Frequency Independent Patterns From Double Shell Lenses Fed by Leaky Wave Feeders

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***Abstract*— This work aims at designing a wideband leaky lens antenna capable of providing frequency independent patterns over a wide frequency band of operation, about one octave, using connected array of leaky slots as lens feeder in presence of a double shell lens. In addition to on-axis feeding, offset feeding is also studied in order to increase the scanning performance of the antenna system within the proposed frequency band of operation. Improvement in terms of pattern stability and scan loss have been demonstrated in the paper.**

***Index Terms*—leaky wave antennas, connected arrays, double shell lenses.**

I. Introduction

Reflector systems fed by wideband antenna feeds are widely used for the applications such as radio astronomy and space observation [1]. For such applications, it is often required to maintain the illumination of the reflector as constant as possible at all frequencies within the large band of operation. Reflector feeds that can operate with high aperture efficiency over wide frequency ranges have been previously developed for low-frequency radio telescopes. Some examples are the focal plane array of tapered slot antennas [2] and the eleven antenna [3]. However, there is currently a need for wideband reflector feeds also at much higher frequencies, for Terahertz (THz) and mm-wave space instruments.

For THz space observation, dielectric lens antennas are typically used, due to their easy integration with the receivers. Elliptical or hyper-hemispherical shapes are frequently employed, which are typically fed efficiently only over a narrow band, e.g. by double slot antennas [4]. An improved solution is the leaky-lens antenna recently proposed in [5] which can achieve multi-octave bandwidth. This antenna consists of a leaky-wave slot kept at an electrically small distance from the dielectric lens, represented by h in Fig. 1(a), in order to obtain directive radiation inside the dielectric and, consequently, efficient illumination of the lens. Although well matched and with stable phase center over a very wide band, the leaky-lens antenna generates radiation patterns that become narrower and more directive when the frequency increases. For this reason, when used as reflector feed over wide bandwidths, this antenna would not lead to high aperture efficiency at all frequencies.

In order to achieve high reflector illumination efficiency over the desired bandwidth, a solution was proposed by some of the authors of this work in order to obtain frequency independent patterns in [6]. It provides a solution to the problem by introducing a novel feed configuration rather than modifying the lens shape. The aim is to improve the reflector illumination efficiency of a single-slot-fed lens antenna by extending the leaky-slot radiation concept to be used in an array configuration as shown in Fig. 1(b). The elements in the array are coherently combined, so that they are associated with a single beam outside the lens. This coherent excitation of the array has the advantage of generating stable radiation patterns over a broad bandwidth, exceeding 1:2 ratios. This characteristic allows wideband illumination of a reflector with high aperture efficiency. However, for this scenario, the reflector is illuminated by only one pixel since all the elements are coherently fed which does not allow us to have multi-pixel solution.

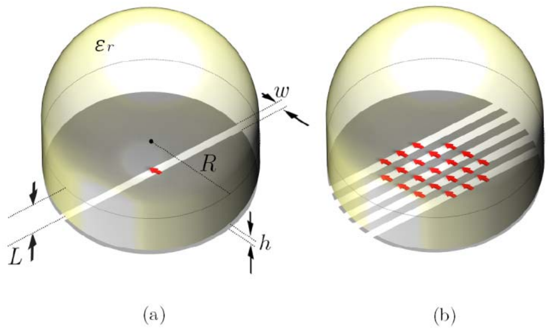

Fig.1 (a) Geometry of extended hemispherical lens fed by a leaky-wave slot kept at distance h from the lens; (b) same lens fed by an array of connected leaky-wave slots

For this purpose, another approach could be to design a multiple shell lens such that the refraction interfaces from the shells are adequately shaped to form frequency stable patterns. A solution of this problem is given [7] where a double shell lens design was presented. By using this concept, one may design an array with many pixels such that each pixel is able to generate more or less a frequency independent beam.

This work aims at designing a double shell lens (DSL) to be used directly as an imager over a wideband frequency band, about 1:2. Due to its wide band characteristics, a connected slot array antenna with many pixels is used as a lens feeder where each pixel is associated to an independent beam illuminating the double shell lens. An Integrated Lens Antenna Shaping tool (ILASH) [8], is used in order to design and optimize the double lens shape. It includes GO tools for quick design of these types of lenses subject to a number of different target specifications, GO/PO tools for the computation of the lens equivalent surface currents and radiation pattern, and a Genetic Algorithm optimization tool for advanced lens design.

This allowed us to study two cases:

- Double shell lens optimization for centered single feed position.
- Double shell lens optimization to maximize scanning performance in terms of scan loss and beamwidth versus frequency both in the slot plane and in the orthogonal plane.

