HIGH FREQUENCY CORRECTIONS TO PHYSICAL OPTICS FOR INTEGRATED DIELECTRIC LENS ANTENNAS

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ABSTRACT

One of the most used technique for computing the radiation pattern of integrated dielectric lens antennas, consists of the integration of the Physical Optics (PO) equivalent currents on the lens surface. This approach does not provide a satisfactory estimate of the radiation pattern far from boresight, since lateral waves diffraction effects are neglected. Those effects have been estimated here by deriving uniform high-frequency expressions from the relevant canonical half-space problem, thus obtaining an additional asymptotic correction. Significant deviations from the PO currents were observed, with relevant impact on the predicted far field.

INTRODUCTION

Integrated dielectric lens antennas are often used as directive antennas in millimeter and sub-millimeter wave receiving systems [1], [2]. A typical application of this kind of antenna is concerned with Earth observation and space missions, where stringent requirements are needed such as low sidelobes, polarization purity and mechanical robustness, especially for spacecraft instruments. Lens antennas offer capability to be integrated with millimeter and sub-millimeter planar feeding structures and the relevant circuitry such as mixer, local oscillator and others; therefore, they may be technologically competitive with respect to the conventional solutions which uses horn or planar antennas. The quasi-optical property of elliptical lenses ensures that the rays from a focal spherical wave source can be refracted in forward direction, thus increasing the antenna directivity. The large dimensions in terms of wavelength authorize the use of high-frequency approximation for the lens analysis. Therefore, the PO methods have been widely used in this context, for both the far field and the internal region. The estimate of the field in the internal region serves for calculating the effects of the lens reflection to the feeding source, as seen in several previous works [3]-[5]. The standard method adopted for computing the lens radiation pattern [2] consists of integrating the PO equivalent currents on the lens surface, as obtained on the basis of the Geometrical Optics (GO) field at the interface. On the other hand, we noted inaccuracy when applied PO to find the radiation pattern, especially for space regions far from boresight. This fact may be attributed to a significant mechanism that is neglected by the conventional PO approach. Indeed, those rays from the source that impinge on the lens surface under critical angle of incidence excite lateral wave contributions and relevant transition field, which significantly deviates from the GO field. The effect may be estimated by deriving a more accurate expression of the currents on the basis of the Green's function of the dielectric half-space locally tangent at the actual lens surface. In analogy to reflector antennas modeling, this approach can be considered as a version of the Physical Theory of Diffraction (PTD) applied to lenses, where the fringe effects are due to the lateral waves rather than to edge diffraction.

LOCAL CANONICAL HALF-PLANE SOLUTION

In order to find the high-frequency corrections to PO currents, the classical problem of the Green's function of an elementary source embedded in a dielectric half-space is treated, by using a novel strategy of asymptotic evaluation of the pertinent Sommerfeld's integrals. The asymptotic treatment of the problem was treated by various authors [7], [8] in terms of non-uniform ray-contributions. In particular, by resorting to the standard SDP technique, the asymptotic field is represented in terms of contributions associated to space-wave and lateral-wave, this latter occurring only for incidence angle greater than the critical angle. The space-wave ray, which coincides at the first asymptotic order with the Geometrical Optics (GO) reflected field, emerges from a specular point, in accordance with the Snell's law; the lateral wave (LW) ray originates at point which is associated to the critical angle of incidence, propagates at grazing and next leaves the surface to reach the observation point. When the two points from which space and lateral wave originates merge together, both types of waves exhibit a transition and the simple non-uniform asymptotics fails. The asymptotic parameterization in the Sommerfeld's spectral plane is given in terms of branch-point and saddle-point coalescence. The absence in literature of a robust uniform asymptotics for treating this transition have motivated a further investigation. While the asymptotic solution uniformly valid everywhere is given for TE case in the classical work of Bleistein [9], [10], the TM case is not yet fully exploited. The difficulty that arises from this latter case resides in the presence of a Leaky-wave pole in an improper Riemann sheet. While this pole is never captured by the SDP deformation for any observation point, its vicinity to branch-point affects the ordinary saddle-point evaluation during the saddle-point/branch-point coalescence. This renders invalid, especially for high dielectric contrast, a conventional uniform asymptotics based on mapping saddle-point/branch-point interactions onto canonical parabolic cylinder functions. To obtain a fully uniform asymptotics, new canonical functions have been introduced for the TM case, which accounts for the presence of a pole on the improper Riemann sheet. Furthermore, each spectral amplitude function has been approximated by a polynomial, which provides the exact value of the spectrum at both saddle-point and branch-points. The outcome of this formulation is a representation which gradually blends into the non-uniform ray-field structure out of the transition region. As mentioned previously, for an elliptical lens fed by a focal source the critical angle of incidence exactly occurs for those rays that impinge on the lens surface at the maximum waist, providing there a smoothing of the PO currents, that may be taken into account by using the half-space canonical solution, derived as described above. The complete expressions of the uniform asymptotic evaluations, both for TE and TM polarizations, will be reported in the poster presentation, emphasizing the special functions used into this expansion.

