ESF Research Networking Programme NEWFOCUS
Final scientific report

Project title: **Variable metasurface based lens antennas: numerical and experimental evaluation**

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Exchange period: 3 weeks (9^{th} February 2012 until 2^{nd} March 2012)

Host institution: Universta' degli Studi di Siena, Italy
Host: Prof. Stefano Maci

Purpose of the visit

Thanks to the findings of the previous NEWFOCUS project "New focusing devices based on periodic surfaces" (NEWFOCUS grant No. 3154) the idea of this visit was to study the problems which were encountered in the realization and initial experiments on the H-plane horn antenna with the inserted metasurface Luneburg lens. Namely, those were related to a significant mismatch on the aperture – air interface and a shift in the central operating frequency of the designed lens. During the stay the intention was to study the problem in details numerically and prepare a new design for experimental verifications.

Also in order to pursue the concept of metasurfaces and their applications a bit further, development of a fast in-house numerical code was initiated since the observed problems are usually very large in terms of wavelength and with a lot of small details which make the use of commercial solvers extremely time consuming, especially if any kind of optimization is required.

Description of the work carried out and main results obtained

During the exchange period at the University of Siena the research was focused, as mentioned, on studying the problems encountered in the realization of the Luneburg H-plane horn antenna and improving the analysis possibilities by developing a fast software tool for problems involving modulated surface impedance. Therefore, this report is divided into these segments:

1. Overview of the previous work on Luneburg lens based horn antenna
2. Improvement of the aperture – air matching problem
3. Numerical code for impedance surface
4. Future collaboration with the host institution
5. Projected publications/articles resulting from the grant

1) Overview of the previous work on Luneburg lens based horn antenna

By gradually modulating the surface impedance profile inside a parallel-plate waveguide it is possible to realize a smooth variation of the effective propagation constant of the wave propagating along the waveguide. In other words this means that the effective refractive index is modulated and therefore by carefully choosing the parameters of the impedance modulation, different lens profiles can be obtained [1]. The refractive index profile and the corresponding surface impedance profile for a Luneburg lens case are shown in Fig. 1. (considered Luneburg lens [3] has a 75.6 mm radius, operates at 13 GHz, and is realized using circular patches placed inside a 3.15 mm grid, with 0.3 mm minimum spacing). Fig. 2 shows the vertical electric field plot inside such parallel-plate waveguide when excited by a unit dipole on the lens edge. The surface impedance profile was here obtained using a periodic array of size-varying circular patches [1].

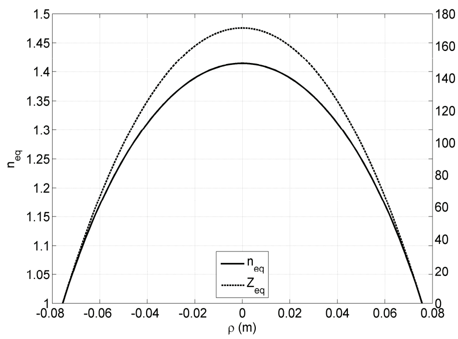


Fig. 1. Refractive index and impedance profile for the observed Luneburg lens case (the parallel-plate waveguide is 1.8 mm high, the substrate dielectric is 0.7 mm high with permittivity of 10.2).

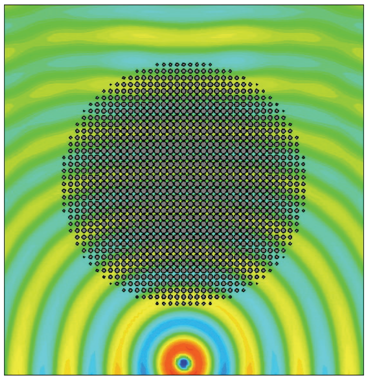


Fig. 2. An array of circular patches with the surface impedance profile corresponding to the Luneburg lens combined with the snapshot of the vertical E field excited by a small point source at the lens edge

The idea was to use this kind of lens inside horn antennas to enhance their properties. Using this structure we can design an *H*-plane horn antenna that will have improved radiation characteristics compared to standard horn antennas thanks to the uniform phasing at the aperture provided by the Luneburg lens effect. Also, if we look at this from another perspective, the new horn can be made shorter compared to some standard one, while retaining the same radiation properties. In particular, the concept was applied to the walls of an H-plane horn antenna with 40° flare angle and the total length of the horn from the feeding waveguide to the edge is equal to the lens diameter (151.2 mm), (depicted in Fig. 3.).

