the main QO components in the security imaging system in [3]. An incident plane wave illuminates the reflector with an incident angle of $\theta_{inc} = 20.3°$, $\phi_{inc} = 0°$ and is reflected by it on the shaped lens which is displaced $\vec{\rho}_l$ along the reflector's focal plane, as shown in Fig. 1. The feed of the lens is a leaky-wave antenna (LWA) which is similar to the one in [5]. It is made of double-slot iris fed by a waveguide and illuminates the lens through a resonant air cavity, as depicted in Fig. 1(b). The phase center of the feed is below the ground plane and is displaced $\vec{d}_a$ along the focal plane of the lens. Here the field radiated by the feed inside the lens (primary field) and the field transmitted outside the lens (secondary field) are represented by the green and purple rays, respectively.



(a) (b)

Fig. 1. (a) Schematic representation of the shaped quartz lens coupled to a parabolic reflector which is illuminated by a plane wave with the incident angle of θ_{inc}. (b) Zoomed-in lens geometry. Green and purple rays represent the antenna primary and lens secondary fields, respectively.

To analyze the coupling between the reflector and the shaped lens, we resort to the field matching technique discussed in [4]. Here, to facilitate the analysis, we consider the field matching surface as the plane at the top of the lens surface, as shown by S_{ap} in Fig. 1(b), instead of the sphere inside the lens as in [4], [6]. The aperture efficiency η_{ap} of this lens-coupled reflector system is proportional to the field correlation between the reflector's focal field and the field radiated by the lens antenna on S_{ap}. To maximize η_{ap}, we need to optimize the lens geometry to achieve the best amplitude and phase matching between the mentioned fields. In this work, we mainly focus on the phase matching since it is a more dominant criteria for wide scanning cases.

III. DESIGN OF THE SHAPED QUARTZ LENS

At the edge of the FPA, due to the large scanning angle of the incident plane wave, the lens is located outside the rim of the reflector, see Fig. 1(a). In this case, the main beam of the reflector's focal field is significantly widened and the phase distribution is distorted. The lens at the edge of the FPA is located at $\vec{\rho}_l = 100.94\lambda_0\,\hat{x}$. Its diameter is designed to be $D_l = 10\lambda_0$ to obtain most of the power contained in the incident focal field and the lens truncation angle is $\theta_0 = 32.7°$. The LWA is displaced within the lens focal plane with $\vec{d}_a = 2.11\lambda_d\,\hat{x}$ to compensate the linear phase term present in the reflector's focal field. And the surface of the lens is modified to compensate the higher-order phase distortion, which is the key step of our work.

A. *Lens Surface Modification*

The lens surface is modified to compensate the phase difference between the reflector's focal field and the lens radiated field, also referred to as the hologram phase. By modifying the z-direction (vertical) thickness of the original ellipsoid, we can change the phase propagation of the lens radiated field, i.e. the purple rays in Fig. 1(b), and thus compensate the hologram phase. Note that this lens modification is dependent on the feed displacement $\vec{d}_a$, since $\vec{d}_a$ changes the hologram phase. As a result, the optimization of the lens surface is a parametric procedure. The optimized lens surface for $\vec{d}_a = 2.11\lambda_d\,\hat{x}$ is shown in Fig. 2(a). It is significantly different from an ellipsoid and has a asymmetric rim thickness. Fig. 2(b) shows the prototype of the shaped quartz lens and this asymmetry is more visible.

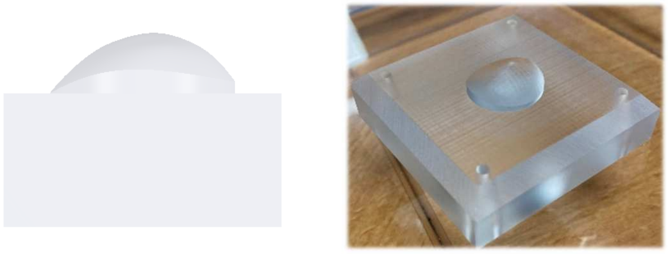
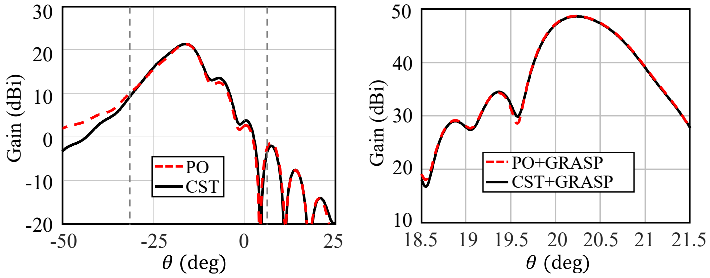

