Analyzing Lens Based Focal Plane Arrays using Coherent Fourier Optics

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***Abstract*—In this paper, a spectral technique based on Fourier Optics for analyzing lens based focal plane arrays with large Field of Views is presented. The proposed spectral technique provides a numerically efficient methodology to derive the Plane Wave Spectrum (PWS) of an elliptical lens under a focusing system including both amplitude and phase. The method can then be used to estimate the power received by an antenna or absorber coupled detector placed at the focal region of the lens. The method is then employed to evaluate and improve the scanning performance of an imaging systems with standard cosine pattern feeds below a lens-based array coupled to a reflector. It is shown that, the scan loss performance of such system which consists of thousands of elements, can be improved significantly and stays below 1 dB by simply evaluating the linear phase term in the PWS. The proposed technique is validated via Physical Optics simulations.**

Keywords— focal plane arrays, Fourier Optics, sub-millimeter imagers.

I. Introduction

Currently, imaging cameras are being developed with moderate size focal plane arrays (FPAs) of detectors operating at (sub-)millimeter wavelengths [1]. For such cameras, fly's eye lens arrays coupled to antennas or absorbers are being developed to enable high sensitivity imaging. In the future, these imagers should accommodate FPAs of over 10k detectors to improve the overall image acquisition speed. In these scenarios, a full-wave electromagnetic analysis that includes the coupling between the quasi-optical (QO) system and the detectors array is not applicable since it is numerically cumbersome and time-consuming. Typical approaches for analyzing such QO systems resorts to Physical Optics (PO) in transmission, or a simplified Gaussian beam analysis. Both approaches decouple the analysis of the detectors and the QO system.

In the previous works, [2] and [3], analytical expressions for the plane wave spectrum (PWS) of focusing elliptical lens or parabolic reflector geometries, illuminated by a plane wave with broadside or slightly squinted incident angle were proposed. In those papers, the field in the focal plane is expressed as a Fourier transform of the field on the equivalent Fourier Optics (FO) sphere centred at the focal point of the system. The PWS was then used to optimized absorber based detectors under QO systems.

This PWS representation was possible by neglecting a phase term, which presents a quadratic dependence of the distance between the focal point and a generic point on the focal plane. Since the analysis was performed for a single-element (lens or parabola) QO system coupled to an array of bare absorbers (incoherent detectors), neglecting such phase term introduced no inaccuracies. In order to analyse the coupling to detectors placed under a lens, the quadratic phase term cannot be simplified anymore. The methodology used to analyse such problem will be discussed in this paper.

In this work, we propose a FO approach which, in its range of validity, allows to effectively analyze the coupling of the QO system, the lens based FPA, and the detectors (either absorbers or antennas). Resorting to a FO approach provides insight and computation speed to effectively design FPAs for maximizing the performance of the imaging system. The technique can be applied to any generic QO system. The examples are discussed for analyzing the coupling between a parabolic reflector and an elliptical lens based FPA. The validity region of the FO analysis in [2] is also extended significantly. Consequently, the ability to design systems with large angular FOVs is obtained.

The imaging system is analyzed in reception as shown in Fig. 1. The reflector is illuminated by a plane wave. The field radiated toward the focal plane of a lens coupled reflector is evaluated over a FO sphere inside the lens. For the lens antennas, this field can be used to obtain the power captured by the antenna, using antenna in reception formalism [4]. The advantage of employing this method is that the field evaluated over the sphere can be used to synthesis antenna feeds with patterns which satisfy the field match condition. Designing such feeds lead to maximize the received power by the QO system.

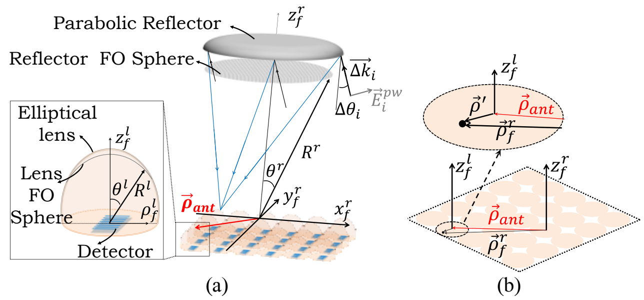

Fig. 1. (a) The Fourier Optics scenario for obtaining the field scattered by a parabolic reflector in the focal plane of each lens. The parabolic reflector is illuminated by a plane wave with an incident angle $\Delta\theta_i$. (b) Top view of the lens array and the local reference system at surrounding the lens position, $\vec{\rho}_{ant}$.

