Hindawi
International Journal of Antennas and Propagation
Volume 2018, Article ID 9461858, 8 pages
https://doi.org/10.1155/2018/9461858

Research Article

Phase Reversal Technique Applied to Fishnet Metalenses

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Received 13 April 2018; Revised 2 July 2018; Accepted 11 July 2018; Published 26 August 2018

Academic Editor: Shah Nawaz Burokur

In this work, the fishnet metamaterial is applied to several converging metalenses by combining the zoning, reference phase, and phase reversal techniques. First, the zoning and reference phase techniques are implemented in several metalenses at 55 GHz ($\lambda_0 = 5.45$ mm) with a short focal length of $1.5\,\lambda_0$. Then, the phase reversal technique is applied to these metalenses by switching from a concave to a convex profile in order to change the phase distribution inside of them. The designs are evaluated both numerically and experimentally demonstrating that chromatic dispersion (the shift of the position of the focus at different frequencies) is reduced when using the phase-reversed profiles. It is shown how the position of the focus remains at the same location within a relatively broadband frequency range of ~4% around the design frequency without affecting the overall behaviour of the metalenses. The best performance is achieved with the design that combines both reference phase and phase reversal techniques, with an experimental position of the focus of $1.75\,\lambda_0$, reduced side lobes, and a power enhancement of 6.5 dB. The metalenses designed here may find applications in situations where a wideband response and low side lobes are required because of the reduced chromatic aberrations of the focus.

1. Introduction

Metamaterials (MTMs) are artificial structures engineered to get control of light propagation beyond the possibilities offered by natural materials [1–4]. One of the first groundbreaking applications of metamaterials was the perfect lens proposed by Pendry in 2000 [5], and since then, many other enhanced focusing devices have been proposed and implemented showing the benefits of applying MTMs within the entire electromagnetic (EM) spectrum. Some of the milestones in this discipline are superlenses and hyperbolic lenses [6, 7], superocillatory lenses [8–10], advanced designs following transformation optics techniques [11–14], and even focusing devices based on extreme refractive index values [15–21]. Several techniques have been proposed to fulfill the specific needs of each spectral window. For instance, the classical arrangement of SRR and wires has been widely used for lenses operating at microwaves [22, 23]. However, for higher frequencies, these structures are limited due to their increasing losses.

Among the large numbers of MTM structures reported in the past years, the fishnet has proven to provide a good performance for high-frequency and quasioptical applications [24–30]. It has been demonstrated that by designing a free-standing fishnet MTM with two in-plane periods, a very low-loss structure can be fabricated in the millimeter wave range [31, 32]. In addition, through manipulation of permittivity (ε) and permeability (μ), a plano-concave lens with good (ideally perfect) matching to free space can be obtained [33, 34].

A major drawback of the abovementioned lenses is the large volume occupied by the lens that leads to a considerable

weight of the structure. To mitigate this problem, one can apply the zoning technique whereby parts of the lens are removed when their phase variation with respect to free-space propagation is an integer multiple of 2π [35–37]. This has been done in the past with the fishnet metalens reducing the concave profile significantly without penalizing seriously the performance [38–40]. More sophisticated techniques borrowed from Fresnel lenses can be proposed to enhance the performance of the zoned fishnet metalenses such as application of a positive reference phase to reduce side lobes [41, 42].

In this paper, we continue this study by changing the typical concave profile to a convex profile; that is, we aim to evaluate the performance when the phase distribution inside the lens is reversed compared to the designs shown in [42]. In a previous letter [42], we showed that the best performance is achieved when a positive reference phase is used. In the present manuscript, we show the design and numerical and experimental results of two different convex profiles with a focal length (FL) of $1.5\,\lambda_0$ using $q = 0$ and $q = 0.35$ at a millimeter wave frequency of 55 GHz. As it will be demonstrated, the zoning technique along with the reference phase is used for the designs [41, 42]. The difference in the present work is that we aim to evaluate the performance of the lenses when the phase reversal technique is also applied. This is done by reversing the phase distribution inside of the lenses and changing its profile from concave to convex. Hence, the designed metamaterial lenses consist of a combination of the three techniques: zoning, reference phase, and phase reversal. As it will be shown, by reversing the profile of the metalenses, the chromatic aberration (i.e., the shift of position of the focal length (FL) at different frequencies around the designed one) is reduced, as compared to the concave profiles. Moreover, a relatively broadband operational frequency range of ~4% around the design frequency is achieved.

2. Design and Dispersion Diagram Results

The metalenses considered here use both the zoning technique and the reference phase. These were already explained in detail in [42], but the basics are briefly exposed here for completeness. The zoning technique consists in reducing the lens profile for a phase advance of 2π; that is, every time the lens thickness reaches a maximum value $t = \lambda_0/(1 - n_{\text{lens}})$, where λ_0 is the operation wavelength in free space and n_{lens} is the effective refractive index of the lens.

