Planoconcave lens by negative refraction of stacked subwavelength hole arrays

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Abstract: This work presents the design of a planoconcave parabolic negative index metamaterial lens operating at millimeter wavelengths fabricated by using stacked subwavelength hole arrays. A staircase approximation to the ideal parabola profile has been done by removing step by step one lattice in each dimension of the transversal section. Theory predicts power concentration at the focal point of the parabola when the refractive index equals -1. Both simulation and measurement results exhibit an excellent agreement and an asymmetrical focus has been observed. The possibility to design similar planoconcave devices in the terahertz and optical wavelengths could be a reality in the near future.

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OCIS codes: (999.9999) Left-handed Metamaterials; (999.9999) Negative Refraction; (999.9999) Extraordinary Transmission.

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1. Introduction

The pioneering work of Veselago [1] predicted that a medium with permittivity and permeability simultaneously negative exhibits unconventional properties such as a Negative Refractive Index (NRI), thus leading to the opposite Snell's refraction law at the interface between a standard and a NRI medium, among other interesting properties.

He also foresaw that a simple slab of thickness *d*, made of a metamaterial having refractive index *n* = - 1, can focus in a point the radiation of a point emitter placed at a distance *l* < *d* from the slab, see [1]. Later, based upon the previous concept, Pendry showed that one of the remarkable properties of such a planar slab is its ability to act as a perfect lens [2], focusing beyond the diffraction limits of propagating waves, through the amplification of the evanescent waves.

Following Veselago's words, this is not a usual lens because it is not able to focus a bundle of rays coming from infinity in a point [1] and, as in conventional lenses, it is necessary to engineer its geometrical profile. An important consequence of metamaterial lenses with refractive index *n* = - 1, is the interchange of roles between convex and concave lenses, see [1].

Since the first experimental confirmation by Smith's group [3] of a NRI medium at microwaves using arrays of metallic wires to get negative dielectric permittivity [4], mixed with arrays of split rings resonators (SRRs) to obtain negative magnetic permeability [5], several attempts have been done to achieve such geometrically profiled lenses. For instance, planoconcave lenses exhibiting negative index of refraction have been built using negative index metamaterials [6] and photonic crystals with constant index of refraction [7-8]. Even, RF lenses with gradient index of refraction have been reported in several works: without any geometrical profiles [9], and also with cylindrical geometry [10,11]. Lastly, at microwave frequencies, spherical negative index metamaterial lenses with physical curvature and flat gradient index of refraction lenses [12] have been proven.

One of today most important challenges are low-loss metamaterials exhibiting a Negative Refractive Index (NRI) at optical frequencies [13]. This possibility has been opened by the fabrication of metamaterials in a pair of subwavelength hole arrays drilled in very thin metallic plates [14,15]. Nevertheless, losses are still a serious drawback in these structures. Similar results have been observed in the millimeter wave range [16] where losses are inherently much lower since metals behave nearly as Perfect Conductors in this range. Moreover, losses have been further minimized due to the use of properly engineered stacked subwavelength hole arrays under Extraordinary Optical Transmission (EOT) [16].

The EOT property can open the way to a novel design procedure of low-loss NRI media at microwave, terahertz, and even optical wavelengths. EOT consists in high transmittance peaks

in the holes cut-off region and it is caused by surface plasmons in optics [17], but it also appears at microwaves [18] although metals here are nearly perfect conductors and therefore do not support plasmons. The explanation is that perforated metallic films support surface waves which somehow mimic surface plasmons [19]. A further refinement to reduce losses can be achieved by constructing a double periodicity in the subwavelength hole array. This increases the hole density and allows to operate in the Fresnel zone of the structure [20]. Very recently, a straightforward pure geometrical and experimental demonstration of a low-loss negative refraction structure in the millimeter wave band has been done by using a metamaterial prism made of the above described structures [21].

In this paper, we report a planoconcave parabolic NRI metamaterial lens operating at millimeter wavelengths designed by using stacked subwavelength hole arrays as a route to achieve the negative index metamaterial. In fact, we are currently developing stacked subwavelength hole arrays made of a very thin metallic layer with the requested subwavelength hole array pattern over a thin dielectric layer exhibiting very low losses at the operating wavelength. We expect to report challenging results at the terahertz in the near future. Besides, there have been also theoretical suggestions for infrared and optical metamaterials which can be fabricated with existing colloidal-chemistry techniques [22,23].