As an example, we evaluate the scan loss of an imaging systems with a field of view (FoV) of ± 60 beams. We show that by placing the lens feed in flash points evaluated with minimizing the phase of PWS, we can improve significantly the scan loss with a low computation effort.

II. Coherent FO Analysis for Lens based FPAs

In the following subsections, the PWS for a parabolic reflector illuminated by a plane wave is discussed. By using this PWS the coupling of the lens with the field scattered by the reflector is obtained.

A. Plane Wave Spectrum of a Parabolic Reflector

Let us consider a parabolic reflector illuminated by a plane wave with amplitude, E_0, wave-vector $\overrightarrow{\Delta k_i}$. An equivalent sphere centered at the focus of the parabola can be used to represent the *direct* focal field, $\vec{e}_f^r(\vec{\rho}_f^r)$ [3]:

$$\vec{e}_f^r(\vec{\rho}_f^r) = \frac{1}{4\pi^2} e^{-jk_0(\rho_f^r)^2/(2R^r)} \iint_{-\infty}^{+\infty} \vec{E}_{FO}^r(\vec{k}_\rho^r) e^{j\vec{k}_\rho^r\cdot\vec{\rho}_f^r} k_\rho^r dk_\rho^r d\alpha^r \quad (1)$$

where R^r is the radius of the equivalent FO sphere of the parabolic reflector, $\vec{k}_\rho^r$ is the spectral vector given by $\vec{k}_\rho^r =$

$k_0 \sin\theta^r \hat{\rho}$, and $\vec{E}^r_{FO}(\vec{k}^r_\rho)$ is a spectral representation of the direct field, and can be calculated analytically for slightly-off broadside cases as described in [3] or via Geometrical Optics (GO) for large incident angles. In order to represent (1) as an anti-Fourier transform, which relates the spectral field $\vec{E}^r_{FO}$ to the spatial one $\vec{e}^r_f(\vec{\rho}^r_f)$, the quadratic phase term, $e^{-jk_0(\rho^r_f)^2/(2R^r)}$, should be included into spectral function. This goal can be achieved by a linearization approximation: $e^{-jk_0\rho_f^{r2}/(2R^r)} \simeq e^{-jk_0|\vec{\rho}_{ant}|^2/(2R^r)}e^{-jk_0\vec{\rho}_{ant}\cdot\vec{\rho}'/R^r}$. In this approximation, the quadratic phase term is simplified at the surrounding of a specific position referred to as the lens antenna position, $\vec{\rho}_{ant}$, Fig. 1(b). By linearizing the phase, and using the Fourier transform properties, (1) can be expressed as:

$$\vec{e}^r_d(\vec{\rho}') = \frac{1}{4\pi^2}\iint_{-\infty}^{+\infty} \vec{E}^r_{CFO}(-\vec{k}^r_\rho)e^{j\vec{k}^r_\rho\cdot\vec{\rho}'}d\vec{k}^r_\rho \qquad (2)$$

where $\vec{\rho}'$ represents a position in the focal plane in the surrounding of $\vec{\rho}_{ant}$; $\vec{E}^r_{CFO}(-\vec{k}^r_\rho)$ is the PWS of focal field of the reflector, and is referred to as the *Coherent* FO spectrum:

$$\vec{E}^r_{CFO}(-\vec{k}^r_\rho) \simeq e^{-j\frac{k_0|\vec{\rho}_{ant}|^2}{2R_r}}\vec{E}^r_{FO}(\vec{k}^r_\rho + \vec{k}_{ant})e^{j(\vec{k}^r_\rho+\vec{k}_{ant})\cdot\vec{\rho}_{ant}} \quad (3)$$

where $\vec{k}_{ant} = k_0/R^r\vec{\rho}_{ant}$ represents how much the original spectrum, $\vec{E}^r_{FO}(\vec{k}^r_\rho)$, is shifted due to linearizing of the quadratic phase term at the surrounding of $\vec{\rho}_{ant}$. The applicability region of the standard FO, as described in [2], is not sufficient to describe the performance of the future imaging systems with large FoVs. In this work, this applicability region is significantly enlarged by introducing off-focus FO spheres with centres displaced along the focal plane of the reflector.

