Research Networking Programmes

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Scientific Report

Scientific report (one single document in WORD or PDF file) should be submitted online within one month of the event. It should not exceed eight A4 pages.

Proposal Title: Development of Physical Optics Tools for the Analysis and Design of Dielectric Lens Antennas Fed by an Arbitrary Field Distribution

Application Reference N°: 4480

Scientific Report on the Research Activity within the framework of the ESF program entitled "New Frontiers in Millimetre/Sub-Millimetre Waves Integrated Dielectric Focusing Systems"

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Date: February 2013

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1) Purpose of the visit

Millimeter and submillimeter wave systems are becoming increasingly important in many scientific applications in areas such as remote sensing, radio astronomy, radar, imaging applications, and communication systems. Receiving and transmitting radio frequency (RF) systems have traditionally been based on waveguide-technology. Modern technologies enable high-level integration of RF devices with electronic circuits directly on dielectric substrate, thus reducing size, weight, and cost of RF systems. The research project is devoted to the development of techniques which allow a systematic analysis and design procedure of elliptical/hemispherical dielectric lens antennas. Such antennas have demonstrated a significant potential for millimeter and submillimeter wave applications, owing to the possibility of integration with electronic components such as detecting diodes, oscillators and mixers [1]–[8]. In addition, the shape of the lens gives a focusing property provided that the eccentricity (for the elliptical lens) or the extension length/radius ratio (for the hemispherical lens) is properly related to the dielectric constant. Under these conditions all the rays leaving a focal source are refracted in the boresight direction, thus providing high directivity to the antennas. Furthermore, lenses provide a good efficiency with respect to other millimeter wave antennas printed on homogeneous substrates, essentially because they do not suffer from loss of power in guided modes [1]–[8]. The use of dielectric lenses in future space science missions [4] requires to host, in the lens focal plane, a large integrated array that can be used efficiently over very wide frequency bands [7]–[8].

For these reasons, during the NEWFOCUS activity entitled “Development of Iterative Physical Optics Tools for the Extreme Speed Analysis and Design Techniques for Elliptical Dielectric Lens Antennas” [9] a numerically efficient Physical Optics (PO) based algorithm was developed to investigate the lens radiation properties. The algorithm assumed that the radiating elements, which illuminate the lens surface, present a localized phase center in the lens focal plane, thus radiating a spherical wavefront with a locally transverse electromagnetic (TEM) field. Such assumption is valid when the lens surface is located in the far-field region of the radiating element. Frequently, in the applications described above, radiating elements can be located close to the lens surface and the illuminating field structure does not exhibit a localized phase center. In such cases, the estimation of the lens radiated field, by using the algorithm in [9], can not provide the desired accuracy. It is then necessary to develop a new strategy to analyze the lens radiation.

2) Description of the work carried out during the visit

With the aim of analyzing a broadband feeding system for the lens, we considered the solution described in [5], [6]. There the canonical problem of an infinite slot between two dielectric media, with an electrically small (small in term of the wavelength) gap, filled by the less dense medium, between the slot and the denser medium, is considered (Fig. 2.1). Using the results in [10], [11], it can be shown that the field radiated by the slot in the denser medium can be asymptotically decomposed into the sum of two wave contributions: a spatial wave (SW) and a leaky wave (LW). When such structure is used to feed a lens, if the lens interface is in the far field region for the slot radiated field, the SW contribution is sufficient to accurately describe the electromagnetic field at the lens interface. Such wave contribution present a spherical wavefront with a locally (TEM) field arising from the feeding point on the slot. The formulas developed during the previous

NEWFOCUS activity, and described in [8], [9], [12], can be used to efficiently calculate the PO radiation integral on the lens surface.

