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A Sequential Geometrical-Optics-Based Technique for Optimizing Multilens Quasi-Optical Systems in Reception Mode

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Abstract—A new generation of quasi-optical (QO) systems with multiple refractive and reflective components are required for several (sub)-millimeter applications such as the next generation of communication systems, sensing and security imagers, and instrumentation for far-infrared astronomy. Currently, there are no numerically efficient and accurate modeling tools available to design such systems tailored to their moderate sizes, in terms of wavelength, and wide operational bandwidths. In this article, a numerically efficient and accurate technique is proposed for designing QO systems containing a cascade of homogeneous dielectric lens components. The methodology is based on sequential geometrical optics (GO) combined with an analysis in reception mode. Thanks to the computational efficiency of the proposed technique, we were able to embed it as the kernel for multiobjective optimizers to design complex multilens QO systems. Here, two indicative examples of such geometries targeting specific requirements and scenarios are showcased. The overall optimization technique is validated against in-house and commercial physical optics (PO) codes, as well as full-wave simulations where possible, with excellent agreement in both efficiency terms and far-field beam patterns. Moreover, the proposed technique achieves orders of magnitude faster execution times with respect to the currently available commercial tools.

Index Terms—Dielectric lens antennas, geometrical optics (GO), quasi-optical (QO) systems, wide field of view.

I. INTRODUCTION

ADVANCED quasi-optical (QO) systems with multiple refractive and reflective components are under development for a wide range of (sub)-millimeter-wave applications (100–1000 GHz). In security imagers, [1], [2], [3], wideband QO systems with large instantaneous field of view (FoV) are desired to enhance the sensitivity at real-time frame rates. Wideband QO based communication links are being investigated [4] for enhancing the data rate [5] and tackling

complex scanning scenarios [6]. In THz sensing applications, cascades of QO components, as in [7], are required to generate and maintain high-frequency radiation throughout the system. In far-infrared astronomy, developing imaging spectrometers with wide instantaneous bandwidth and multiple spatial pixels is the current focus of the community [8], [9] while advanced and compact QO systems [10] are being investigated to meet demanding performance requirements for specific scenarios. Development of gradient-index lenses operating at millimeter wavelengths [11], [12], [13], [14], [15], [16] is also receiving special attention by the community, thanks to advances in 3-D printing fabrication processes and synthesizing techniques. Moreover, dielectric loss control [1], [17], [18] and wideband anti-reflection (AR) coatings, [19], [20] are also contributing to realization of QO systems based on refractive components.

Designing lens-based systems using ray tracing is a common practice in the optical domain. Oversized¹ refractive solutions such as the ones in [21] and [22] are currently the state-of-the-art solutions for ground-based astronomical observations. Another approach for shaping single lens components is based on physical optics (PO) [23], [24], [25] which requires unrealistic execution times to optimize the shape of a chain of refractive components simultaneously. In commercial software such as TICRA tools [26] and ILASH [27], sequential PO or a geometrical optics (GO) combined with PO technique is available to analyze free-standing lenses and core-shell lens architectures [28], respectively. Sequential GO formulation was described by Deschamps [29], included in [30] by James, and was implemented in works such as [31] for analyzing spherical dielectric radomes. However, to the best of our knowledge, GO-based optimization techniques are typically implemented for single components [12], [32] and [33].

In this contribution, we focus on practical multicomponent QO systems with a combination of reflective and refractive components which are typically not sufficiently large (>1000 s of wavelengths in diameter) to allow for optimal solutions obtained by standard ray tracing, and not sufficiently small (<5 wavelength in diameter) to allow for a numerically efficient method-of-moment-based technique such as [34]. Instead, we propose here a rapid and accurate technique enabling the optimization of the next generation of complex QO systems with moderate dimensions and meeting the demanding requirements imposed on them. Specifically,

¹Where components' domain is extended to minimize the diffraction effects originated by their finiteness since such effects are not typically modeled in optical ray-tracing techniques.

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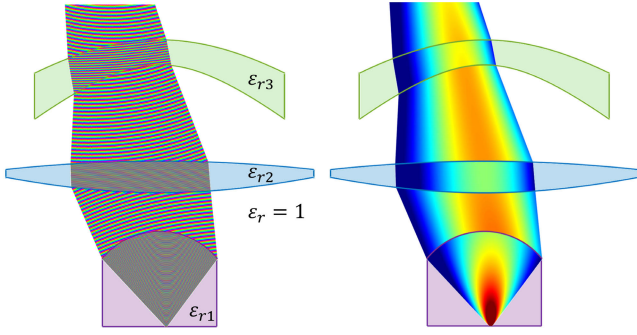


Fig. 1. Illustration of a refractive QO system and its sequential GO propagation scenario where the phase (left panel) and magnitude (right panel) distribution of the electric field are tracked through multiple homogeneous dielectric components with indicated relative permittivities when $\epsilon_{r1} > \epsilon_{r2} > \epsilon_{r3}$. Here, an antenna feeder with a Gaussian far-field is located within the integrated lens. Ideal quarter wavelength AR coatings are included on all the lens interfaces, but they are not drawn for readability.

requirements in terms of wide operation bandwidths, compact footprints, and wide FoVs where the existing high-frequency tools face numerical efficiency challenges; and rapid ray tracing techniques lack the insight gained from considering also the amplitude and polarization of the electromagnetic (EM) fields. Our proposed technique is based on a sequential GO propagation, Fig. 1, combined with an antenna in reception analysis to form the kernel of a flexible multi-objective optimizer. This optimizer can then generate QO solutions to achieve specific field distributions as their outputs. This technique can also be used to synthesize and analyze gradient-index lenses by discretizing the geometry into multiple homogeneous sections.

This article is structured as follows. Section II describes the proposed approach to optimize multilens antenna systems via a kernel based on sequential GO technique in reception mode. The proposed technique is then applied in Section III for optimizing two example cases of multilens QO systems. The performance of these geometries in terms of their output fields and aperture efficiency is also discussed in Section III and compared against the ones obtained by full-wave simulation, or commercial and in-house PO codes. Concluding remarks are provided in Section IV.

II. QO ANALYSIS AND OPTIMIZATION OF MULTILENS ANTENNA SYSTEMS

In Section II, the applied field shaping technique in reception mode is reviewed; the sequential GO technique for propagating the EM radiation through multiple refractive components is described; and a multiobjective optimizer with a kernel based on the previous two steps is proposed.

