ESF Research Networking Programme NEWFOCUS
Final scientific report

Project title: **New focusing devices based on periodic surfaces**

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

Purpose of the visit

Within this project the idea was to develop and characterize new approaches in lens and antenna design based on periodic surfaces. Periodic surfaces or artificial surfaces offer us the possibility to precisely control the path of the electromagnetic waves and thus even focus the waves. One concept which allows this uses a class of periodic surfaces known as electromagnetic bangap surfaces and traps the electromagnetic energy into channels within the bandgap. An example of this concept is the recently introduced gap-waveguide. However, an alternative concept is based on the modulation of the surface impedance and can be realized with typical dielectric substrates. This concept showed more promise and was therefore pursued within this research period.

Description of the work carried out and main results obtained

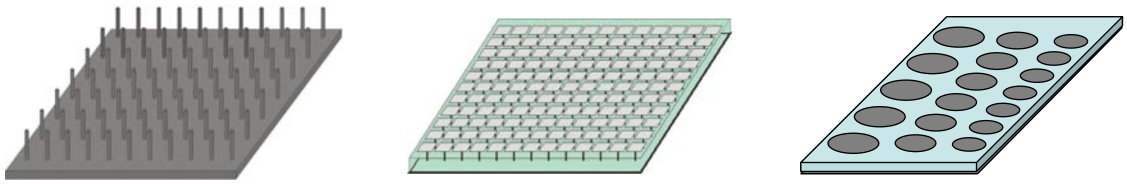
During the exchange period at the University of Siena the research was focused, as mentioned, on studying the properties and applications of surface impedance modulation. The idea was to use the pole zero matching method [1] and the MoM code for circular patches developed at University of Siena as a starting point in the analysis of variable surfaces. After initial introduction with the code and its possibilities the work was carried out in four segments;

1. Study of modulation of periodic arrays of circular patches
2. Synthesizing a Luneburg lens inside a parallel plate waveguide
3. Improving the characteristics of H-plane horn antenna with the developed Luneburg lens
4. Optimization of the H-plane horn antenna

This division will also be used in the continuation of this report.

1) Study of modulation of periodic arrays of circular patches

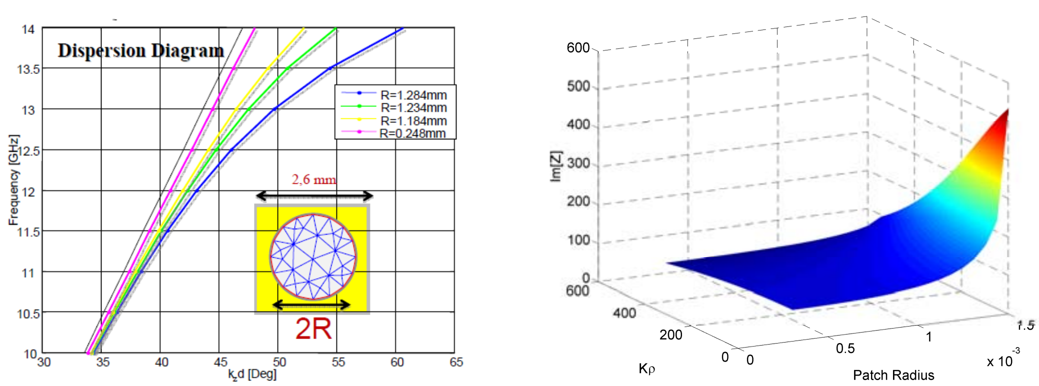
In order to achieve the necessary variation of the surface impedance various artificial periodic or quasi periodic surfaces are at our disposal [2][3]. Several examples are shown in Fig. 1. The surface shown in Fig. 1.c proved to be the most interesting one due to the simplicity and manufacturing advantages. Since it is essentially an array of patches on a planar substrate it can be very easily produced and used in many different surroundings.



(a) *"Bed of nails"*   *(b)* *Mushroom surface*   *(c)* *Circular patches*

Fig. 1. Artificial surfaces whose properties can be modified in order to obtain modulation of the surface impedance.

Such infinite arrays of circular patches with different radii were analyzed using an existing MoM code paired with pole zero matching method developed at UNISI. The dispersion diagram and the impedance plot which were obtained are shown in Figs. 2.a. and b. From Fig. 2.a it is clearly seen how we can delay the wave propagating along this surface by changing the radius of the patches. This figure also shows the unit cell or single pixel of the considered array. Fig. 2.b plots the impedance of the array with respect to the radial wave number and patch radius showing which are the maximum obtainable values of impedances for certain cases. The parameters of the substrate used in this case are; permittivity ε_r = 10.2 and substrate thickness d = 0.7 mm. The considered frequency is 13 GHz.