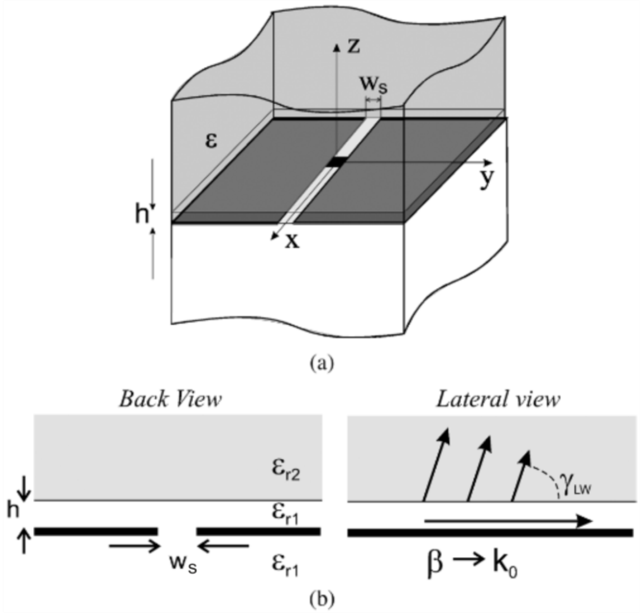

Fig. 2.1. (a) Canonical problem of a slot, of width w_s and separation layer h. (b) Schematic drawing of the geometry and of the leaky wave radiation [5].

When the lens interface is close to the slot feeding point, the LW field can not be neglected since it significantly contribute to the field impinging on the interface. In the present NEWFOCUS activity we developed an *ad-hoc* efficient quadrature rule, which can be used under a LW illumination, for calculating the PO radiation integral. In Fig. 2.2 both the spatial and the leaky wave path are represented. The LW field in Q_{LW} is locally approximated by a plane wave field coming from the direction $\hat{\mathbf{r}}'_{LW}$. For each point on the lens interface the equivalent electric and magnetic currents are then calculated under PO approximation as

$$\begin{aligned} \mathbf{J}_{\text{eq}} &\simeq \hat{\mathbf{n}} \times \left(\mathbf{H}^i + \mathbf{H}^r \right) \\ \mathbf{M}_{\text{eq}} &\simeq \left(\mathbf{E}^i + \mathbf{E}^r \right) \times \hat{\mathbf{n}} \end{aligned} \tag{2.1}$$

where $\hat{\mathbf{n}}$ is the outer pointing normal to the lens interface, and the indexes *i* and *r* identifies the incident and reflected field at the lens interface. It is worth noting that in the angular region where only the SW exists [11] $\mathbf{E}^i$ and $\mathbf{H}^i$ contain only the incident SW contribution and $\mathbf{E}^r$ and $\mathbf{H}^r$ contain only the reflected SW contribution; conversely, in the angular region where the LW also exists [11], $\mathbf{E}^i$ and $\mathbf{H}^i$ contain both the incident spatial and leaky wave contributions as well as $\mathbf{E}^r$ and $\mathbf{H}^r$ contain both the reflected spatial and leaky wave contributions. The reflected field contributions can be calculated by using proper dyadic Fresnel reflection coefficients defined as in [2], [3], [13]–[15]. Furthermore, in such asymptotic decomposition, it is worth noting that the SWs (both incident and reflected) contain a transitional field contribution which is negligible far from the leaky wave shadow boundary (LWSB) and becomes significant close to the LWSB, since it has to guaranteeing a uniform description of the total field (SW+LW) [10], [11]. It was proven that the quadrature formulas adopted for the evaluation of the field radiated by the currents associated to the SW [8], [9], [12], can be also used for the currents induced by the LW, after introducing the following change in the gradient expression of the integrand phase function. Namely, for the SW contribution the quadrature rule on each triangle, in which the lens surface is meshed, involves the gradient of the phase function where the incident direction $\hat{\mathbf{r}}'$ appears [8], [9], [12]; conversely, for the LW contribution the quadrature rule on each triangle involves the incident direction $\hat{\mathbf{r}}'_{LW}$. The formulas are omitted here for the sake of brevity. The reader, who is interested, is referred to [8], [9], [12], for the analytical details.

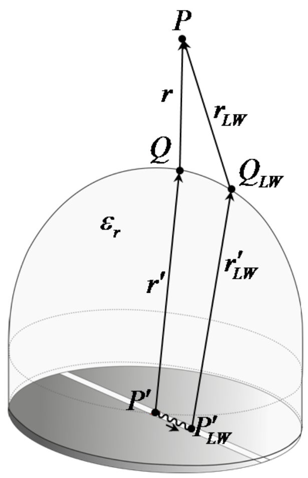

Fig. 2.2. Lens reference geometry. Space wave and leaky wave field contributions.