II. LENS OPTIMIZATION

The requirements in the project considered in the optimization are listed below:

- The bandwidth should cover one octave. In the project, it was aimed at designing the lens within a band starting from 0.3THz to 0.6THz
- Since the lens is planned to be used directly as an imager itself, the secondary beams after the lens should be highly directive and relatively narrow. Namely, the desired gain is about 45dB and the corresponding half power beamwidth is about 1^0.
- Considering the scanning scenario as well, the antenna should have as many pixels as possible. In this work, the aim is to have a total pixel number about 529 (23x23 pixel matrix) which corresponds to a maximum scanning angle approximately 11^0 from each side (22^0 in total assuming each pixel has a field of view of about 1^0).

It is important to remind here that, due to the requirements of the project, the lens should provide collimated beams not only for the onset feeding but also for the scanning scenario as well. Therefore, the lens geometry has been optimized using a modified version of the Abbe sine condition [7] which is able to provide highly directive beams and high beam scanning performance for off-axis feed displacement.

The optimized lens can be seen in Fig. 2(a). The material of the inner lens is silicon (ε_{r1}=11.9) and it has a height of *F*=40mm with having a radius of 27mm. Outer shell, on the other hand, is made of fused quartz (ε_{r2}=3.8) with a thickness of *T*=40mm and a radius of 55mm. In order to compare the double shell lens performance with a classical reference, a single shell hyper hemispherical silicon lens (SSL) was also designed such that it has similar gain and beamwidth as the double shell one at the center frequency, f=0.45THz. The lens geometry is shown in Fig. 2(b). It has a radius of R=44.6mm and an extension length L=0.35R.

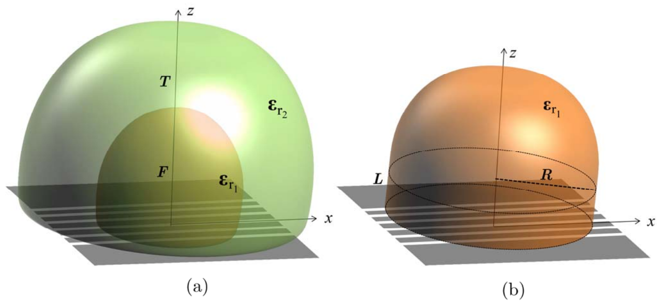

Fig.2 Designed lens geometries: (a) Optimized double shell lens and (b) single shell lens.

To get an initial idea about the performance of the lens, as a first step, the ray distribution inside and outside the each shell were investigated in ILASH. For this purpose, a point source was located in the center of the lens for two cases: First, the source was located at the center of the feed plane whereas in the second case the source was shifted by 3.3mm which corresponds to the last pixel of the feed array. The ray distributions were shown in Fig. 3 and as it can be seen from the figure, indeed, for both scenarios the rays due to a point source exit the lens almost parallel which is the desired case in order to have frequency stable beams as we scan the feed position.

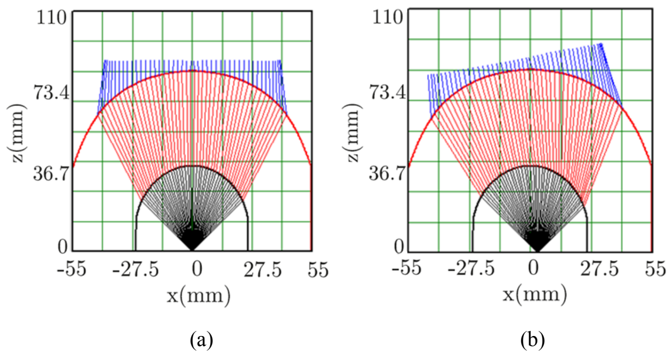

Fig.3 Ray distributions when the lens is fed by a point source which is placed at (a) the center of the lens, and, (b) 3.3mm shifted from the center to the edge

III. NUMERICAL RESULTS

Secondary beams generated by the double shell lens and single shell lens can be seen in Fig. 4 for 0.3, 0.45 and 0.6 THz selected within the band of operation. Compared to conventional single shell lens approach, it is quite clear that the proposed double shell lens design is able to provide much more stable secondary beams in terms of gain variation within the frequency band.