(a)   *(b)*

Fig. 2. Dispersion diagram and the impedance plot of the circular patch array for different patch radii.

The knowledge about the behaviour of our array can be used in order to synthesize an impedance profile corresponding to a desired lens. In our case, the Luneburg lens was the objective.

2) Synthesizing a Luneburg lens inside a parallel plate waveguide

The Luneburg lens is defined by the following refraction index law [4]

$$n(\rho) = \sqrt{2 - \left(\frac{\rho}{R}\right)^2}, \tag{1}$$

where R is the lens radius and ρ is the radial coordinate. If excited in one focal point on one side it ensures a uniform phase wave front at the opposite side. In other words in an ideal case we can obtain a perfect planar wave using a lens with this refractive index profile and because of this property Luneburg lenses are quite extensively used in many focusing, radar or similar applications where a very narrow radiation beam is required.

Lunburg law gives a smooth variation of the refractive index which can be very well approximated using our approach with surface impedance modulation. The standard way to achieve this refractive index variation would be to realize the lens using a number of dielectric layers with slowly changing refractive index. However, such lenses are not easy to manufacture and are quite expensive. In our case it was possible to make the lens on a commercially available planar substrate using a standard printing technique, thus making this approach much more economically appealing.

To construct the lens we will have to confine the waves inside a parallel plate structure where one wall will be replaced with the impedance surface as shown in Fig. 3. If the z - direction is set as the direction of propagation the wave number in that direction can be written in the following way

$$k_z = \sqrt{k^2 - k_y^2} = k \cdot n_{eq}, \tag{2}$$

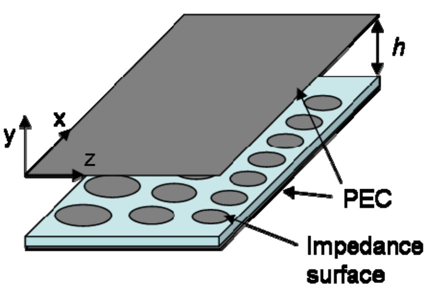


Fig. 3. Printed circular patches on a dielectric substrate inside a parallel-plate waveguide.

where k is the free space propagation constant and n_{eq} is the equivalent index of our desired medium (in our case it will correspond to the refractive index profile of the Luneburg lens). From this we see that k_z can be observed as being modulated by this equivalent refractive index. Furthermore, we have to confine ourselves to operation in the frequency range of the parallel-plate structure where only TMy mode can propagate, which leads to a relatively small structure height. Based on these assumptions and using the PEC boundary condition on the upper wall of the parallel-plate structure we can obtain the expression for the required impedance

$$Z_{TM} = j\frac{k_y}{\omega\varepsilon_0}\tan(k_y h). \tag{5}$$

Fig. 4. shows the plot of the refractive index and the calculated equivalent impedance profile for the Luneburg lens case where the waveguide height was chosen to be 1.8 mm.

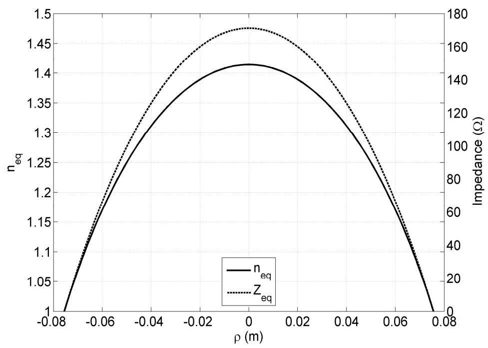


Fig. 4. Refractive index and impedance profile for the observed Luneburg lens case.

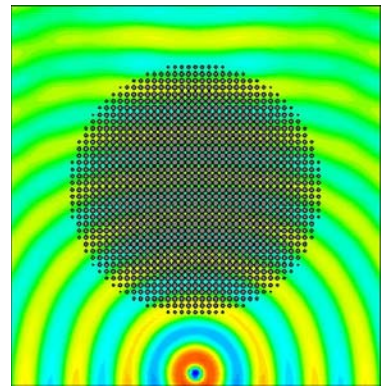


Fig. 5. An array of circular patches with the surface impedance profile corresponding to the Luneburg lens combined with the snapshot of the vertical E field excited by a small point source at the lens edge

The lens synthesized using this impedance profile is shown in Fig. 5. To obtain this array it was necessary to combine the information about the surface impedance obtainable with different patch radii (shown in Fig. 2.b.) with the nominal or desired profile shown in Fig. 4. Fig. 5. also shows the plot of the magnitude of the vertical *E* field that visualizes the Luneburg effect at the design frequency of 13 GHz (simulated using CST Microwave Studio [5] inside an infinite parallel-plate structure).