The results could open the route for the design of similar planoconcave devices in the terahertz and optical wavelengths.
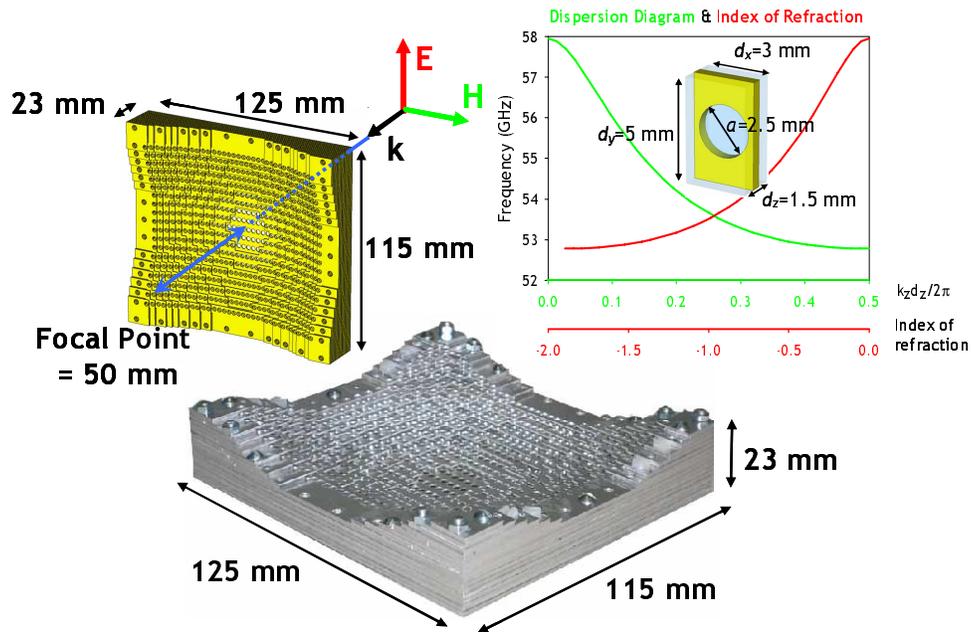
Fig. 1. (top left) Sketch with the step by step stair-case fabrication of the planoconcave lens with parameters, $a = 2.5$ mm, $d_x = 3$ mm, $d_y = 5$ mm, and $d_z = 1.5$ mm, (bottom) a picture of the real prototype and (top right) the corresponding longitudinal dispersion diagram for this structure.
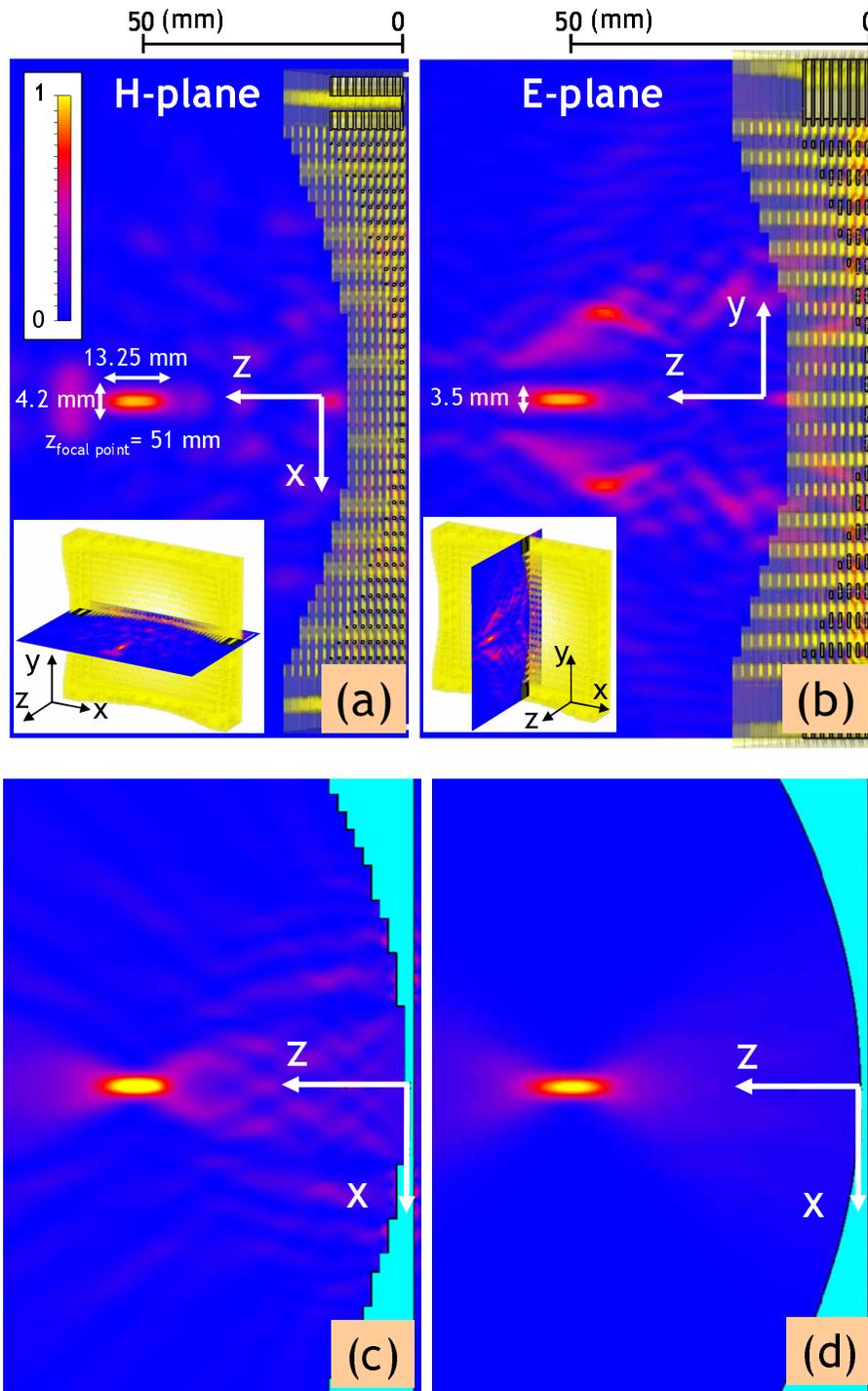
Fig. 2. Simulated power density evolution along (a) *x-z* and (b) *y-z* planes when a plane wave is impinging on the planoconcave lens at 53.5 GHz. Note that the power is focused at 50 mm. (c) Staircase approximation of a planoconcave parabolic lens with homogeneous material of refractive index n = -1. (d) Ideal planoconcave parabolic lens.