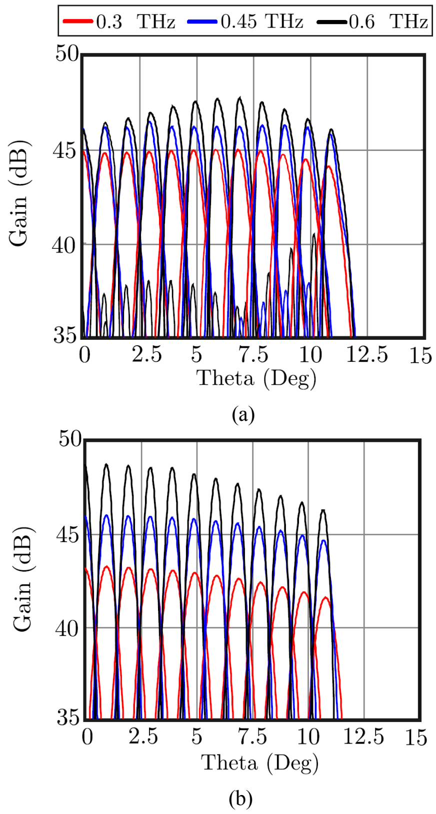

Fig.4 Secondary beams generated by: (a) Double shell lens, and, (b) single shell lens.

In Fig. 4, the maximum gain variation is about 2.7dB for optimized double shell lens geometry whereas the variation becomes higher and it goes up to 6dB for the single shell lens design. From Fig. 4, one can also see that the level of the side lobes generated by the optimized double shell lens structure seems to be higher compared to the single shell lens, especially at the highest frequency. This is because of the phase modification phenomena of the double shell lenses. Since the desired antenna gain is relatively high and the antenna dimensions are very large in terms of wavelength, it is difficult to adjust the phase accordingly on the shells. These side-lobes are mainly due to this reason but they are extremely narrow and lower than 7dB with respect to the maximum gain associated to the adjacent pixel at the worst case scenario.

One other important parameter for the lens, especially for the scanning scenario, is the scanning loss. The loss due to scanning should be as least as possible if one wants to maximize pattern stability as the feed position is being shifted from the center. For this purpose, scanning loss versus frequency was also calculated and highlighted in Fig. 5. They show that the proposed double shell lens design improves the scanning loss compared to the single shell one as well.

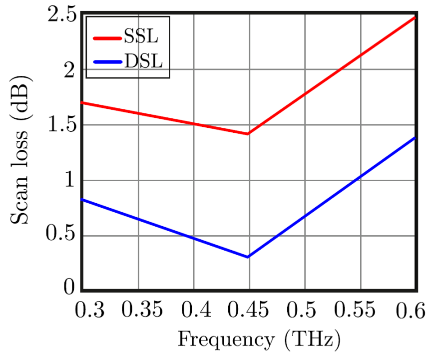

Fig.5 Scanning loss as a function of frequency for double shell and single shell lenses.

The beamwidth variation should also be kept at minimum as we aim at providing a solution in order to have frequency stable beams by means of shaping the lens. To see how much the double shell lens solution improves the performance in terms of the beamwidth stability compared to single shell lens, the results were highlighted in Fig. 6. It is clear that the beamwidth variation is much less than the variation one may have by using a single shell lens.

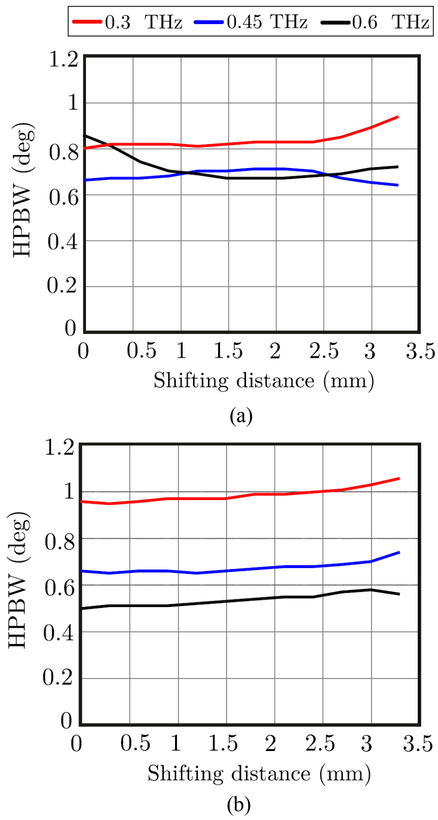

Fig.6 Beamwidth variation as a function of feed position for three frequencies within the band for (a) double shell, and, (b) single shell lenses.

IV. CONCLUSIONS

We have proved that the proposed concept works for leaky slot antenna fed double shell lens design, indeed improving significantly the frequency stability of the beams compared to the classical single shell lens. In addition to the on axis feed case, offset feed position scenario was also investigated and it has been demonstrated that our solution is also able to provide high beam scanning performance with frequency stable radiation patterns over 1:2 bandwidth at THz.

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