A. Field Matching Analysis in Reception Mode

To evaluate the performance of an antenna system, one can consider an equivalent scenario in reception mode, thanks to reciprocity [35]. Such a scenario is shown in Fig. 2. The power received by an antenna system from an incident EM field with an arbitrary distribution can be calculated resorting to an equivalent Thévenin circuit model. By resorting to the

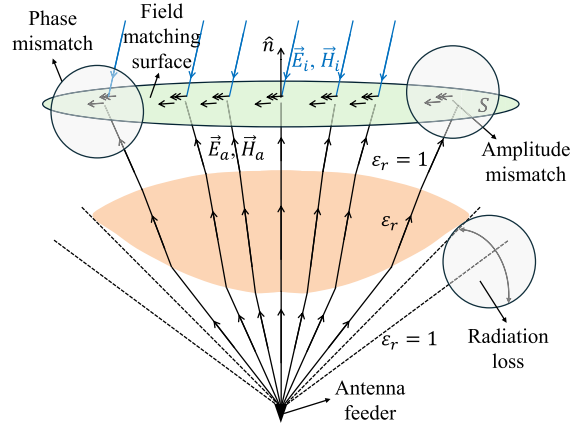


Fig. 2. Illustration of the antenna in reception analysis where the EM fields radiated by the antenna feeder in transmission mode are propagated to an arbitrary surface, S , and the incident EM fields are evaluated at the same surface.

reciprocity theorem, one can write (1), where V_{oc} corresponds to the circuit's induced open-circuit voltage generator and I_0 is the current which equivalently fed the antenna feeder in transmission mode and effectively acts as a normalization factor. These parameters are obtained as a reaction integral between the incident field and the field radiated by the antenna system [35] and [36], as

$$V_{oc}I_0 = \iint_S [\vec{H}_i \cdot \vec{M}_a - \vec{E}_i \cdot \vec{J}_a] dS \quad (1)$$

where $\vec{E}_i$ and $\vec{H}_i$ are the incident electric and magnetic fields illuminating the antenna system and evaluated at an arbitrary surface S along the optical path, respectively; $\vec{M}_a = \vec{E}_a \times \hat{n}$ and $\vec{J}_a = \hat{n} \times \vec{H}_a$ are the equivalent magnetic and electric currents, respectively. These currents are evaluated at the same surface S with a normal unit vector $\hat{n}$ outward from the feeder's perspective; $\vec{E}_a$ and $\vec{H}_a$ are the EM fields radiated by the antenna system in transmission mode. The power received by the antenna feeder and delivered to its load (assuming impedance matching condition) is

$$P_{Rx} = \frac{|V_{oc}I_0|^2}{16P_{rad}^{tot}} \quad (2)$$

where P_{rad}^{tot} is the total power radiated by the antenna feeder in transmission mode when fed by the current I_0 . In an arbitrary scenario, one can define a coupling efficiency in reception mode between the incident field and antenna's transmitted field. However, here without the loss of generality, we focus on the coupling of the antenna to the equivalent aperture of a QO system leading to the definition of an aperture efficiency as

$$\eta_{ap} = \frac{P_{Rx}}{P_{inc}} \quad (3)$$

where $P_{inc} = 0.5 \text{Re} \left\{ \iint_S [\vec{E}_i \times \vec{H}_i^*] \cdot (-\hat{n}) dS \right\}$ is the available power at an equivalent aperture of the QO system. To gain more insight into the coupling mechanism in reception, the aperture efficiency is separated into radiation and field matching efficiencies as described in Appendix A.

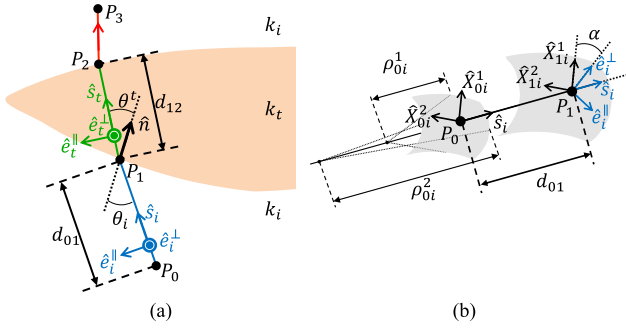


Fig. 3. (a) GO propagation scenario where an incident EM field is transmitted into a homogeneous dielectric material at interface point P_1 , propagated to the second interface point P_2 , and transmitted out of the medium to the observation point P_3 . (b) Illustration of the GO incident wavefront in (a), at positions P_0 and P_1 .

As it can be deduced, a degree of freedom exists on the choice for the evaluation surface in the described antenna in reception technique. To develop a fast and reliable optimization kernel, this field matching surface is chosen where a sequential GO technique could accurately estimate the terms in the integrand of (1), i.e., sufficiently far from the GO's caustic points.

B. Sequential GOs Technique

In this section, a description of the developed sequential GO technique for refractive components is provided. Here, let us assume an arbitrary propagation scenario as shown in Fig. 3(a), where a refractive component is placed within an optical path. This component is made of a homogeneous dielectric material; the radii of curvature of its two air–dielectric interfaces are large in terms of wavelength. Such a scenario is an indicative representation of a refractive component in an antenna-based QO system. Within the applicability conditions of the GO approximation, the EM field at the interface of two homogeneous media is assumed to behave locally as a plane wave; and the interface is assumed locally flat.

Let us now consider that both an incident EM field, propagating from bottom to top in Fig. 3(a), and the geometry of interest satisfy the GO applicability conditions. The electric field at location P_0 , associated with a ray path with direction of propagation $\hat{s}_i$, can be modeled as a wavefront with radii of curvature, ρ_{0i}^1 and ρ_{0i}^2 , and principal directions of $\hat{X}_{0i}^1$ and $\hat{X}_{0i}^2$, respectively, as shown in Fig. 3(b). These principal directions and the incident direction of propagation form a coordinate system as $\hat{X}_{0i}^1 \times \hat{X}_{0i}^2 = \hat{s}_i$. The electric and magnetic fields propagating within this homogeneous medium can be approximated at observation point P_1 as

$$\vec{E}_i^{GO}(P_1) = \vec{E}_i^{GO}(P_0) \sqrt{\frac{\rho_{0i}^1 \rho_{0i}^2}{(\rho_{0i}^1 + d_{01})(\rho_{0i}^2 + d_{01})}} e^{-jk_i d_{01}} \quad (4a)$$

$$\vec{H}_i^{GO}(P_1) = \frac{1}{\zeta_i} \hat{s}_i \times \vec{E}_i^{GO}(P_1) \quad (4b)$$

where d_{01} is the distance along the ray path between P_1 and P_0 , k_i is the propagation constant of the incident medium, and ζ_i is its characteristic impedance. In (4) and throughout this article,

an $e^{j\omega t}$ time, t , dependence is assumed and suppressed, where ω is the angular frequency. The wavefront curvature matrix of this GO field at location P_1 with respect to the $\hat{X}_{1i}^1, \hat{X}_{1i}^2, \hat{s}_i$, where $\hat{X}_{1i}^1 = \hat{X}_{0i}^1$ and $\hat{X}_{1i}^2 = \hat{X}_{0i}^2$, the coordinates system is

$$\mathcal{Q}_0^i(P_1) = \begin{bmatrix} (\rho_{0i}^1 + d_{01})^{-1} & 0 \\ 0 & (\rho_{0i}^2 + d_{01})^{-1} \end{bmatrix}. \quad (5)$$

The GO contribution of the electric and magnetic fields transmitted into the homogeneous dielectric medium at interface point P_1 and propagated to location P_2 is calculated as

$$\vec{E}_t^{GO}(P_2) = \bar{\tau} \cdot \vec{E}_i^{GO}(P_1) \sqrt{\frac{\rho_{1t}^1 \rho_{1t}^2}{(\rho_{1t}^1 + d_{12})(\rho_{1t}^2 + d_{12})}} e^{-jk_t d_{12}} \quad (6a)$$

$$\vec{H}_t^{GO}(P_2) = \frac{1}{\zeta_t} \hat{s}_t \times \vec{E}_t^{GO}(P_2) \quad (6b)$$

where $\bar{\tau} = \tau^\perp \hat{e}_t^\perp \hat{e}_t^\perp + \tau^\parallel \hat{e}_t^\parallel \hat{e}_t^\parallel$ is the Fresnel transmission dyad; $\tau^\perp$ and $\tau^\parallel$ are the perpendicular and parallel Fresnel transmission coefficients, respectively; $\hat{e}_t^\perp = \hat{s}_i \times (-\hat{n})$ and $\hat{e}_t^\parallel = \hat{e}_i^\perp \times \hat{s}_i$ are the perpendicular and parallel polarization unit vectors of the incident field, respectively; $\hat{n}$ is the outward unit normal vector of the interface at P_1 oriented as shown in Fig. 3(a); $\hat{e}_t^\perp = \hat{e}_i^\perp$ and $\hat{e}_t^\parallel = \hat{e}_i^\parallel \times \hat{s}_i$ are the perpendicular and parallel polarization unit vectors of the transmitted field, respectively; $\hat{s}_t$ is direction of the transmitted ray and calculated using Snell's law; d_{12} is the path length between P_1 and P_2 over the transmitted ray; k_t and ζ_t are the propagation constant and the characteristic impedance of the second medium, respectively; and ρ_{1t}^1 and ρ_{1t}^2 are the radii of curvature of the transmitted wavefront at P_1 .