Simulated results for this H-plane horn are shown in Fig. 4. Fig. 5. shows a comparison of H-plane radiation patterns of the lens horn with a 40° flare angle and an optimized horn designed for the same aperture width.

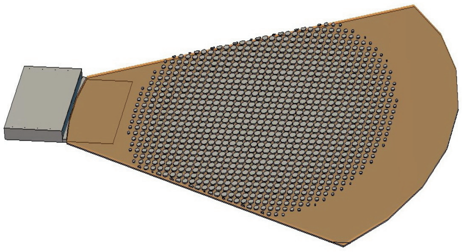


Fig. 3. Luneburg H-plane horn without the top and side metallic plates

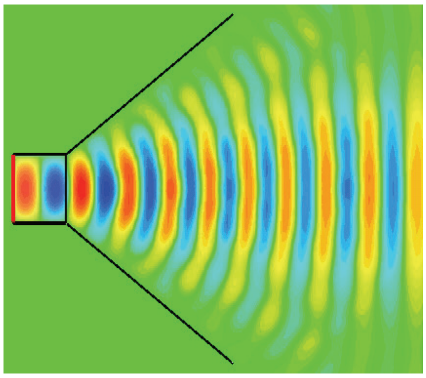


Fig. 4. Snapshot of the vertical E field inside the 40° H-plane horn with the inserted Luneburg lens

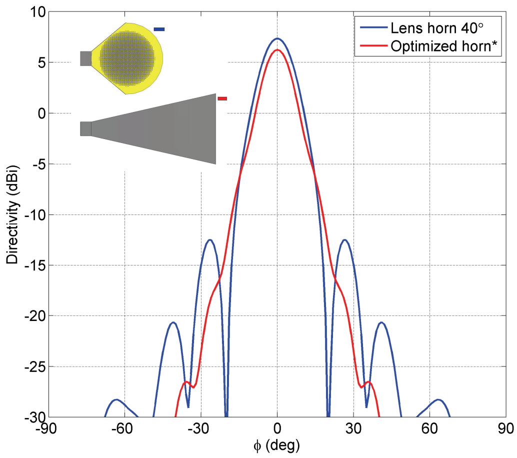


Fig. 5. Comparison of H plane radiation patterns at 13 GHz of the lens horn with a 40° flare angle and optimized horn designed for the same aperture width (the insets are in scale and they show the difference in size).

2) *Improvement of the aperture – air matching problem*

It needs to be pointed out that the fields and patterns in the previous figures were obtained using the assumption of an infinite parallel-plate waveguide. If the actual finite size horn is simulated the field at the aperture - air interface experiences a mismatch and there is a strong reflection back into the lens causing poor return loss and disruption in the field pattern. The field in this case is shown in Fig. 6 and the mentioned mismatch problem is clearly seen.

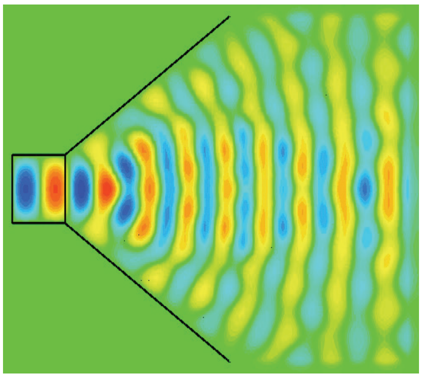
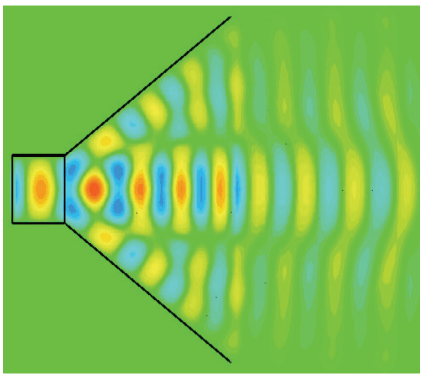


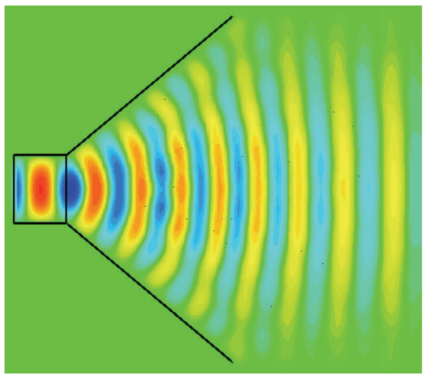
Fig. 6. Snapshot of the vertical E field inside the 40° H-plane horn with the inserted Luneburg lens (simulated in open space).