By asymptotically interpreting the field which impinges on the lens surface as the sum of two wave contributions, one can locally approximate the field on the lens surface as that dues to two plane waves which dominate the plane wave spectrum associated to equivalent currents on the lens focal plane. Using this interpretation, one can recover the results discussed in [16] for the analysis and design of radomes.

In detail, in [16] the authors describe a method for an accurate boresight analysis of three-dimensional antenna-radome systems, when the radome is located in the Fresnel region of the radiating antenna [16], [17]. Starting from a two-dimensional geometry the authors expand the field radiated by an aperture covered by the radome into its plane wave spectrum. Such plane wave spectrum is used to illuminate the radome surface and to estimate equivalent currents (under the PO approximation) on it. The field radiated by these currents outside the radome is calculated by numerically evaluating the relevant radiation integral on the lens. After performing such straightforward analysis, the authors compare the obtained radiation patterns against those resulting by assuming (locally on each point of the surface) an impinging single plane wave (SPW) which is propagating in the direction of the real part of the Poynting vector of the field radiated by the antenna (we remark that the field impinging on the radome present a Fresnel region behavior [16], [17]). The authors showed that the results obtained with this simple approach were in fair agreement with those obtained by using the more straightforward plane wave expansion technique. They extended the SPW approach to the three-dimensional case and validated it by also comparing the obtained results against measurements.

In the second part of the research activity we decided to use the concepts discussed in [16] for analyzing the field radiated by a lens when its interface is illuminated by a field which presents a Fresnel region behavior, which is the case of the LW illumination. In detail, we considered the field impinging on the surface, which consists of both the SW and the LW contributions in the LW existence region, and we associated it a local SPW propagating in the direction of the real part of the relevant Poynting vector. Then, we specialized the quadrature formulas in [8], [9], [12] to such kind of illumination. We stress that by using the approach developed in the first part of the activity, one has to perform the integration on the surface for both the SW and the LW illumination, since the quadrature formulas requires two different wave impinging directions; conversely, by using the method developed in the second part of the activity, one has to perform a single integration on the surface.

The SPW approach is also justified from the following reasons. In the angular region were only the SW contribution exists, which coincides with the upper part of the lens (which is also the region of the lens mainly illuminated and which significantly contributes to the main lobe of the radiated pattern), the real part of the Poyting vector is aligned with the propagation direction of the SW. At the LWSB, the propagation directions of the SW and the LW are the same since, in the uniform description of the total field, at this angular aspect the SW behavior has to match that of the LW in order to compensate for the field discontinuity of the LW [11]. In the neighborhood of the LWSB, in the angular region where both the SW and the LW exist, the propagation directions of the SW and the LW are approximately parallel. For these reasons close to the LWSB, the real part of the Poynting vector is again approximately aligned to the propagation directions of the impinging waves on the surface. Far from the LWSB, the propagation directions of the LW and the SW are no more parallel, but they tend to slightly diverge. The approximation of considering a local SPW is less accurate. However, this angular region coincides with the lateral part of the lens, which does not significantly affect the main lobe of the radiated pattern.

3) Description of the main results obtained

To validate the results obtained by using the developed algorithms we compared them against the results obtained by the algorithm discussed in [8], [9], and against those obtained by the commercial software CST [18]. Referring to Fig. 3.1, we considered a slot of width $w_s = 1\,\text{mm}$, whose radiated field illuminates a hemispherical dielectric lens with relative dielectric constant $\varepsilon_r = 11.9$, radius $R = 95\,\text{mm}$, and extension length $L_{ext} = 30\,\text{mm}$. The slot is located at a distance $h = 0.6\,\text{mm}$.

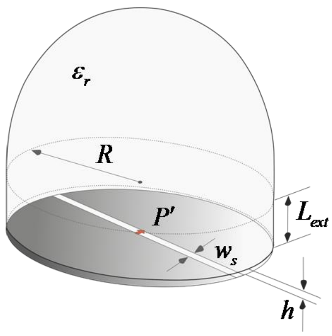

Fig. 3.1. Lens reference geometry used for the numerical results.

