PROCEEDINGS OF ISAP '96, CHIBA, JAPAN

INFLUENCE OF INTERNAL REFLECTIONS ON THE FAR-FIELD PATTERN OF INTEGRATED LENS ANTENNAS

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Abstract

This paper deals with the first-order reflected waves within integrated lens antennas, consisting of a planar antenna on which a lens is mounted. It appears that if the relative dielectric constant of the lens is not too high ($\varepsilon_r \leq 4$) the single- and double-reflected waves are sufficient to describe the internal reflections, and it is shown that mainly the cross-polar far-field is affected for small angles from boresight. On the other hand, if the far-field angle is further increased both the co- and cross-polar patterns change significantly.

1. Introduction

A new generation of scientific instruments, included in both Earth observation and scientific missions, is under consideration at millimeter and submillimeter wavelengths. In the present ESA Earth observation studies, millimeter and submillimeter limbsounding instruments (e.g. MASTER and SOPRANO) are already using frequencies up to 1 THz. Also projected in this frequency band are astronomy missions (e.g. FIRST) in which the frequency range may even extend to above 3 THz.

The specifications of these instruments are very stringent; crucial points being very high beam efficiency, high pattern gaussicity and very low receiver noise temperature. These lead to the need for low loss, very high-quality antenna patterns with low sidelobes. If the receiver is used for spacecraft applications, the requirement of robustness naturally arises. Furthermore, certain atmospheric constituents are somewhat polarized and this requires knowledge of the polarization purity of the antenna patterns. Traditionally, waveguide front-ends are used in the millimeter-wave regions, where a Schottky diode and usually a horn (corrugated, diagonal or Potter) acts as standard mixing element and feed, respectively. In this conventional technology the feed, mixer, demultiplexing circuitry and local oscillator are all realized as separate devices. As the frequency increases, it becomes more and more complex to manufacture these devices and to assemble them due to their small size.

However, the small size can be turned into an advantage if the dimensions and tolerances required become compatible to those achieved by lithography. In this case a planar structure which integrates the antenna, mixer, local oscillator and all peripheral circuitry onto one single substrate becomes an alternative solution that could be competitive with the conventional technology. Furthermore, these integrated front-ends promise advantages such as reproducibility, robustness, possible extension into an array antenna and low production cost if they are produced in large quantities.

A problem that prevented a previous widespread use of this technology in millimeter- and submillimeter-wave receivers is their perceived poor performance. But with an increasing understanding of planar designs, this is gradually changing and it is now recognized that competitive performance can be achieved. One of the problems that has been encountered is the fact that planar antennas on dielectric substrates couple power into substrate modes, and since these do not contribute to the primary radiation pattern, substrate mode power is generally considered as a loss mechanism. The problem of substrate modes can be overcome in two ways. Either the substrate is replaced by a membrane, which is much thinner than the free space wavelength, simulating in this way an antenna in free space, or the dielectric substrate is made infinitely thick so that most of the radiation goes into the dielectric. This infinitely thick substrate can be simulated by using some kind of lens shape such as the extended hemisphere (e.g. hyperhemisphere) or an ellipse.

A disadvantage of all lens antenna designs is that they suffer from reflection "losses", which can affect the radiation pattern and degrade the performance of the integrated antenna. For this reason single- and double-reflected field contributions will be taken into account in this paper to calculate the vectorial far-field radiation patterns. Due to the high reflected power inside high dielectric constant lenses, which therefore require a matching layer, only materials with a maximum relative dielectric constant of four are considered.

2. Geometry and internal reflection contributions

The general geometry of an integrated lens antenna is depicted by its two-dimensional cross-section in Figure 1. As can be seen from this figure, the antenna consists of a planar radiating element, a dielectric slab and a mounted lens, whose center is chosen to lie on top of the slab. This geometry allows the extension of the model to an array configuration in which more lenses are put on the dielectric slab. It is assumed that the lens has the same dielectric constant as the slab, and that its shape is either elliptical or extended hemispherical. In order to calculate the far-field radiation patterns (co- and cross-polar) of this antenna a Geometrical Optics (GO) approach is applied inside the lens and Physical Optics (PO) outside the lens [1].