2. Design of the Planoconcave Lens made of Stacked Subwavelength Hole Arrays.

As it is well known, a parabolic-shaped mirror has the property of focusing all the incident parallel rays on a point called focus of the parabola. Reciprocally, also all the rays emitted by a point source located on the focus are reflected by the parabolic mirror in a set of parallel rays.

Following the usual formalism of geometrical optics, the reflection is usually described as being a material with refractive index $n = -1$ [24]. This is an advantageous interpretation in order to study reflection as the equivalent refraction on an idealized material, a mere mathematical tool.

However, with the incoming of the metamaterials formalism this abstract idea can be seen to take a real form. In fact, when shaping with a parabola the interface of a standard medium, say air with $n = 1$, and a NRI medium with $n = -1$, and using as a emitter a point source on the focus of the parabola, the rays emerging from the source diverge as spherical waves until they reach the interface. Then, applying Snell's law, the rays propagate parallel in the metamaterial. In the particular case when there is impedance matching between the two media, waves can traverse the surface without any reflection. Furthermore, it is well known that planar NRI slabs are not capable to focus a plane wave due to the fact that a negative angle of refraction only occurs under oblique incidence. Therefore, to produce such focusing a curved profile of the lens is compulsive. Note that for positive index media, one can focus (diverge) a plane wave by using a convex (concave) lens. By contrast, for NRI media, the focusing (divergence) of a plane wave is produced by means of a concave (convex) lens [1,25].

The analysis and design of such a lens can be done in two steps by using the CST Microwave Studio^{TM} code, which is based upon the Finite Integration Time Domain Method. Firstly, thanks to the eigenmode solver of the code, the dispersion diagram is calculated and secondly, the field and power densities evolution when the structure is excited by a plane wave can be easily computed allowing one to gain physical insight on the behavior of these structures.