3) *Improving the characteristics of an H-plane horn antenna with the developed Luneburg lens*

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.

Fig. 6 shows the basic view of the new horn antenna with 20° flare angle. Also seen is the inserted part of the Luneburg lens realized using circular metallic patches (the substrate has the permittivity ε_r = 10.2, thickness d = 0.7 mm and the height of the waveguide is 1.8 mm). The upper metallic plate and the side walls are not shown in the figure. The lens and therefore the entire antenna are designed for the central frequency of 13 GHz with the diameter of 151.2 mm (this diameter corresponds also to the total length of the horn from the feed waveguide to the edge of the lens). Simulated results for this H-plane horn are shown in Fig. 7. together with the results for the normal H-plane horn with equal aperture size.

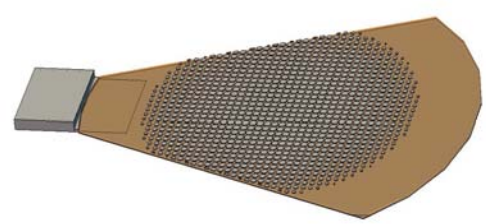
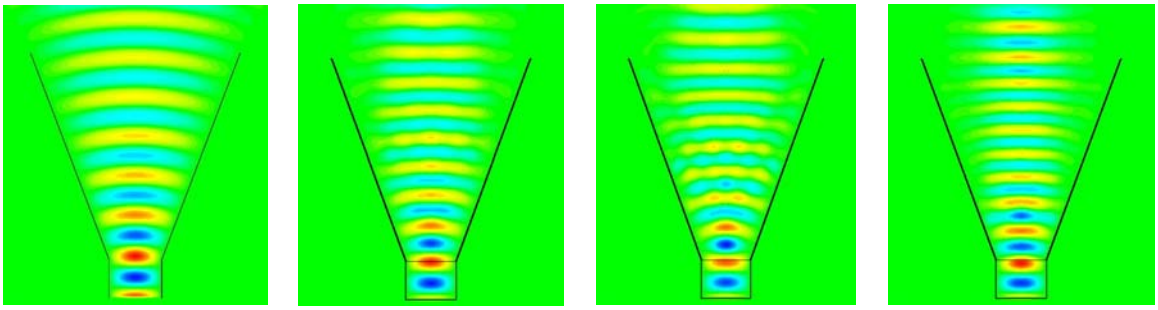


Fig. 6. Luneburg H-plane horn without the top and side metallic plates



(a) (b) (c) (d)

Fig. 7. Snapshots of the simulated vertical E field for; (a) equivalent normal H-plane horn at 13 GHz, (b) lens horn at 12.5 GHz, (c) lens horn at 13 GHz and (d) lens horn at 13.5 GHz.

As seen from the field snapshots, the lens incorporated into the horn structure ensures the uniform phasing at the aperture. The actual benefit from this is seen in the radiation pattern diagrams shown in Figs. 8 and 9. Fig. 8. shows the comparison between the new lens horn, normal horn with equal aperture and an optimized horn (optimized using standard techniques [6] for optimized horns using the aperture size as the reference point) of the same aperture. A small inset in this figure gives the comparison of the dimensions for these cases. Fig. 9. shows the comparison of the radiation patterns for our H-plane lens horn at different frequencies.

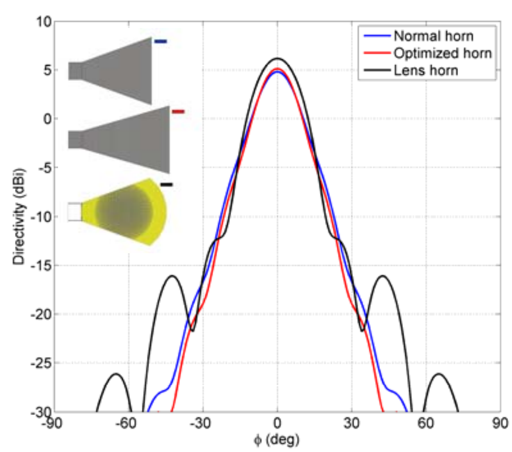


Fig. 8. Comparison of H plane radiation patterns at 13 GHz of the lens horn, simple 20° horn and optimal horn designed for the same aperture width.