(a) (b)

Fig. 2. Optimized shaped quartz lens: (a) side view of the model, and (b) photograph of the fabricated prototype.

B. *Far-field Performance*

The shaped quartz lens shown in Fig. 2 will be aligned with the LWA and fed by a waveguide. The entire structure has been simulated and here we compare its far-field performance between our in-house Physical Optics (PO) approach and CST full-wave simulation [7]. Fig. 3(a) shows the co-polar far fields radiated by the lens in H-plane. We can see the agreement between the PO approach and the CST simulation is excellent inside the reflector's rim angles which are marked by the grey lines. Then we can use these fields to illuminate the reflector and evaluate its far fields. This is done by using the PO solver in TICRA GRASP [8] and the co-polar far fields in H-plane are shown in Fig. 3(b). The agreement is again excellent and the beam points towards the desired direction, i.e. 20.3°. The resulting aperture efficiency of the CST+GRASP simulation is $\eta_{ap} = 37.1\%$ and this corresponds to the scan loss of 2.6 dB (with respect to the broadside η_{ap}), agreeing with the in-house method. This achieved scan loss is much lower than the one of the horn-based FPA in [3] when considering the same scanning scenario (larger than 5 dB). This is because we can synthesize the radiation pattern of the lens antenna with better control than the one of the horn antenna.



(a) (b)

Fig. 3. Co-polar far fields in H-plane radiated by (a) the optimized shaped quartz lens and (b) the lens-coupled reflector. Our PO approach is compared to full-wave simulations. The grey lines represent the rim angles of the reflector.

IV. CONCLUSION

In this work, we have presented the design of a shaped quartz lens coupled to a reflector with the scanning angle of 20.3°. The lens is analyzed by using the field matching technique performed on the lens aperture plane. By shaping the lens surface, we can compensate the hologram phase and achieve a high phase matching efficiency. Although the far field of the optimized lens looks very asymmetric, it can illuminate the reflector well and leads to the maximum aperture efficiency of 37.1% which corresponds to 2.6 dB scan loss. A prototype has been fabricated and it will be measured to validate the simulated performace.

REFERENCES

[1]. R. Al Hadi *et al.*, "A 1 k-pixel video camera for 0.7–1.1 terahertz imaging applications in 65-nm CMOS," *IEEE J. Solid-State Circuits*, 2012.

[2]. J. J. A. Baselmans *et al.*, "A kilo-pixel imaging system for future space based far-infrared observatories using microwave kinetic inductance detectors," *A&A,* 2017.

[3]. D. A. Robertson *et al.*, "The CONSORTIS 16-channel 340-GHz security imaging radar," *Proc. SPIE*, 2018 .

[4]. S. O. Dabironezare *et al.*, "Coherent Fourier Optics Model for the Synthesis of Large Format Lens-Based Focal Plane Arrays," *IEEE Trans. Antennas Propag.*, 2021.

[5]. M. Arias Campo *et al.*, "On the Use of Fly's Eye Lenses with Leaky-Wave Feeds for Wideband Communications," *IEEE Trans. Antennas Propag.*, 2020.

[6]. H. Zhang *et al.*, "Design of Lens Based Focal Plane Arrays for Wide Field-of-View Imagers at Sub-millimeter Wavelengths," *IRMMW*, 2021.

[7]. *CST Microwave Studio*. Accessed: 2022. [Online]. Available: http://www.cst.com.

[8] *TICRA Tools GRASP*, TICRA, Accessed: 2022. [Online]. Available: https://www.ticra.com.