B. Coupling of the Reflector to the Lens Array

Let us consider the geometry of a lens array at the focal plane of a reflector illuminated by a plane wave, Fig. 1(a). By using (3), one can represent the focal field of the parabolic reflector as a summation of plane waves. Moreover, similar to [2], when an elliptical lens is illuminated by a single plane wave, the field transmitted into the lens to its FO sphere is calculated. This field is obtained by propagating the plane wave into the lens surface analytically or for large incident angles via GO. Combining the two, one can represent the coupling between the parabolic reflector and the elliptical lens, i.e. the field at the FO sphere of the lens, by summing the contribution of each plane wave transmitted into the lens.

III. Improving Scanning Performance of the FPA

In this section, firstly, we use the results obtained from Section II, to analyze the coupling of the entire QO system (reflector + lens) with antenna-based detectors. The analysis is also employed to improve the scanning performance of a large focal plane array of lens antennas below a parabolic reflector.

The coupling mechanism between the QO system and the antenna can be represented by resorting to antenna in reception formulations [4] to evaluate the power received by the detector placed under the lens, P_r. As discussed in [5], this power is evaluated as a reaction integral between the transmitted direct field into the lens and the far field of the antenna. Both these fields are evaluated over the lens FO sphere.

One can represent the scan loss as a function of number of beams scanned by the system. In this work, by using the analysis in reception terminology, the scan loss is expressed as:

$$SL(N^s_b) = -10\log_{10}\left[\frac{P_r(N^s_b)}{P_r(0)}\right] \text{(dB)} \qquad (5)$$

where $N^s_b = \Delta\theta_i/(D_r/\lambda_0)$ represents the number of beams scanned by the reflector, and $\Delta\theta_i$ is the illuminating angle of the incident plane wave.

Here two antennas are considered as feeds for the lens based FPA: 1) A standard cosine pattern antenna feed with a far field pattern shape of $\cos^n(\theta^l)$, where n is chosen such that the antenna illuminates the lens surface with an edge taper of -11 dB; 2) Optimized version of the same cosine pattern feed. For lenses placed farther from the center of the reflector FPA, the position of their feed inside the focal plane of the lens is adjusted to maximize the received power. The optimized position of the feed is found by minimizing the phase of the integrand of the PWS representation.

As an example, the following scenario is assumed: a parabolic reflector with diameter of $500\lambda_0$ and f-number of $f^r_\# = 4$ is illuminated by an incident TM polarized plane wave with amplitude of $|E_0| = 1$ V/m; the operation frequency is 300 GHz; the diameter of each lens (size of an element in the FPA) is $2\lambda_0 f^r_\#$, the lens f-number is $f^l_\# = 0.6$; therefore, $n = 2.1$ in the cosine patterned feed.

In Fig. 2, the scan loss of the two feeds are compared. By introducing the first off-centered FO sphere, the FO applicability region is extended from analyzing ± 25 beams to ± 60 beams in the FoV. As expected, the adjusted cosine pattern feed coupled to the QO system performs significantly better than the standard one. Specifically, the scan loss for the adjusted feed is almost 6 dB lower than the one of the standard feeds when the reflector is scanning 60 beams (A FPA with 3600 elements). These results are validated at a few scanning positions, marked in the figure, using the PO solver of GRASP.

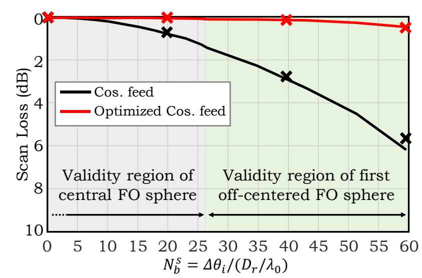

Fig. 2. The scan loss of an imaging system as a function of number of beams scanned. The cross marks represent the results from PO solver of GRASP. The central FO applicability region, and its extension due to introducing the first off-focus sphere are indicated by grey and green regions, respectively.

IV. Conclusion

In this paper, the original FO procedure has been extended to derive the spectra of the incident field on a reference system centered at antennas with large distance from the focus including the quadratic phase term. The procedure, named here "Coherent" FO, has been used to express the spectral incidence field in realistic cases that include large arrays of lenses within reflectors focal planes. The methodology is then linked to antenna in reception formalism to analyze the performance of such feeds. It is shown that the scan loss of an imaging system can be improved significantly by just minimizing the phase of the PWS to find the lens feed optimal position.

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