The steps to calculate the radii of curvature and principal directions of the transmitted wavefront are described in Appendix B. The expressions for the former and latter are given in (12) and (13), respectively. By deriving these parameters, the transmitted wavefront at P_1 is fully defined. As the result, one could apply the described analysis again to calculate the GO fields at observation point P_3 located outside of the refractive component. In this work, such an analysis is developed into a sequential algorithm to represent the incident and transmitted GO fields at positions of interest within a multilens system.

C. Multiobjective Optimizer for Multilens QO Systems

In this section, the techniques described in Sections II-A and II-B are applied to form an optimizer for homogeneous multilens QO systems. The optimization goal here is to shape the response of multilens antenna systems to a desired field distribution. For the purpose of this article, without the loss of generality of the method, the desired (target) field distributions are chosen in such a way to achieve a high coupling to a main QO component, i.e., efficient illumination of the largest aperture of the system.

The multiobjective optimizer from MATLAB [37], gamutobj, is used here. Such an optimizer provides a Pareto front of solutions which is a set of optimized geometries where none of the objectives can be improved without deterioration of at least another objective [38]. In the case of an integrated

multilens system with a single output beam, see Section III-A, to avoid solutions where a large portion of the fields are internally reflected, field matching and radiation efficiencies (see Appendix A) are defined as the two objectives of the optimizer. In the case of free-standing multilenses with multibeam capabilities (i.e., QO system is shared by multiple antenna feeds), see Section III-B, two objectives are defined as the aperture efficiencies for the beams at the center, and the edge of the FoV to optimize the QO system over its full FoV.

1) *Antenna Feeder*: To keep the focus of this article on the multilens optimization, antenna feeders are modeled here as point sources located at a z -plane with a symmetric Gaussian shaped y -polarized far-field. This Gaussian feed simplification is a common practice in designing QO systems as in [39], and [40]. The Gaussian far-field profile is modeled as in (20) of [40]. In the multibeam scenario considered in Section III-B, to ensure a planar focal plane solution with a low implementation complexity, the vertical position of the antenna feeders is not independently optimized while their lateral positions are. The Gaussian far-field shape is also fixed for all the feeds to avoid introducing further complexity in the focal plane array (FPA) design.

2) *Lens Surfaces*: The lens interfaces are defined as rotationally symmetric surfaces using the conical equation [41] with added higher order symmetric polynomials

$$z(\rho) = \frac{c\rho^2}{1 + \sqrt{1 - pc^2\rho^2}} + a^0 + \sum_{i=1}^N a^i \rho^{2i} \quad (7)$$

where z is the vertical position of a lens surface, ρ is the radial independent parameter which defines this surface, p is the conic constant, $c = 1/r$ is the curvature of the conic, r is its radius of curvature; a^0 indicates a vertical displacement of the surface with respect to a reference system, and a^i are the weights of the i th order symmetric polynomial with in total N polynomials. The latter are used to shape a lens surface close to the edges of its domain. The optimized parameters in (7) are emboldened. Moreover, in the scenario of free-standing multilenses, the optimizer was allowed to modify the lens diameters and the relative distances between them.

III. EXAMPLES OF OPTIMIZED MULTILENS QO SYSTEMS

In this section, two example scenarios of multilens systems are described. These systems are optimized using the techniques discussed in Section II. For each scenario, a multiobjective optimizer is implemented with a kernel based on the proposed sequential GO technique combined with the field matching in reception mode. The optimized geometries are also reported and their performance was validated against full-wave simulation, numerical in-house, and commercial PO codes.

A. Example Case I: A Multilayer Integrated Lens System for Single Beam Wide Scanning Scenarios

In this section, an integrated multilens system, Fig. 4, is optimized aiming for a wide scanning scenario in a Fly's eye system similar to [36]. The example case here is included to test the proposed technique for geometries with relatively

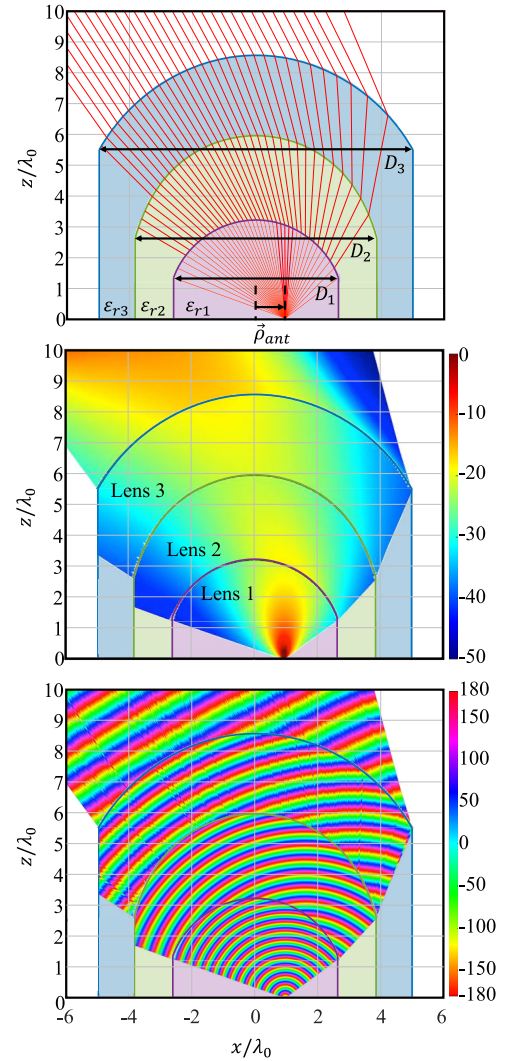


Fig. 4. Example case of a multilayer integrated lens system as an element in a wide scanning scenario. Top panel: a standard ray tracing picture of the scenario where some of its relevant parameters are indicated. A sequential GOs propagation of the EM fields through the example case is shown in the middle and bottom panels for the magnitude and phase of the electric field, respectively.

TABLE I
TARGETED SCENARIO FOR THE EXAMPLE CASE I

Target scenario	Pointing to 28.5° with an aperture of $\varnothing 10\lambda_0$					
Antenna feeder	Gaussian shaped far field with -11 dB edge taper at 40°					
	Lens 1		Lens 2		Lens 3	
	D_1	$5.26\lambda_0$	D_2	$7.7\lambda_0$	D_3	$10\lambda_0$
	ϵ_1	11.9	ϵ_2	5	ϵ_3	2.4

small sizes, in terms of wavelength, where analysis via full-wave simulation is still possible but extremely time-consuming for optimization purposes. Moreover, this example geometry is relevant for synthesizing and analyzing gradient-index lenses when discretized into a finite number of homogeneous dielectric sections.