Taking advantage of previous numerical simulations of the structure dispersion diagram, see the inset of Fig. 1 [21], it follows that a first band of the stacked sub-wavelength hole array structure emerges around the EOT frequency and it clearly shows a negative slope, i.e. phase velocity opposite to the group velocity. It has to be noted that the dispersion diagram computation has been limited to the perfect conductor case since we found experimentally in a previous work that this structure suffers moderate losses levels at 60 GHz [16], as well as we face simpler computational effort. In this way we deal with an artificial media that exhibits negative refraction. It also has to be noted that the implicit frequency variation causes dispersion in the structure which limits its useful bandwidth and causes chromatic aberration.

The planoconcave lens is designed to exhibit a negative index of refraction $n = -1$ at the EOT frequency of subwavelength perforated plates with the following parameters: hole diameter $a = 2.5$ mm, $d_x = 3$ mm, $d_y = 5$ mm, metal thickness $w = 0.5$ mm, $f_{EOT} = 53.5$ GHz as it is explained in [21]. The whole structure, including the frame for the assembly, has maximum dimensions of 125 mm × 115 mm × 22.5 mm.

The geometrical profile is achieved when one removes step by step one lattice in each dimension of the transversal section to form a parabolic shape with nearly revolution symmetry, see Fig. 1. This results in a staircase approximation of the ideal parabola. The fabricated prototype has been designed to have a focal length $f = 50$ mm, i.e., the focus is centered at a distance of 27.5 mm from the nearest transversal plane of the lens. Therefore, we are working in the near-field region.

In the next step, the structure is excited by a plane wave impinging on the planar face. In Fig. 2 is depicted the evolution of the power density in the planoconcave lens along the x-z (panel (a)) and y-z (panel (b)) cutting planes (where the radiation pattern is recorded in the experiment) at 53.5 GHz where the dispersion diagram predicts n = -1. Notice the clear power concentration observed at 51 mm, the focus location predicted by geometrical optics. As it can

be seen in the power plot (panel (a)) the focus is very narrow in the x direction but more extended in the z direction probably due in part to the staircase approximation to the ideal parabolic shape and also to the high level of anisotropy exhibited in this metamaterial, see [20,21]. Also, the focus is less defined along the y direction, although the main spot is also very narrow there as panel (b) shows. This fact could be expected considering the less accurate parabolic shape due to the larger hole array period in that direction necessary to excite EOT resonance.

To verify this fact, in Fig. 2, panels (c) and (d) show the simulation of the power density distribution for the case of a planoconcave parabolic lens made of an homogeneous metamaterial having refraction index n = -1 when it is excited by a plane wave impinging over the planar face of the lens. Firstly, we have computed the case of the staircase approximation of the parabolic profile, see panel (c), and, second, the ideal parabolic profile in panel (d). To reduce the computational cost we have limited to the two dimensional problem in panels (c) and (d). From the observation of panels (c) and (d) one can deduce that the effect of the staircase approximation in the parabolic profile causes a noticeable effect on the focus quality. This result can be deduced from Fourier optics principles, see [26].

3. Experimental results.

Employing an AB Millimetre™ quasioptical vector network analyzer, the evolution of the received radiated power was recorded along the H- (or x-z) and E- (or y-z) cutting planes $f =$ 53.5 GHz (wavelength 5.61 mm) where negative refraction has already been demonstrated in this structure [21]. Illumination at the input and power scanning at the output were done by employing two identical corrugated horn antennas. The emitter is fixed at 900 mm from the planar face of the lens and the focal region of the concave lens face was scanned with the receiver in the two principal planes at four different axial distances: z = 35, 40, 50, 75 mm.

The measurement results are presented in Fig. 3. From these results, it follows that an asymmetrical focus emerges. At all the considered distances, the focus is narrower in the H-plane (panel (a)) than in the E-plane (panel (b)), in concordance with the predicted results of Fig. 2. The longitudinal focus dimension can be evaluated looking at the maxima of each curve in Fig. 3. It follows that the focus along this dimension is larger than the simulation prediction, probably due to the inherent limitations of our experimental set-up. In fact, the horn antenna cannot resolve a point focus; rather it performs an integration of power along its longitudinal dimension.

Besides, the transmitted power enhancement achieved with the lens was measured applying the next equation:

$$T_{enh} = 10\log\left(\frac{P_{R\_lens}}{P_{R\_free-space}}\right)(\text{dB})$$

where P_{R_lens} is the power received with the lens and $P_{R\_free-space}$ is the power received when only the two horn antennas are present.