With the reference phase, an extra phase advance is allowed inside the lens [43, 44]. This additional phase is modulated between 0 and 2π, giving as a result a total phase that varies within the range [0–4π]. This means that the lens thickness has an increment compared to that of a lens without a reference phase that can be calculated as

$$\Delta t = q\frac{\lambda_0}{1 - n_{\text{lens}}}, \tag{1}$$

where Δt is the additional thickness due to the reference phase technique and q is a factor between 0 and 1 that corresponds to an extra phase advance from 0 to 2π. So, for a lens with simultaneous zoning and reference phase techniques, the profile is reduced when a thickness $t_{\text{total}} = \Delta t + t$ is reached. Finally, the profile of the metalens is then

$$z = \text{mod}\left[\frac{\text{FL}(1 - n_{\text{lens}}) - \sqrt{\text{FL}^2(1 - n_{\text{lens}})^2 - x^2(1 - n_{\text{lens}})}}{1 - n_{\text{lens}}^2}\right],$$
$$t_{\text{total}} = t(q + 1), \tag{2}$$

where mod is the modulo operation.

The unit cell employed is the same as the one used in our previous paper [42] and is reproduced in the inset of Figure 1(a) for completeness. Its dimensions are $w = 0.35$ m m, $d_x = 3$ mm, $d_y = 5$ mm, $d_z = 1.35$ mm, and $a = 2.4$ mm. The metal layers are made of copper with conductivity $\sigma_{\text{Cu}} = 5.8 \times 10^7$ S/m and are separated by an air layer of thickness 1 mm ($d_z - w$). With these parameters, the effective refractive index of an infinite array of such unit cells was calculated using the Eigenmode solver of the commercial software CST Microwave Studio®. The results are shown in Figure 1(a).

From these results, we select an operation frequency of 55 GHz because it falls in the range where n_{lens} has a smooth variation so that the design is less sensitive to manufacturing tolerances and alignment. At this frequency, the refractive index has a magnitude $|n_{\text{lens}}| = 0.68$ which is a good trade-off because, according to (1), for very small $|n_{\text{lens}}|$, the first zone would be very thick. Moreover, since we are dealing with a small focal length (FL), from (2), the first zone is narrower and the lens profile becomes more abrupt. Therefore, we would need a narrower unit cell (along the x-axis, d_x) to discretize properly the lens profile.

Taking into account these factors, two metalenses were designed: without ($q = 0$, Figure 1(b)) and with ($q = 0.35$, Figure 1(c)) a reference phase. Due to the application of the phase reversal technique, the regions with air and the fishnet MTM are exchanged, and hence convex profiles are obtained. Notice that when $q = 0$, only the phase reversal is applied to the metalens and when $q = 0.35$, both the reference phase and phase reversal techniques are applied.

3. Results and Discussion

The focusing performance of the metalenses was evaluated both numerically and experimentally. The numerical simulations were carried out using the transient solver of CST Microwave Studio. In the first study, the focal position and the operation frequency in the numerical simulations were found by exciting the lens with a plane wave (with linear polarization, E_y) impinging normally on the flat face and recording the spectra at the output along the z-axis by means of point electric field probes. They were located at 0.2 mm $< z <$ 20 mm with a step of 0.2 mm in order to accurately record the electric field along the propagation axis. The experimental characterization was performed using an ABmm™ VNA operating in the V-band of millimeter waves. The experimental setup is shown in Figure 2(a). A high gain