NUMERICAL RESULTS

A simple example to illustrate the effectiveness of this novel uniform asymptotic is reported in Fig. 1; see details in the captions.

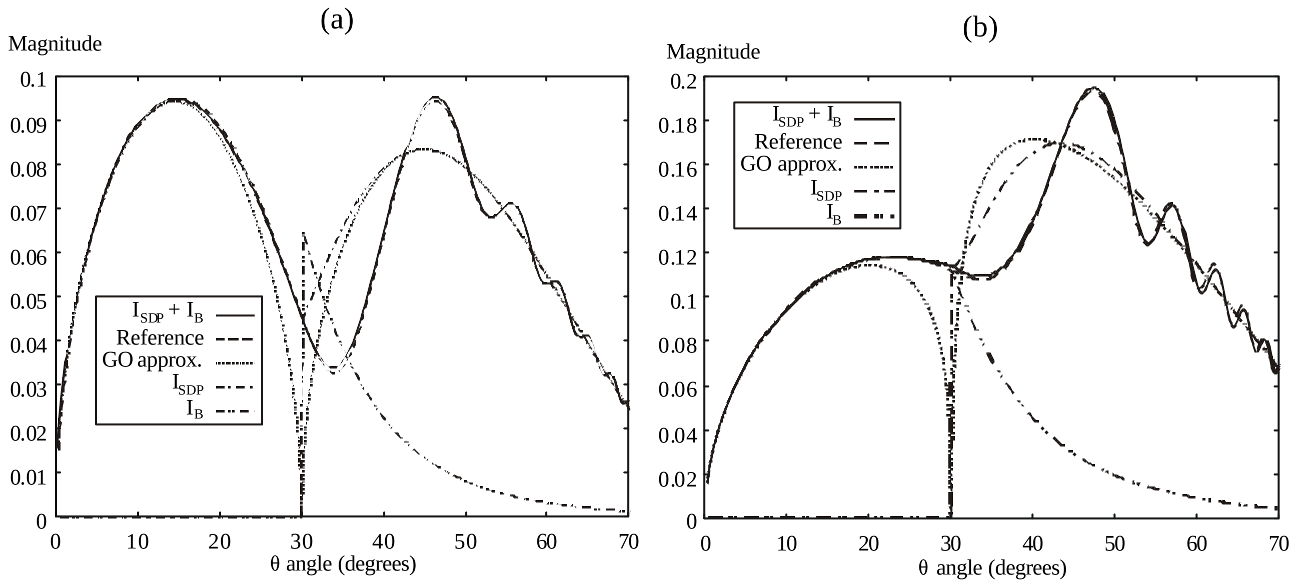

Fig. 1. Uniform asymptotic evaluation of the equivalent magnetic current at an interface between two semi-infinite media. The source is a magnetic dipole arbitrarily oriented embedded into a dense medium (e_r = 4), located at a distance equal to $4\lambda_0$ from the interface with the vacuum, where λ_0 is the free-space wavelength. Here, the critical angle is at θ = 30 degrees, where is located the branch-cut singularity, related to the incipient lateral wave. (a) TE polarization; (b) TM polarization.