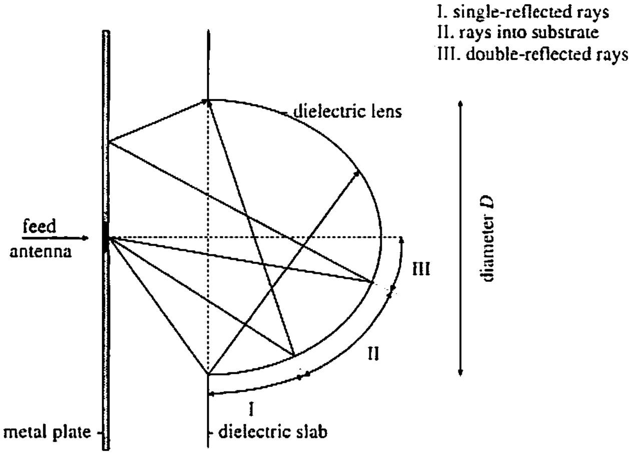

Figure 1 : Antenna geometry and angular domain of three types of reflected rays.

To justify the use of GO inside the lens, the diameter of the lens should be large compared to the wavelength in the dielectric. This also justifies the assumption that all rays originate from the center of the feed antenna. A common problem arising in these lens antennas is that the incident wave is partly reflected at the lens-air interface. Of course the corresponding reflected power should not really be treated as loss but as interference, because part of the reflected wave can leave the lens after one or more internal reflections and therefore affect the radiation pattern.

Close examination of Figure 1 reveals three different angular domains of which domain I and III actually contribute to the field outside the dielectric lens. The first group of internal reflected rays, the so-called single-reflected rays (angular domain I), have been reflected once at the surface of the lens before they contribute to the far-field radiation pattem. For rays having an angle of propagation within angular domain II it can be seen that after reflection at the lens surface they propagate directly into the substrate and there they will most likely be trapped as substrate modes. Finally, angular domain III consists of rays which will also hit the lens for a second time, but now after complete reflection at the metal plate. It is worth noting that this metal plate is present if the feed is either a (double) slot or a (double) dipole with backing reflector [2], but it is not a limitation of this model. Without metal plate there are still double-reflected rays, although their contribution will be smaller.

Both above-mentioned internal reflected field contributions can be treated as follows. Via a ray-tracing technique inside the lens, the induced equivalent magnetic and electric current densities just outside the lens can be found. In order to account for the divergence losses of the reflected waves a (divergence) factor is included, which describes the amplitude variation along a reflected ray [3]. Once the separate equivalent current density contributions just outside the lens are determined, PO is applied to calculate each far-field contribution, decomposed into its co- and cross-polar components.

3. Theoretical results

By including the previously described internal reflected field contributions one is able to determine the impact of the reflected waves on the antenna performance. As an example a planar double-dipole with backing reflector will be used and the dielectric material is selected to be HDP and quartz with an ε_r of 2.31 and 4.0, respectively. The dimensions of the planar feed are $0.5\lambda_d$ for the length and $0.4\lambda_d$ for the distance between the elements. The metallic backing reflector is placed at a distance of $0.25\lambda_d$ behind the array. This configuration results in good rotationally symmetric patterns in the dielectric. In order to determine the significance and the completeness of the single- and double-reflected fields for different dielectric materials, a table has been made showing the relative powers of the different types of reflected waves.

Table 1 : Power distribution of an elliptical lens illuminated by a double-dipole feed with backing reflector. All power values are given in percentages of the total power incident to the lens.

ε_r	P_{trans}	P_{refl}	P_{single}	P_{double}	P_{sub}	P^t_{single}	P^r_{single}	P^t_{double}	P^r_{double}	P_{naf}
2.31	76.9	23.1	18.9	0.0	4.2	17.4	1.5	0.0	0.0	1.5
4.00	76.8	23.2	19.1	0.2	3.9	13.8	5.3	0.1	0.1	5.4