We analyze the lens radiation performance at an operating frequency of $f = 3.5\,\text{GHz}$ and $f = 5\,\text{GHz}$, when it is fed at the center of the focal plane (Fig. 3.2) and when it is fed off-axis (Fig. 3.3). In both the figures we report the normalized radiation patterns in the H and E planes obtained by using different approaches; namely, the full-wave CST simulation (black dashed line), the PO solution assuming that only the SW illuminates the lens interface (red dash-dotted line), the PO solution assuming that both the SW and the LW illuminate the lens interface (blue solid line), and the PO solution assuming that locally a SPW illuminates the lens interface (magenta dotted line). In figures 3.3(a) and 3.3(c) the H-plane patterns refer to the case in which the feeding point was shifted of $20\,\mathrm{mm}$ along the slot respect to the central position; conversely, in figures 3.3(b) and 3.3(d) the E-plane patterns refer to the case in which the slot (fed at its center) was shifted of $20\,\mathrm{mm}$ in the direction orthogonal respect to that of its extension. As it can be seen from the figures, by neglecting the LW contribution in the evaluation of the PO currents, the estimated patterns do not recover those obtained by the CST reference solution in the H plane, which is that more affected by the LW radiation. By introducing the LW contribution in the estimation of the PO currents, the accuracy of the PO solution in the H plane increases and it is in fair agreement with the reference solution. The E plane is not significantly affected by the introduction of the LW field. Fig 3.2 and Fig 3.3 also show that the PO solution where the SPW approach was used is also in fair agreement with the reference solution. Indeed, in all the figures the SPW patterns present the same behavior of the reference solution and of the PO solution which include both SW and LW contributions a above $-15\,\mathrm{dB}$ respect to the normalized maximum of the patterns.

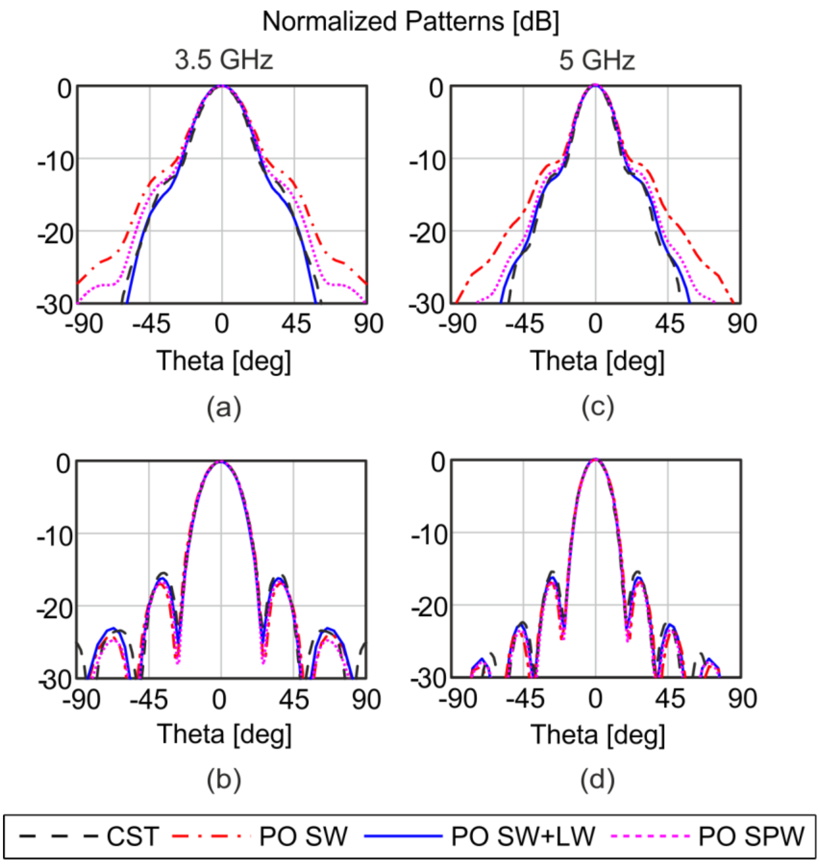

Fig. 3.2. Lens radiation patterns obtained by using different methods when the lens is fed at the center of the focal plane: black dashed line refers to CST full wave simulation, red dash-dotted line refers to PO solution assuming that only the SW illuminates the lens interface, blue solid line refers to PO solution assuming that both the SW and the LW illuminate the lens interface, and magenta dotted line refers to PO solution assuming that locally a SPW illuminates the lens interface. Figures (a) and (b) report the patterns in the H and in the E planes at 3.5 GHz, respectively; whereas Figures (c) and (d) report the patterns in the H and in the E planes at 5.0 GHz, respectively.