The test scenario is the efficient utilization of a fixed aperture size, $10\lambda_0$ where λ_0 is the free-space wavelength at the operation frequency of 277.5 GHz, to point toward a

TABLE II
OPTIMIZED PARAMETERS OF EXAMPLE CASE I. THE SUBSCRIPTS $i = 1, 2, 3$ INDICATE A PARAMETER
CORRESPONDING TO A LENS SURFACE IN FIG. 4

Lens 1		Lens 2		Lens 3		Antenna feeder	
$c_1 \times \lambda_0$	-0.373	$c_2 \times \lambda_0$	-0.272	$c_3 \times \lambda_0$	-0.181	$\vec{p}_{ant}$	$0.935\lambda_0\hat{x}$
p_1	0.941	p_2	0.780	p_3	0.564		
a_1^0/λ_0	3.199	a_2^0/λ_0	5.947	a_3^0/λ_0	8.562		
$a_1^1 \times \lambda_0$	-2.322×10^{-4}	$a_2^1 \times \lambda_0$	7.925×10^{-4}	$a_3^1 \times \lambda_0$	-6.7×10^{-3}		
$a_1^2 \times (\lambda_0)^3$	1.051×10^{-4}	$a_2^2 \times (\lambda_0)^3$	-2.686×10^{-4}	$a_3^2 \times (\lambda_0)^3$	-8.139×10^{-5}		
$a_1^3 \times (\lambda_0)^5$	3.214×10^{-5}	$a_2^3 \times (\lambda_0)^5$	-3.026×10^{-5}	$a_3^3 \times (\lambda_0)^5$	-9.181×10^{-7}		
$a_1^4 \times (\lambda_0)^7$	9.482×10^{-6}	$a_2^4 \times (\lambda_0)^7$	-3.206×10^{-6}	$a_3^4 \times (\lambda_0)^7$	-3.102×10^{-7}		
$a_1^5 \times (\lambda_0)^9$	6.006×10^{-7}	$a_2^5 \times (\lambda_0)^9$	-1.611×10^{-7}	$a_3^5 \times (\lambda_0)^9$	-1.163×10^{-8}		

relatively large skew angle, 28.5° , using a multilens system fed by a single planar antenna. The scenario's specific parameters are listed in Table I. The geometry consists of lens layers in a core-shell architecture conceptually similar to geometries in [6] and [28]. It is worth noting that a larger number of lens layers would lead to more degrees of freedom in the optimization, potentially better performance, and a more complex geometry. In this specific example case, we focused on a three-lens system since: 1) it showcases the applicability of the proposed sequential GO technique with a sufficient number of refractive components and 2) a larger number of lens layers do not significantly enhance the performance in the targeted scenario and increase the numerical complexity of the full-wave validations.

The parameters which are not optimized are described in the following. The diameter of the largest lens is fixed to the aperture size of the scenario, $10\lambda_0$. The diameter of the two inner lenses is fixed to approximately 70% of the diameter of the lens that encompasses them. The relative permittivity of each lens component is chosen based on the availability of low loss materials in (sub)-millimeter wavelengths [44]. No matching layer is considered at the lens interfaces. The multilens system is fed by a Gaussian far-field profile with the phase center located at the $z = 0$ plane [see top panel of Fig. 4] with an edge taper level of -11 dB at 40° angle when propagating in the material of the most inner lens (Lens 1) [see the antenna feeder description in Section II-C]. The relevant and above-mentioned parameters describing the scenario are listed in Table I.

The main optimized figure of merit is the aperture efficiency with respect to the broadside direction. The optimizer searches for solutions that illuminate the contour of the largest lens efficiently while it includes the loss in performance due to the projection of the aperture toward the targeted pointing direction. To avoid solutions that favor significantly the radiation efficiency of the system over its illumination efficiency or vice versa, we resort to a multiobjective optimizer. In other words, this optimization strategy searches for solutions with high-quality far-field beam patterns (low side lobes and diffraction limited main beam) and avoiding solutions with shadow regions and high spillover loss between the lenses. This approach is implemented using the described in reception analysis technique, see Section II-A, where field matching and radiation efficiencies [see (8) and (9) in Appendix A] are optimized simultaneously. The optimized parameters are the lens surface profiles, based on (7), and the horizontal position of the phase center of the Gaussian feeder, $\vec{p}_{ant}$. The

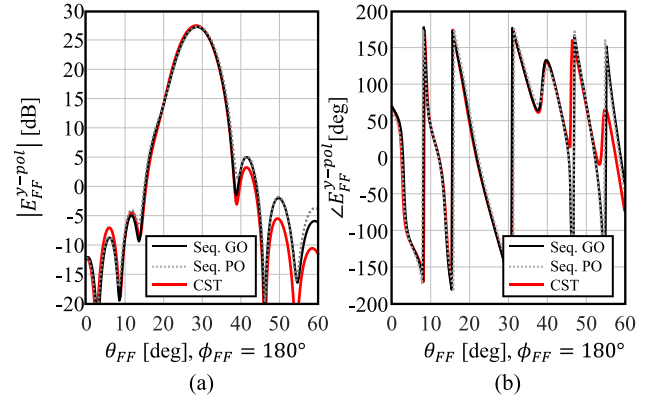


Fig. 5. (a) Magnitude and (b) phase of the y-polarized far-field after the outer lens in the geometry shown in Fig. 4. The validation against full-wave simulation in CST is also shown with excellent agreement against the proposed GO-based technique.

full list of optimized lens parameters is provided in Table II for completeness.

The kernel of the optimization is as follows. The incident field is a plane wave arriving from colatitude angle of $\theta_i = 28.5^\circ$ and azimuth angle of $\phi_i = 180^\circ$ with respect to the optical axis of the lens system. The field matching is performed at the surface of the most outer lens (Lens 3) between this incident field and the field radiated by the described antenna feeder and refracted by the lens interfaces. This refracted field is propagated using the sequential GO technique described in Section II-B. The magnitude and phase of these refracted fields are shown in the middle and bottom panels of Fig. 4, respectively. Such a field picture is not available using a standard ray-tracing technique. Moreover, computing these fields using full-wave simulations or sequential PO based codes is extremely time-consuming leading to unfeasibility of these methods as the kernels of a field matching optimizer. In particular, the refracted fields at the outer lens surface are computed in 9 s, 34 and 120 min, using the proposed sequential GO, a standard in-house sequential PO, and a time domain full-wave simulation in CST Microwave Suite [42], respectively, using the same workstation PC. It is worth noting that the antenna feeder is implemented in CST as a set of equivalent electric and magnetic currents similar to the implementation in [43].