The high-frequency analysis of the surface induced currents on dielectric lenses, based on the above lateral waves effects, provides a significant refinement to the PO currents, whose profile is now free by non-physical sharp peaks emerging from a conventional GO approximation in correspondence of the critical angle of incidence. We have considered lenses of elliptical shape and several dielectric permittivities, fed by one or more elementary magnetic sources, doing a comparison with the ordinary PO method. Also, simulations have been performed on other technologically feasible dielectric lenses, as the extended hemispherical lenses, that can be realized in such a way to geometrically approximate the elliptical lens contour. Fig. 2 shows the equivalent magnetic currents on the surface of an elliptical dielectric lens antenna (e_{r1} = 4, major axis length $10\lambda_0$) versus observation angle $\boldsymbol{a}$ (see the inset), in the H (Fig. 2a) and E plane (Fig. 2b) cuts. The uniform asymptotic magnetic current solution (solid curve) is compared with standard GO approximation (dashed curve), that generates the PO current.

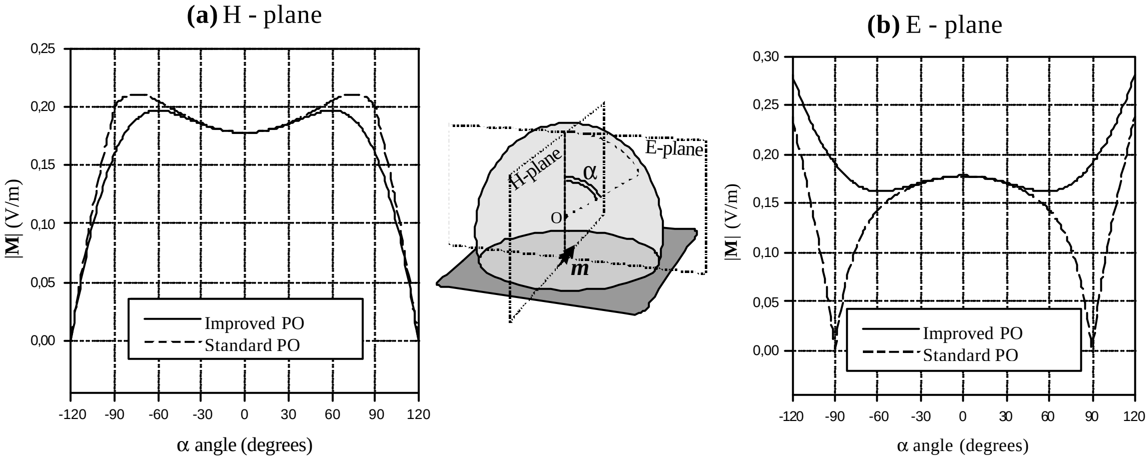

Fig. 2. Amplitude of total magnetic currents excited on the surface of an elliptical lens in principal planes: comparison between GO formulation and (a) uniform asymptotics in H – plane (parallel to the source *m*); (b) uniform asymptotics in E – plane (perpendicular to the source *m*).

Finally, the radiation integral of these refined PO currents exhibits significant deviations from PO patterns especially for the side lobe level. As an example, in Fig. 3 and Fig. 4 we show a comparison between measurements and simulations obtained by using the standard PO-GO technique and the improved PO. The measurements are inferred from [11], regarding to a silicon lens fed by a focused couple of slots.