Following this method the measured lens enhancement is 3 dB. This relatively high value is probably obtained thanks to the low loss level of stacked subwavelength hole arrays as it has been proven at 50 GHz in [16,20] . This result is consistent with the 5 dB measured at 15 GHz in [12] using a metamaterial parabolic lens constructed with SRRs and wires. Notice that in [12] the authors measure the far-field gain. In our case we are within the Fresnel Zone region and, therefore, the concept of gain becomes ambiguous. Probably, an attempt to increase the operation frequency following the strategy of Ref. 12 would lead to inacceptable losses associated to the degradation of SRRs characteristics. As presented here, the inherent low losses of stacked hole arrays alleviate this constraint.

Further efforts are under development in order to correct the observed deviations from the ideal response of the proposed lens. In any way, the results presented in this paper open the

possibility to design planoconcave negative refraction lenses based upon stacked subwavelength hole arrays at terahertz and optical wavelengths.
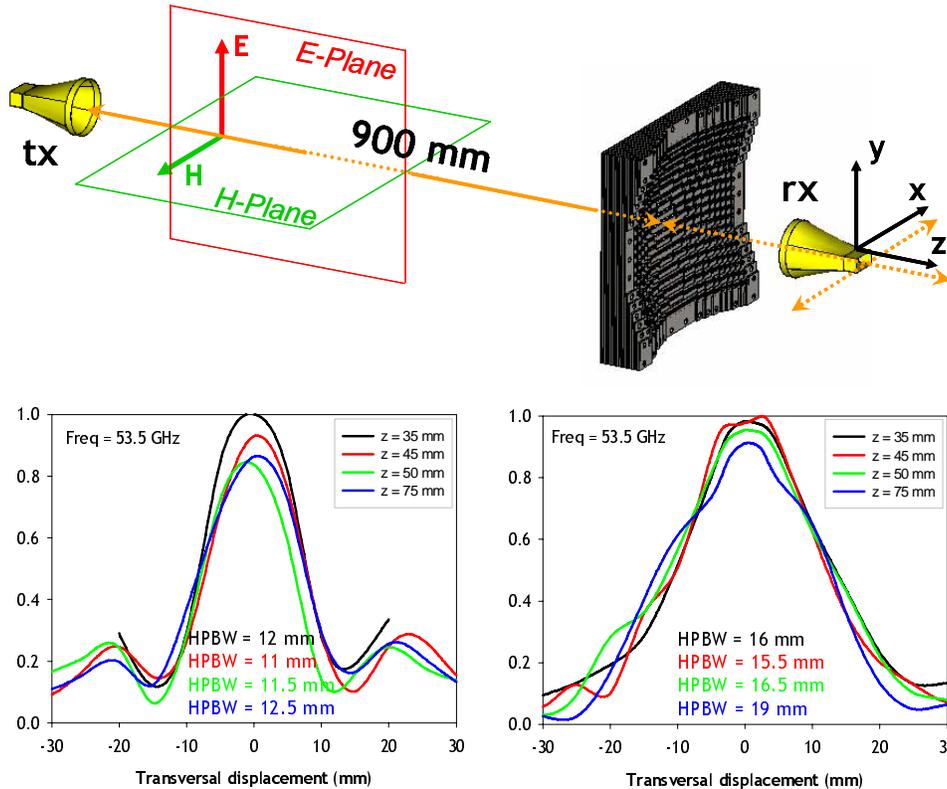
Fig. 3. Sketch of the experimental set-up. Measurements of the planoconcave lens constructed by stacked subwavelength hole arrays along the H-plane (left) and E-plane (right).

5. Conclusion

A planoconcave parabolic negative index metamaterial lens operating at millimeter wavelengths has been designed by using stacked subwavelength hole arrays as a route to achieve the negative index metamaterial. The design has been done following a staircase approximation of the ideal parabola profile by removing step by step one lattice in each dimension of the transversal section to form the aimed parabolic section. Simulation and measurement results are in good agreement and they show an asymmetrical focus. Improvements over the gain as well as the asymmetry can be the key factors in determining whether it is possible to deliver a negative refraction stacked subwavelength hole array lens for practical applications. The result could open the route for the design of similar planoconcave devices in the terahertz and optical wavelengths.

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