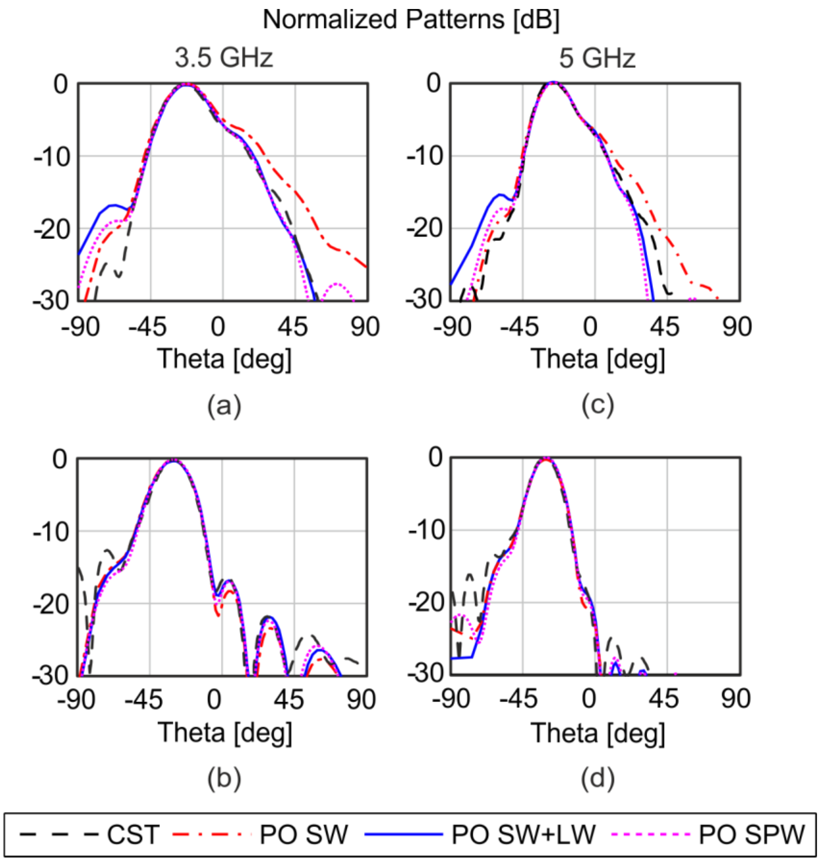

Fig. 3.3. Lens radiation patterns obtained by using different methods when the lens is fed by an off-axis configuration: black dashed line refers to CST full wave simulation, red dash-dotted line refers to PO solution assuming that only the SW illuminates the lens interface, blue solid line refers to PO solution assuming that both the SW and the LW illuminate the lens interface, and magenta dotted line refers to PO solution assuming that locally a SPW illuminates the lens interface. Figures (a) and (b) report the patterns in the H and in the E planes at 3.5 GHz, respectively; whereas Figures (c) and (d) report the patterns in the H and in the E planes at 5.0 GHz, respectively.

4) Future collaboration with host institution (if applicable)

The knowhow acquired during the research activity by the groups of the University of Siena and of the Delft University of Technology may constitute the starting point for future collaborations for developing numerical tools for the analysis and design of dielectric lens antennas and for their relevant manufacture.

5) Projected publications / articles resulting from the grant *(ESF must be acknowledged in publications resulting from the grantee's work in relation with the grant)*

The work developed during the research activity may be presented during conferences that will be taken in the next future and it may be object of publications on scientific journals.

6) Other comments (if any) - Concluding Remarks

In the framework of the NEWFOCUS research programme we developed an efficient algorithm for the calculation of the field radiated from a dielectric lens antenna under PO approximation, which improves the accuracy of that developed in the previous activity [9], when feeds which radiate a LW type field are located close to lens or when they are used for illuminating lens which are small in terms of the wavelength. The proposed algorithm was applied to some preliminary tests for analyzing the scattering of the lens when its interface is illuminated by a LW slot, which recently found large application since it constitutes an efficient broadband lens feeding system. The presented examples show that the developed algorithm reaches accurate results.

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