Initial studies of the solutions that would solve the mismatch problem showed in which direction to proceed. Namely, this anomaly can be avoided by expanding the aperture in the vertical direction or in other words by tapering the structure. Since it would be counterproductive from the point of size-reduction to add an additional tapering flange, we have decided to perform the tapering from the middle of the horn. This can be achieved by performing the tapering and simultaneously modifying the patch array in order to correspond to the change in the waveguide height. Two cases where this has been performed are shown in Fig. 7., the first case where a jump in waveguide height to 5.75 mm was introduced, and the second case where a gradual linear change of height from 1.8 to 5.75 mm was made.

In the first case the introduced jump creates a significant disturbance of the field and disrupts the plane wavefront (Fig. 7.a). Gradual change, actually works much better and it is a solution that is acceptable and that could be easily used in practice.



(a)



(b)

Fig. 7. Snapshots of the simulated vertical E-fields for the lens horn at 13 GHz with two tapering solutions; (a) step tapering using a jump in waveguide height, (b) gradual tapering where the change in height was linearly modified (results were obtained using CST MS [2]).

Since, the aperture size is changed in the cases where tapering has been applied, it is not possible to compare the directivity levels directly. However, it is still interesting to see a directivity comparison between all the mentioned cases. In order to compare them their boresight H-plane levels have been normalized to 0 dB and shown in Fig. 8. The ideal case is in a way a reference and it is clearly seen that the second tapering solution recreates this reference beam pattern almost exactly proving that the field is now very well matched to free space. This is not the case for the first tapering solution which resulted in a significantly wider beam. From Fig. 8 it would seem that the case without tapering is also acceptable, however apart from higher sidelobe levels this case generates a strong reflection causing a very poor return loss.

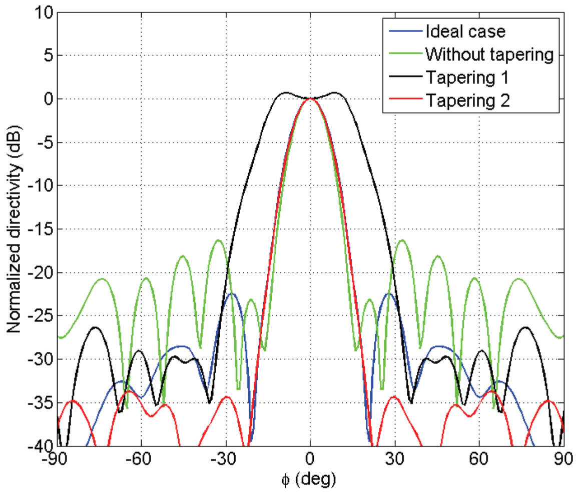


Fig .8. Normalized directivity at 13 GHz of the lens horn for different tapering cases (results obtained with CST MS [2]).

Several prototypes based on this idea were being designed during this exchange period in Siena and it is expected that they will be manufactured in the next few months.

3) *Method of Moments based code for impedance surface*

Since optimization of the structures based on metasurfaces can be very time consuming due to a large number of small details it is necessary to develop a numerical code which will be able to solve these kind of problems very efficiently. For this reason we have started to develop a planar Method of Moments [4] code for impedance surfaces which in combination with already existing Pole-zero matching method [5] based code will be able to perform the optimization of metasurfaces in a relatively fast way.
The basis of the problem is the electric field integral equation of the form [6]:

$$\hat{n}\times\vec{E}(\vec{r}) = -\frac{\vec{M}(\vec{r})}{2} + \frac{j}{4\pi\omega\varepsilon_0}\hat{n}\times\int_{S'}\left\{k_0^2\vec{J}(\vec{r}\,')\frac{e^{-jk_0R}}{R} - j\omega\varepsilon_0\vec{M}(\vec{r}\,')\times\nabla'\left(\frac{e^{-jk_0R}}{R}\right)\right.$$
$$\left. -\left[\nabla'\cdot\vec{J}(\vec{r}\,')\right]\nabla'\left(\frac{e^{-jk_0R}}{R}\right)\right\}dS' \quad (1)$$

where the dash indicates the coordinates of the source. This is a well known formulation which is used in the impedance boundary problems. Considering that our problem involves an impedance surface the boundary condition can be written as

$$-\hat{n}\times\vec{E}(\vec{r})=\overline{\overline{Z}}_{IBC}\left\{\hat{n}\times\left[\hat{n}\times\vec{H}(\vec{r})\right]\right\}. \tag{2}$$