Aiming to estimate the far-field performance of the optimized multilens system in transmission mode, the Fourier transform of the GO-based electric and magnetic fields at the surface of Lens 3 in the free-space region is implemented. The

TABLE III

STANDARD EFFICIENCY TERMS AND ELAPSED TIMES IN TRANSMISSION MODE FOR THE MULTILENS GEOMETRY SHOWN IN FIG. 4

Technique	Aperture Eff.	Radiation Eff.	Taper Eff.	Time
Seq. GO	52.7%	77.5%	68.1%	9 sec
Seq. PO	53.5%	78.2%	68.3%	34 min
CST	55.7%	78.6%	70.9%	120 min

magnitude and phase of this far-field after the outer lens are shown in Fig. 5(a) and (b), respectively. As can be seen, the proposed GO-based technique is in excellent agreement with the CST full-wave simulation. This agreement is maintained in the gain pattern of the antenna system up to -30 dB with respect to the maximum value. The phase of the far-field is also in excellent agreement within the main lobe and first side lobes. Due to reciprocity, the response of the optimized geometry to incident plane waves impinging at different angles on the main aperture is equivalent to the patterns shown in Fig. 5. A comparison between the standard in-transmission efficiency terms between the three methods is provided in Table III showing the same excellent agreement. The previously mentioned execution time for computing the refracted fields using the three methods is also reported in this table. It is worth noting that since the symmetry, with respect to the optical axis, is maintained, the optimized multilens geometry exhibits a ring-shaped focal plane. By positioning the antenna feeder at the optimized radial position of $\vec{\rho}_{ant} = 0.935\lambda_0\hat{\rho}$, a beam is generated pointing to the colatitude angle of 28.5° with a corresponding azimuth angle between 0° and 360° .

B. Example Case II: A Multilens Free-Standing Lens System for Multibeam Wide Scanning Applications

The geometry under consideration for this section is indicated in Fig. 6: a multilens system consisting of an integrated lens, referred to as the feed lens, with an FPA of antenna elements, and two free standing lenses, referred to as the scan lens, and the field lens. The array of antenna feeders is located below the feed lens (at $z = 0$ plane) sharing the complete QO system to generate multiple independent beams. This example geometry represents the optical chain within a cryogenic system for astronomical observations where the components are large in terms of wavelength and a full-wave simulation is unfeasible even for analysis purposes.

Each lens is homogeneous and made of high resistivity silicon with a permittivity of $\epsilon_r = 11.44$ at cryogenic temperatures. An AR coating is assumed over all five dielectric-to-air interfaces. Here, this layer is implemented as a quarter wavelength matching layer between each air and silicon interface with a relative permittivity and thickness of $\sqrt{11.44}$, and $\lambda_0/(4\sqrt{11.44})$, respectively. AR structures as in [19], and [20] can be fabricated to achieve a comparable performance over a wide band of operation.

The main aperture in this scenario is an equivalent on-axis parabolic reflector with a diameter and focal length of D_r and F_r , respectively, and the field matching surface is referred to as S_r in Fig. 6(a). In this scenario, the efficiency described in (3) is the aperture efficiency (with respect to broadside direction) of this reflector when $P_{inc} = 1/(2\zeta_0)|\vec{E}_i|^2 A_{ref}$ is the

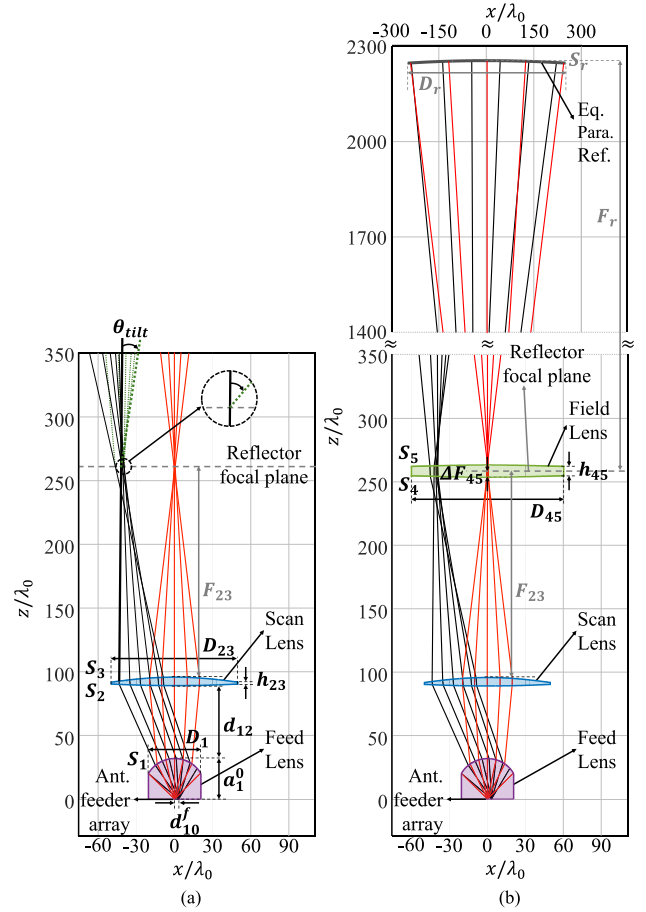


Fig. 6. Considered optimization scenario where a multibeam antenna system is envisioned using free-standing lenses. The QO system consists of FPA of antenna feeders coupled through three homogeneous dielectric lens components to an on-axis parabolic reflector. (a) Optimization scenario A where the field lens is replaced by an optimizable tilt angle (the reflector is visually omitted here). (b) Optimization scenario B where the field lens is optimized to replace the tilt angle. The relevant geometrical parameters of the scenarios are also provided. The gray-colored parameters are fixed values (not optimized). A ray picture for the central antenna feeder and the one at the edge of the FPA, corresponding to the beams at broadside and the edge of the FoV are provided in red- and black-colored lines, respectively.

incident power on the reflector from the broadside direction, ζ_0 is the characteristic impedance in air, $|\vec{E}_i|$ is the magnitude of the incident plane wave, and A_{ref} is the projected area of the reflector. The geometry of the feed and scan lenses are optimized to achieve this goal, while the purpose of the field lens is to tilt the orientation of the output rays toward the reflector.

The multiobjective optimizer described in Section II-C is also used here to maximize simultaneously the aperture efficiencies for beams at the center, $\eta_{ap,c}$, and edge of the FoV, $\eta_{ap,e}$. The edge beam in this example corresponds to scanning ten HPBWs at the central frequency, e.g., pointing to an angle, after the reflector, of $10(\lambda_0/D_r) = 68.75$ arcmin, where λ_0 is the free-space wavelength at 277.5 GHz, and $D_r = 500\lambda_0$.

The additional complexity in this example case with respect to the one in Section III-A is the presence of a field lens in the optical path to ensure a wide FoV performance. This lens is responsible for redirecting the radiation of the off-axis beams toward the center of the reflector's aperture. Its design

TABLE IV
PARAMETERS FOR OPTIMIZATION SCENARIO A. THE SUBSCRIPTS $i = 1, 2, 3, r$ INDICATE A PARAMETER CORRESPONDING TO A SURFACE IN FIG. 6(A)