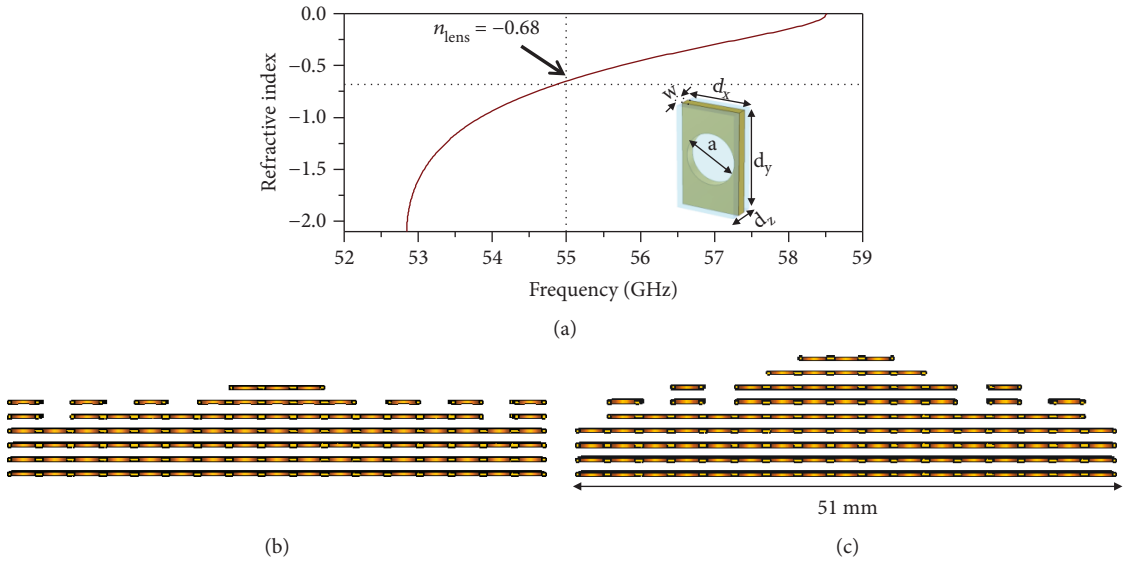

FIGURE 1: Dispersion diagram of the unit cell and profiles of the metalenses. (a) Refractive index of the fishnet structure used to design the lenses, assuming it to be infinitely periodic. Unit cell (inset) with dimensions: $d_x = 3$ mm, $d_y = 5$ mm, $d_z = 1.35$ mm, and $a = 2.4$ mm. The thickness of the metal is $w = 0.35$ mm. Top view of the schematic representation of the reversed-phase zoned fishnet metalenses with (b) $q = 0$ and (c) $q = 0.35$.

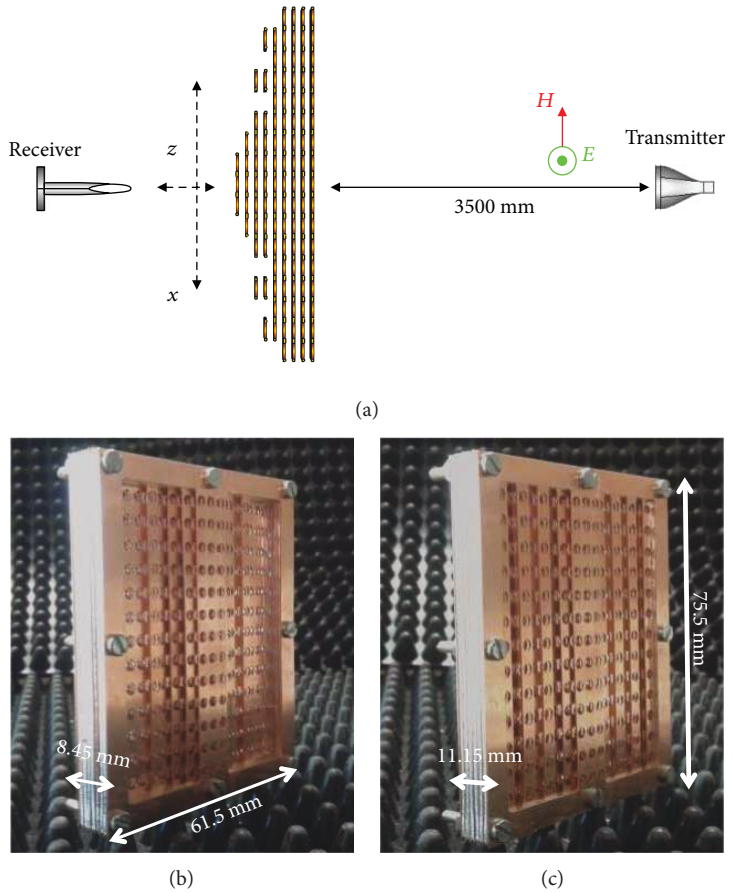

FIGURE 2: Fabricated prototypes. (a) Sketch of the experimental setup used for characterizing the metalenses. Photographs of the fabricated metalenses with (b) $q = 0$ and (c) $q = 0.35$, both with the phase reversal technique.