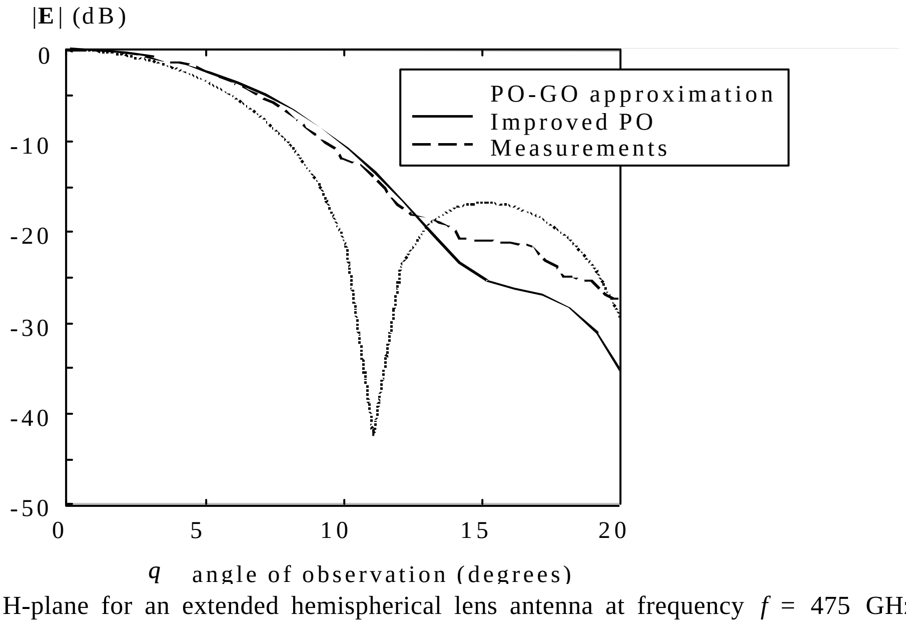

Fig. 3. Radiation pattern in the H-plane for an extended hemispherical lens antenna at frequency f = 475 GHz. Comparison between simulations performed by standard PO-GO (dotted), improved PO (continuous) and measurements (dashed).

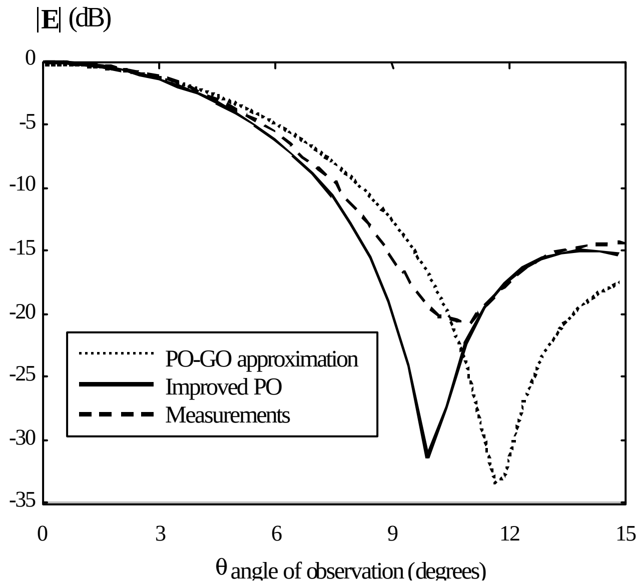

Fig. 4. Radiation pattern in the E-plane for an extended hemispherical lens antenna at frequency *f* = 486 GHz. Comparison between simulations performed by standard PO-GO (dotted), improved PO (continuous) and measurements (dashed).

CONCLUSION

Uniform high-frequency expressions of the equivalent currents at the interface between two media, for the canonical problem of a radiating source into a dense half-space have been derived. These latter have been applied to the case of dielectric lenses. Significant deviations from the PO currents were observed, especially at the maximum waist of the lens, where the critical angles are localized. In the present paper, the technique is applied to elliptical and extended hemispherical lens antennas fed by one or more elementary sources (slots etched in a ground plane). It is found that, especially when the feeding element are defocused, a rather extended area on the lens surface occurs where the PO currents fail, thus implying in certain cases a significant impact on the far field pattern calculation.

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