Feed Lens (S1)		Scan Lens (S2)		Scan Lens (S3)		Other Parameters	
D_1/λ_0	41.2	D_{23}/λ_0	100.3	h_{23}/λ_0	2	D_r/λ_0	500
$c_1 \times \lambda_0$	-0.041	$c_2 \times \lambda_0$	9.35×10^{-4}	$c_3 \times \lambda_0$	-3.8×10^{-3}	F_r/λ_0	2000
p_1	1.056	p_2	-20.39	p_3	-22.98	d_{10}^f/λ_0	3.22
a_1^0/λ_0	31.88	-	-	-	-	d_{12}/λ_0	57.24
$a_1^1 \times \lambda_0$	-3.89×10^{-5}	$a_2^1 \times \lambda_0$	4.9×10^{-5}	$a_3^1 \times \lambda_0$	-7.26×10^{-7}	F_{23}/λ_0	160
$a_1^2 \times (\lambda_0)^3$	-7.02×10^{-8}	$a_2^2 \times (\lambda_0)^3$	-1.96×10^{-9}	$a_3^2 \times (\lambda_0)^3$	-6.78×10^{-9}	θ_{tilt}	5.03
$a_1^3 \times (\lambda_0)^5$	-8.47×10^{-10}	$a_2^3 \times (\lambda_0)^5$	3.45×10^{-12}	$a_3^3 \times (\lambda_0)^5$	-3.02×10^{-14}	-	-
$a_1^4 \times (\lambda_0)^7$	9.67×10^{-14}	$a_2^4 \times (\lambda_0)^7$	-1.35×10^{-16}	$a_3^4 \times (\lambda_0)^7$	-6.11×10^{-16}	-	-
$a_1^5 \times (\lambda_0)^9$	1.27×10^{-15}	$a_2^5 \times (\lambda_0)^9$	-5.09×10^{-19}	$a_3^5 \times (\lambda_0)^9$	-1.49×10^{-19}	-	-
$a_1^6 \times (\lambda_0)^{11}$	-3.47×10^{-18}	$a_2^6 \times (\lambda_0)^{11}$	-8.68×10^{-23}	$a_3^6 \times (\lambda_0)^{11}$	1.48×10^{-22}	-	-

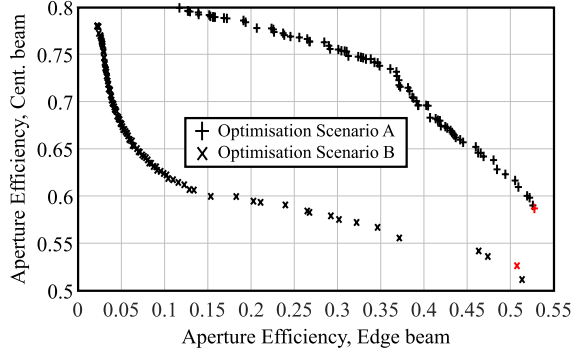


Fig. 7. Pareto fronts of the two multiobjective optimization scenarios. The red-colored marks indicate the chosen solutions shown in Fig. 6.

TABLE V

PARAMETERS FOR OPTIMIZATION SCENARIO B. THE SUBSCRIPTS $i = 4, 5$ INDICATE A PARAMETER CORRESPONDING TO A SURFACE IN FIG. 6(B)

Field Lens (S4)		Field Lens (S5)	
D_{45}/λ_0	121.14	$\Delta F_{45}/\lambda_0$	-2.099
$c_4 \times \lambda_0$	6.68×10^{-4}	$c_5 \times \lambda_0$	-7.33×10^{-4}
p_4	-12.198	p_5	-23.328
h_{45}/λ_0	8.23	-	-
$a_4^1 \times \lambda_0$	2.38×10^{-5}	$a_5^1 \times \lambda_0$	1.51×10^{-5}
$a_4^2 \times (\lambda_0)^3$	-7.35×10^{-9}	$a_5^2 \times (\lambda_0)^3$	9.60×10^{-9}
$a_4^3 \times (\lambda_0)^5$	-1.97×10^{-12}	$a_5^3 \times (\lambda_0)^5$	-7.84×10^{-13}
$a_4^4 \times (\lambda_0)^7$	-8.45×10^{-16}	$a_5^4 \times (\lambda_0)^7$	3.44×10^{-16}

is tackled in two steps due to resorting to a general purpose optimizer code. First, the field lens is modeled ideally by an optimizable tilt angle, θ_{tilt} , to rotate the output off-axis beam at the location of the reflector focal plane. The rest of the geometry is optimized together with this tilt angle. This scenario is illustrated in Fig. 6(a) and referred to as optimization scenario A. Afterward, the optimized geometry is imported to a second optimization scenario (B), see Fig. 6(b), where only the field lens is optimized to replace its ideal representation via the tilt angle.

The Pareto fronts obtained from the multiobjective optimizer are shown in Fig. 7 for scenarios A and B. Each symbol corresponds to an optimized lens system achieving the indicated aperture efficiencies for broadside and edge beams simultaneously. The selected solutions are indicated by the red-colored symbols corresponding to geometries shown in Fig. 6. The optimized parameters are listed in Tables IV and V for optimization scenarios A and B, respectively.

For the chosen multilens solution, the magnitude and phase of the electric fields at each lens interface are shown in Fig. 8,

for the beam corresponding to the edge of the FoV. These fields are calculated by propagating the electrical field radiated by the antenna feeder through the lens system to the surface of the reflector using the described sequential GO technique. The regions of a lens where the EM fields are totally reflected due to the critical angle are modeled by artificially equating the transmitted fields to 0. Such a region is clearly visible in the phase pattern of Fig. 8(b).

To calculate the far-field after the reflector, the incident fields on its surface calculated using sequential GO [see Fig. 8(k)] are propagated to the far-field using a final PO step. These far-fields over the scanning plane ($\phi_{FF} = 0^\circ$) at 277.5 GHz are shown in Fig. 9. The sidelobe levels for all the beams are below -15 dB and the off-centered beams exhibit negligible beam squints. Here, the antenna feeder location leading to scanning five HPBW (mid. beam) is obtained by linearly interpolating the optimized result for ten HPBW (edge beam) case, e.g., $d_5^f = 0.5 d_{10}^f$. The obtained results indicate that optimizing this multilens geometry aiming for maximizing the aperture efficiency at the two extremes (center and edge of the FoV) is sufficient to generate a range of independent beams over its FoV. It is also worth noting that since the multilens system is rotationally symmetric, a 2-D FoV with independent diffraction limited beams is achieved but only one side of a cut of this FoV is shown here.

The radiation (8), field matching (9), and aperture (3) efficiencies of the multilens system coupled to the parabolic reflector are obtained by the analysis in reception mode and shown in Fig. 10. A high field matching efficiency value indicates that the optimized design achieves an output beam after the reflector close to the diffraction limit.

To validate the performance of the optimized design and the proposed technique with large apertures, in terms of wavelength, a full-wave simulation similar to the one in Section III-A is computationally impossible. Instead, two sequential PO codes are used here. First option is a standard in-house sequential PO code, similar to [45] as used in Section III-A. This in-house code is robust but not optimized for calculation speed. Second option is the PO solver of TICRA tools, GRASP [26]. This solver is numerically optimized and commercially available. However, at the moment and to the best of authors' knowledge, it has three relevant limitations: 1) adding matching layers is not supported; 2) analysis with an antenna feeder located at an air-dielectric interface is not possible; and 3) it is not possible to export the