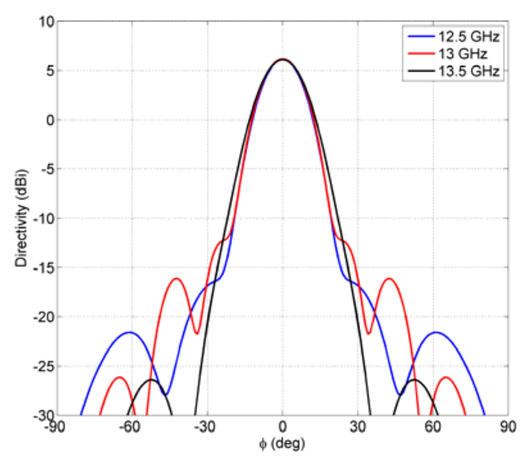


Fig. 9. Comparison of H plane radiation patterns for lens horn at different frequencies.

4) Optimization of the H-plane horn antenna

The results obtained using the Luneburg lens inside the H-plane horn showed promise (shown in Fig. 8.), however, the 1.5 dB difference in directivity which was obtained is not a significant gain in this case. It has to be pointed out that in the first case a large portion of the Luneburg lens was cut out due to the horn dimensions. It was reasonable to expect that much better results could be obtained if a larger portion of the lens was used as the horn antenna. For that reason we have considered a horn with a 40° flare angle.

The radiation pattern for that case is shown in Fig. 10. and compared to the optimized normal horn with the same aperture width. The difference in the directivity is again only 1.5 dB, but it is important to mention that for this case the optimized horn has a length of 266.4 mm, which is 115.2 mm (≈5λ) longer then the lens horn.

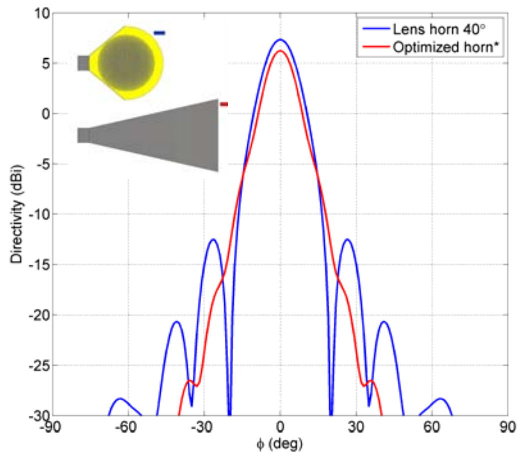


Fig. 10. Comparison of H plane radiation patterns at 13 GHz of the lens horn with a 40° flare angle and optimized horn designed for the same aperture width

It is important to mention that all of these results were obtained by simulation in infinite parallel-plate conditions using CST Microwave Studio. Furthermore, due to the fact that our H-plane horn has very small height, the field inside is strongly confined to the lens plate causing a certain level of mismatch at the boundary with open space. This mismatch naturally causes reflections which significantly disrupt the uniform field. To avoid the reflections, either a higher structure should be considered or certain tapering should be implemented in the lens design. Reasonably good results can be obtained using exponential tapering in such a way that the upper plate is bent upwards following the exponential law.

Finally, although the lens prototype was constructed during this exchange period, the metallic enclosure was not finished in time to perform the measurements. Nevertheless, with the first opportunity the measurements will be completed and included into the publications which are in preparation.

References

[1] "Special issue on metamaterials," *IEEE Trans. On Antennas and Propagation*, vol. 51, no.10, pt.1, Oct. 2003.

[2] D. Sievenpiper, L. Zhang, F.J. Broas, N.G. Alexopulos and E. Yablonovitch, "High-impedance electromagnetic surfaces with a forbidden frequency band," *IEEE Trans. On Microwave Theory and Techniques*, vol. 47, no.11, pp. 2059-2074, Nov. 1999.

[3] 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.

[4] R. K. Luneburg, Mathematical Theory of Optics. Brown Univ. Press 1944.

[5] CST Microwave Studio 2010, www.cst.com

[6] C. A. Balanis, Antenna Theory: Analysis and Design, Wiley-Interscience; 3 ed., February 2005.

Future collaboration with host institution

As mentioned in the final remarks of the previous section, since the measurements were not completed in time they will be performed in very near future at the University of Siena. Furthermore, several alternative designs for antennas using the surface modulation concept were also considered during this period and their development will be continued in collaboration with the host institution.

Projected publications/articles resulting from the grant

During the exchange period two conference articles were prepared and submitted to international conferences. They will be forwarded to the NEWFOCUS office as soon as the acceptance confirmation is received from the organizers. Furthermore, also one more elaborate journal paper is in preparation.