From Table 1 it can be seen that the reflection "losses" (P_{refl}) only slightly increase with an increasing dielectric constant. The reason for this is that, although the feed patterns in the dielectric are equal, the lens illuminations are quite different for both antenna designs due to the different lens shapes. By selecting a higher dielectric constant material as quartz, the feed location shifts towards the center of the elliptical lens and this results in smaller angles of incidence and thus lower reflection coefficients at the lens surface. Furthermore, the distribution of the reflected power shows that this power is mainly contained within the single-reflected fields (P_{single}), whereas the double-reflected field contribution is negligible for both materials. Another observation that can be made is that for the two antenna designs almost the same amount of power goes directly into the substrate (P_{sub}). These findings together with the higher dielectric constant of quartz compared with HDP result in less internal reflected power that is contributing to the far-field radiation pattern ($P^t_{single}+P^t_{double}$). The amount of the internal reflected power that is reflected for a second time at the lens surface ($P^r_{single}+P^r_{double}$) is denoted by P_{naf} and stands for the power that is *not accounted for* in the present model. In fact this reflected power belongs to the higher-order internal reflected fields and in Table 1 it is shown that for the higher dielectric constant material more power is not taken into account. This means that the accuracy of the radiation patterns obtained with the inclusion of the single- and double-reflected fields is higher for HDP than for quartz (e.g. for quartz P_{naf} is 5.4%).

As an example the co- and cross-polar patterns of the elliptical lens antenna made of quartz and illuminated by a double-dipole antenna with backing reflector are calculated in the diagonal plane at 246 GHz and these normalized patterns are depicted in Figure 2. The far-field radiation patterns show that for small angles from boresight mainly the cross-polar pattern is affected by the internal reflection contributions. However, if one observes the patterns for larger far-field angles, both the co- and cross-polar radiation patterns change significantly. Table 1 shows that by neglecting the first-order internal reflected field contributions, the beam efficiency is overestimated by more than 10%.

4. Conclusions

Comparing the radiation patterns of the integrated lens antennas with and without the inclusion of internal reflections, reveals that in case of elliptical lenses the differences found in the main lobe and the first few sidelobes of the co-polar patterns are negligible. Only for larger angles from boresight the influence of the internal reflections on the co-polar patterns becomes significant, but then the co-polar pattern levels are usually more than 30 dB down the peak directivity. For the cross-polar patterns on the other hand, it has become clear that the internal reflected rays can have a major effect on the shape and level of the cross-polar radiation patterns.

Additional computations for hyperhemispherical lenses, made of various materials, demonstrate that they suffer from less reflection "losses" than the elliptical ones and for these special extended hemispherical lenses also a larger part of the reflected power is propagating into the substrate. This proves once again that besides the relative dielectric constant also the shape of the lens is an important parameter in relation to the influence of the internal reflected waves on the vectorial far-field pattern.

Finally, it can be concluded that for the integrated lens antennas considered in this paper ($\varepsilon_r \leq 4$) the first-order internal reflected fields are sufficient to describe the influence of the reflected fields on the antenna performance.

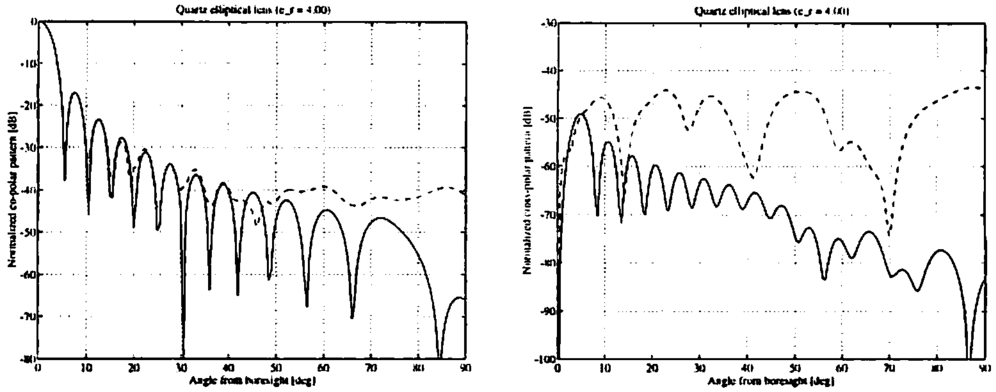

Figure 2 : Normalized co- and cross-polar patterns, in the diagonal plane at 246 GHz, of a 15 mm diameter elliptical lens antenna made of quartz and illuminated by a double-dipole antenna with backing reflector. (solid curve: internal reflections excluded ; dashed curve : first-order internal reflections included)

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