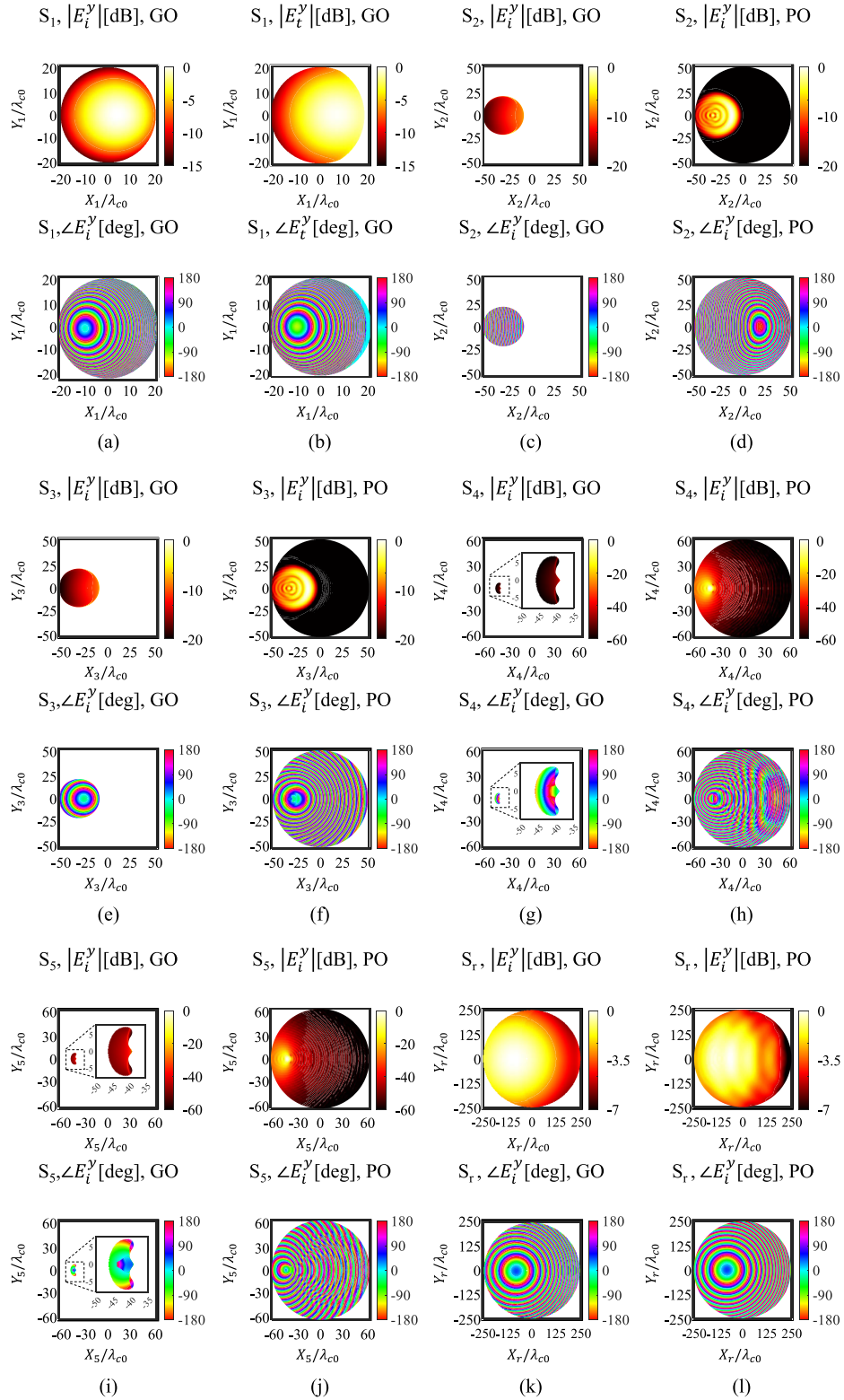


Fig. 8. Normalized magnitude, top panels, and phase, bottom panels, of y-polarized electric fields at QO interfaces for the edge beam. (a) Incident and (b) transmitted GO fields at the feed lens surface. Incident (c) GO and (d) PO fields at the bottom surface of the scan lens. Incident (e) GO and (f) PO fields at the top surface of the scan lens. Incident (g) GO and (h) PO fields at the bottom surface of the field lens. Incident (i) GO and (j) PO fields at the top surface of the field lens. Incident (k) GO and (l) PO fields at the parabola's surface.

PO equivalent currents (or fields) at tabulated lens surfaces. First limitation is addressed by artificially compensating for the reflection losses at each lens–air interface by assuming a broadside transmission through a quarter wavelength AR

coating. The EM fields transmitted out of the feed lens are calculated over a near-field spherical grid located between the feed and scan lens using our in-house PO code and given to GRASP as a tabulated source to address the second limitation.

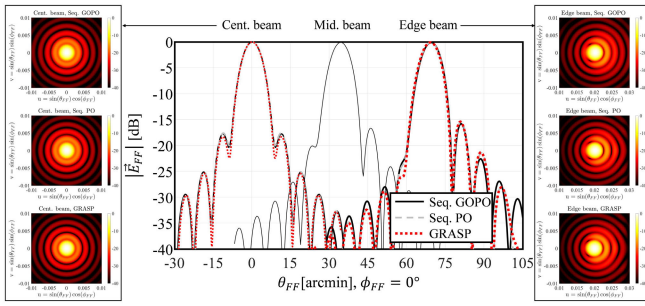


Fig. 9. Normalized magnitude of the electric far fields after the parabolic reflector at 277.5 GHz. These field cuts are evaluated at the scanning plane ($\phi_{FF} = 0^\circ$). The insets indicate the same far-field patterns in u - v space.

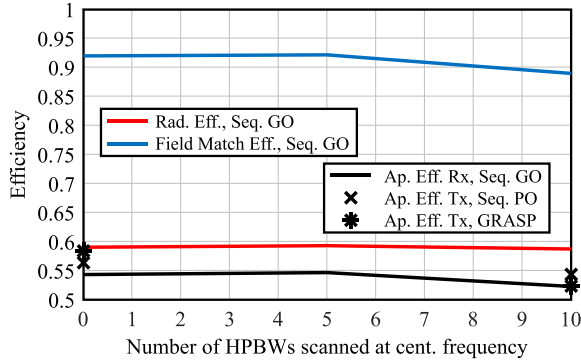


Fig. 10. Efficiency terms of the optimized QO system evaluated in reception mode compared with the ones in transmission at 277.5 GHz.

As for the third one, only the far-fields after the lens system were calculated using GRASP.

The electric fields at the lens interfaces are calculated using our in-house PO code and shown in Fig. 8 for the beam at the edge of the FoV. By comparing the GO and PO fields in Fig. 8(g)–(j), it is evident that the GO results are inaccurate at the interfaces of the field lens. This inaccuracy is due to close proximity of the observation point to the GO caustics. However, the GO method, far from the caustics, e.g., at the reflector surface, is in very good agreement with the results obtained using the PO analysis. This behavior indicates that the proposed sequential GO technique can be used even when caustic points are in the proximity of a dielectric–air interface. This statement is valid as long as the proper phase modifications due to passing the caustics are included [46], and the final, field matching surface is located far (in terms of wavelength) from the caustic points.

The far-fields after the multilens system are also calculated using in-house and GRASP PO codes and shown in Fig. 9. As can be seen, the methods are in agreement for both the central beam and the edge beam in the main lobe and the first few side lobes. In the inset of these figures, the far-fields are compared over the u - v space. The aperture efficiency of the QO system in transmission mode is also compared between the methods and shown in Fig. 10 indicating a similar agreement.

Each iteration of the free-standing multilens system, analyzed by the sequential GO technique, elapses in about 10 s in the same workstation PC as in Section III-A. In comparison, our in-house sequential PO technique without any numerical enhancements performs the same analysis in about 35 h using

the same workstation. The PO solver of GRASP achieves an execution time of about 30 min using the same PC workstation. However, our GO-based technique, without any focus on code optimization, is still about 180-folds faster. In addition, due to the mentioned limitations of the PO solver of GRASP, specially the second limitation, forming an optimization routine based on this software for such a scenario is currently not feasible.