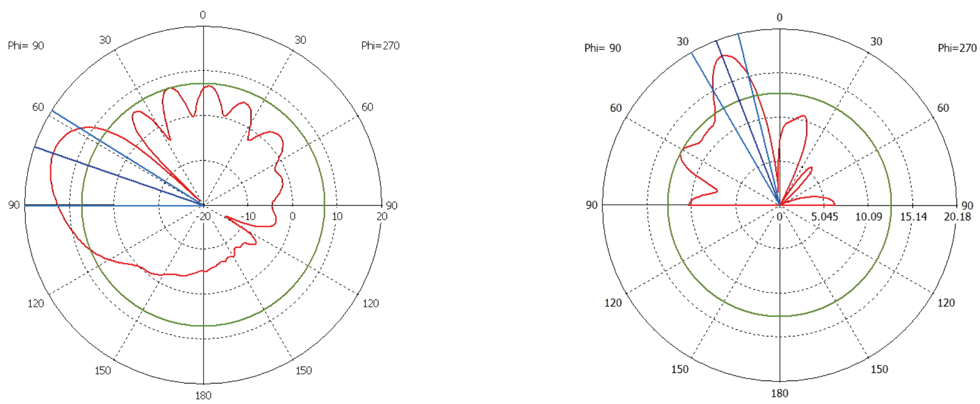
Using the surface equivalence theorem the equivalent currents can be defined as

$$\begin{aligned}\hat{n}\times\vec{H}(\vec{r})&=\vec{J}(\vec{r})\\ \hat{n}\times\vec{E}(\vec{r})&=-\vec{M}(\vec{r})\end{aligned} \tag{3}$$

which combined with (2) allows that (1) is rewritten using only one type of equivalent currents. To solve the equation which is obtained in that way using Method of Moments the current has to be developed into a sum of orthogonal basis currents with unknown coefficients. To realize a fast code here we have to assume that our problem will be circularly symmetric and the used basis functions will therefore be based on this property. Several options were and still are considered for this step.

4) Future collaboration with the host institution

As mentioned in the previous sections, the collaboration with host institution is continued on developing several prototypes for Luneburg lens based *H*-plane horn antennas. Furthermore, a project which was initiated during this exchange involves the development of a fast Method of Moments based code for analysis of these types of lenses and it will be continued in the following months.
Also, in pursuing the idea/concept of metasurfaces a bit more it became evident that by opening a part of the Luneburg lens (removing a part of the top cover of the parallel-plate waveguide excited by the horn) radiation in some arbitrary direction is possible. This occurs since by opening a part of the structure the surface wave is transformed into a leaky wave. By also applying additional modulation of the surface radiation in arbitrary directions is possible (examples of this radiation for a non-modulated lens and a modulated lens are shown in Fig. 9.). This interesting property will be analyzed in more details in the future once the code for the metasurface analysis will be finished.



(a) (b)

Fig. 9. Radiation patterns for a horn excited Luneburg lens where the second half of the top parallel-plate cover was removed; (a) no additional modulation of the lens profile, (b) with additional sinusoidal modulation of the lens profile.

5) Projected publications/articles resulting from the grant

In preparation for this exchange one conference paper has already been submitted to an international conference (EuCAP 2012) and one more is in preparation. They will be forwarded to the NEWFOCUS office as soon as the acceptance confirmation is received from the organizers. Furthermore, a journal paper dealing with the properties Luneburg based horn antennas is in preparation.

References

[1] M. Bosiljevac, M. Casaletti, F. Caminita, Z. Sipus and S. Maci, “Highly tapered, uniform phased horn based on variable impedance lens effect,” Proceedings of the 5th European Conference on Antennas and Propagation (EUCAP), Rome, Italy 2011, pp 3683 – 3686.

[2] CST Microwave Studio 2011, www.cst.com

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[5] S. Maci, M. Caiazzo, A. Cucini, M. Casaletti, “A pole-zero matching method for EBG surfaces composed of a dipole FSS printed on a grounded dielectric slab,” *IEEE Transactions on Antennas and Propagation*, Vol. 53, No. 1, pp. 70-78, Jan. 2005.

[6] John. L. Volakis and Kubilay Sertel, *Integral Equation Methods for Electromagnetics*, SciTech Publishing, 2011.