IV. CONCLUSION

In this work, a novel multiobjective optimization technique based on a sequential GO technique in reception mode was developed. Two example multilens scenarios were chosen to represent two distinct cases.

1) A multilayer integrated lens system aiming for single beam wide scanning applications with components in the size range of 5–10 wavelengths. Such a case is also relevant for synthesizing and analyzing gradient-index lenses via discretization into multiple homogeneous sections.

2) A compact multilens QO system generating multiple independent beams and scanning efficiently up to ten HPBW's of its central operation frequency with a size range of 40–500 wavelengths. In the first example case, the size of the components allowed for a validation against full-wave simulation in CST. In the second case, full-wave simulations are currently numerically impossible. As a result, numerical validations based on a high-frequency technique, i.e., an in-house sequential PO code and the PO solver of TICRA tools, GRASP, were performed. In both the scenarios, we demonstrate an excellent agreement both in efficiency terms and output far-field beams between the proposed technique and the commercial tools. The kernel of the proposed optimizer is about three orders of magnitude faster than a commercially available full-wave simulator and more than two orders of magnitude faster than the one based on a commercially available high-frequency technique. This performance is key for developing a numerically efficient and accurate optimizer. It is worth noting that the focus of this work was on developing a technique and not on generating numerically efficient codes. Therefore, the described technique was coded in MATLAB using available functions. Moreover, the proposed technique is not limited to these specific examples cases. The technique can be readily used to optimize complex QO systems with moderate sizes (in terms of wavelength) with combination of refractive and reflective components to address demanding requirements at (sub)-millimeter-wave applications.

APPENDIX A

DEFINITION OF EFFICIENCY TERMS IN RECEPTION MODE

Based on the described analysis in reception mode in Section II-A, one can define the aperture efficiency of a QO system in reception. A radiation efficiency can also be defined as

$$\eta_{\text{rad}} = \frac{P_{\text{rad}}^s}{P_{\text{rad}}^{\text{tot}}} \quad (8)$$

where $P_{\text{rad}}^S = 0.5 \operatorname{Re} \left\{ \iint_S [\vec{E}_a \times \vec{H}_a^*] \cdot \hat{n} dS \right\}$ is the power radiated by the antenna feeder, in transmission mode, passing the surface of evaluation.

A field matching efficiency can also be introduced to represent how well the field radiated by the antenna system matches to the incident field

$$\eta_{\text{fm}} = \frac{|V_{oc} I_0|^2}{16 P_{\text{rad}}^S P_{\text{inc}}}. \quad (9)$$

These radiation and field matching efficiencies are defined in such a way that the following relation is achieved: $\eta_{\text{ap}} = \eta_{\text{rad}} \eta_{\text{fm}}$ and design insights could be derived by considering each term in a QO system.

APPENDIX B

TRANSMITTED WAVEFRONT OF THE SEQUENTIAL GOS

In this appendix, the radii of curvature of the transmitted wavefront at P_1 dielectric interface, shown in Fig. 3(a), and its corresponding principal directions are calculated. To do so, the curvature matrix of the transmitted wavefront must be obtained at point P_1 . However, we need to express the relationship between the coordinate systems of the perpendicular and parallel polarizations of the incident field and the one of its wavefront. The curvature matrix of the incident wavefront, (5), given with respect to $\hat{X}_{1i}^1 \hat{X}_{1i}^2 \hat{s}_i$ coordinate system is recalculated with respect to the incident polarization coordinate system, i.e., $\hat{e}_i^1 \hat{e}_i^2 \hat{s}_i$, which identifies the incidence plane, as

$$Q^i(P_1) = J_\alpha^T Q_0^i(P_1) J_\alpha \quad (10)$$

where $J_\alpha = \begin{bmatrix} \cos(\alpha) & \sin(\alpha) \\ -\sin(\alpha) & \cos(\alpha) \end{bmatrix}$ is a rotation matrix, $\alpha = \arccos(\hat{e}_i^1 \cdot \hat{X}_{1i}^1)$ is the angle between $\hat{e}_i^1$ and $\hat{X}_{1i}^1$ as shown in Fig. 3(b), and T is the matrix transpose operation.

As described by Deschamps [29] and also discussed by James [30], one can now resort to a phase matching between the incident, reflected, and transmitted pencil beams at the interface point P_1 to calculate the curvature matrix of the transmitted and reflected wave fronts with respect to their own principal directions. The transmitted wavefront curvature matrix with respect to the incidence and transmission planes is obtained as

$$Q^t(P_1) = \begin{bmatrix} \frac{k_i Q_{11}^i + h C_{11}}{k_i \cos(\theta_i) Q_{21}^i - h C_{21}} & \frac{k_i \cos(\theta_i) Q_{12}^i - h C_{12}}{k_i \cos^2(\theta_i) Q_{22}^i + h C_{22}} \\ \frac{k_i \cos(\theta_i) Q_{21}^i - h C_{21}}{k_i \cos(\theta_i)} & \frac{k_i \cos^2(\theta_i) Q_{22}^i + h C_{22}}{k_i \cos^2(\theta_i)} \end{bmatrix} \quad (11)$$

where Q_{mn}^i is an element at m th row and n th column of the $Q^i(P_1)$ matrix; θ_i and θ_t are the incident and transmission angles with respect to $\hat{n}$ as shown in Fig. 3(a); $C(P_1) = \begin{bmatrix} C_{11} & C_{12} \\ C_{21} & C_{22} \end{bmatrix}$ is the curvature matrix of the interface at P_1 with its own principal directions, $\hat{U}^1$ and $\hat{U}^2$, and with respect to the curvature coordinate system of $\hat{U}^1 \hat{U}^2 \hat{n}$; and $h = k_i \cos(\theta_i) - k_t \cos(\theta_t)$. The radii of curvature of the transmitted wavefront are the inverse of the eigenvalues of its curvature matrix

$$\rho_{1t}^{1,2} = \frac{2}{Q_{11}^t + Q_{22}^t \pm \sqrt{(Q_{11}^t - Q_{22}^t)^2 + 4Q_{12}^t Q_{21}^t}} \quad (12)$$

where Q_{mn}^t is an element at the m th row and n th column of $Q^t(P_1)$ matrix; and $\pm$ indicates the sign for calculating ρ_{1t}^1 and ρ_{1t}^2 , respectively. Using similar steps to the ones taken in [47], the principal direction vectors of the transmitted wavefront at location P_1 are calculated as

$$\vec{X}_{1t}^1 = \frac{\left(Q_{22}^t - \frac{1}{\rho_{1t}^1} \right) \hat{x}_t^1 - Q_{12}^t \hat{x}_t^2}{\sqrt{\left(Q_{22}^t - \frac{1}{\rho_{1t}^1} \right)^2 + Q_{12}^t Q_{21}^t}} \quad (13a)$$

$$\vec{X}_{1t}^2 = \hat{s}_t \times \vec{X}_{1t}^1 \quad (13b)$$

where $\hat{x}_t^1 = (-\hat{n}) \times \hat{s}_t$ and $\hat{x}_t^2 = \hat{s}_t \times \hat{x}_t^1$ are two axillary unit vectors perpendicular to the direction of propagation of the transmitted field [47].

Similar steps can be performed to calculate the parameters corresponding to the reflected wave fronts [30]. Although the contribution of the reflected GO fields is omitted in this article, one could consider a case where multiple reflected and transmitted GO fields are taken into account, similar to the analysis shown in [43].

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