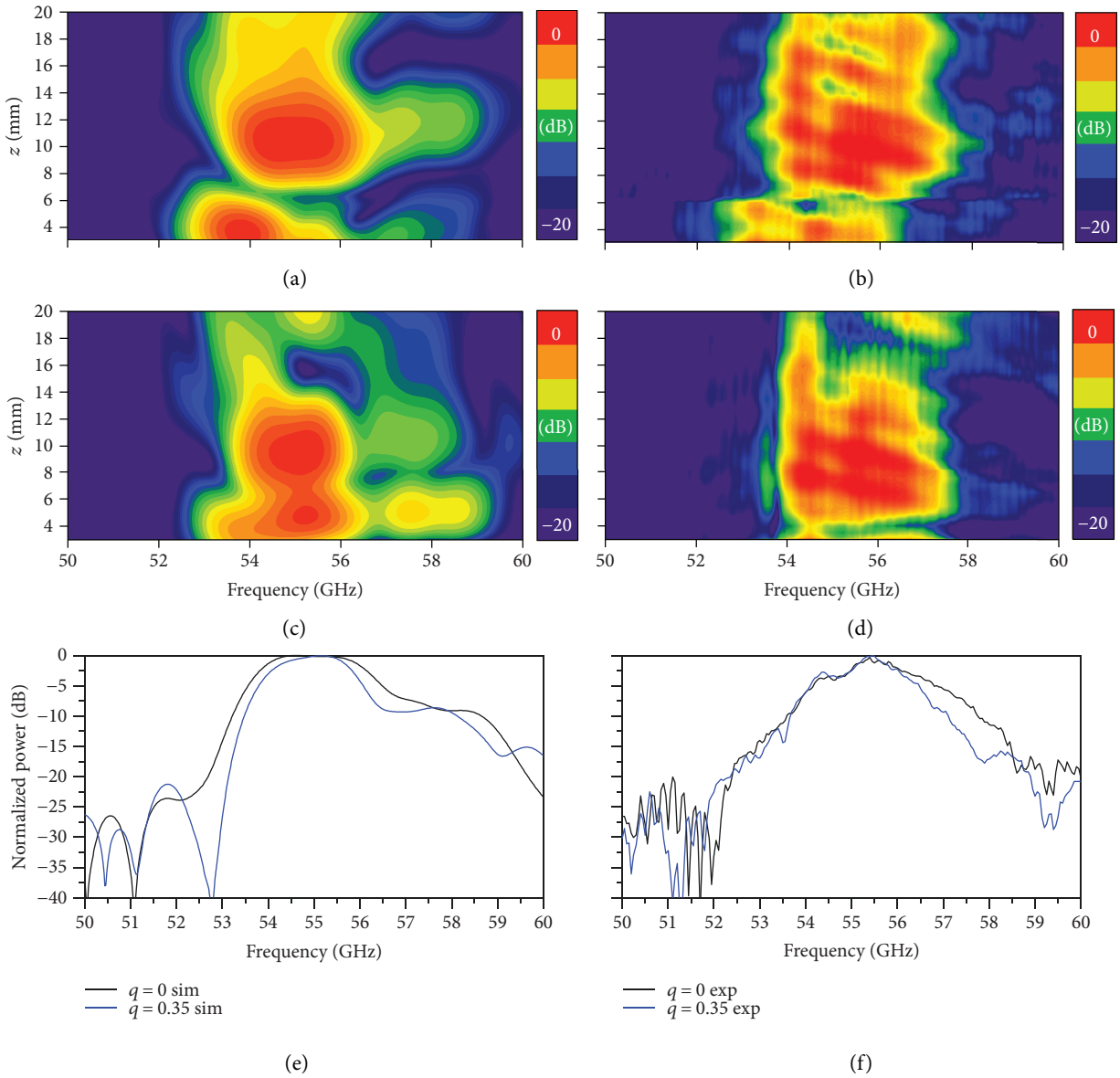

FIGURE 3: Spectral response. Numerical (a, c) and experimental results (b, d) of the power distribution spectra along the propagation z-axis for the phase reversal designs with $q = 0$ (a, b) and $q = 0.35$ (c, d). The simulation and experimental results of the spectral response of power distribution at each FL are shown in (e) and (f), respectively.

horn antenna was used as a transmitter. It was placed at 3500 mm from the flat face of the metalenses to ensure a uniform illumination. The transmitted power was scanned with an open-ended waveguide probe located on a translation stage to record the spectral response of the metalenses at each z position and determine both the position of the focus and the operation frequency. The photographs of the fabricated metalenses and their whole dimensions are presented in Figures 2(b) and 2(c) for the prototypes with $q = 0$ and $q = 0.35$, respectively. Note that they have the same thickness as the concave structures shown in [42] as expected because we have only exchanged the air-metal regions which results in a fixed volume of metalenses. Both lenses have 17×13 holes in the transversal plane $(x \times y)$, with total dimensions of 61.5 mm × 75.5 mm (including the frame). As discussed in [26, 42], the number of plates at the input are critical to reproduce the refractive index of the infinite structure given that we are operating in the limit where n_{lens} has abrupt or smooth variations. Based on this, in the central part of the metalenses, we placed four plates with holes to have a performance similar to that of the ideal infinite fishnet MTM.

With this configuration, the results (numerical and experimental) of the normalized power distribution spectra along the z-axis for each design are shown in Figures 3(a)–3(d), respectively. In general, a good agreement is observed. Note that with these designs, the

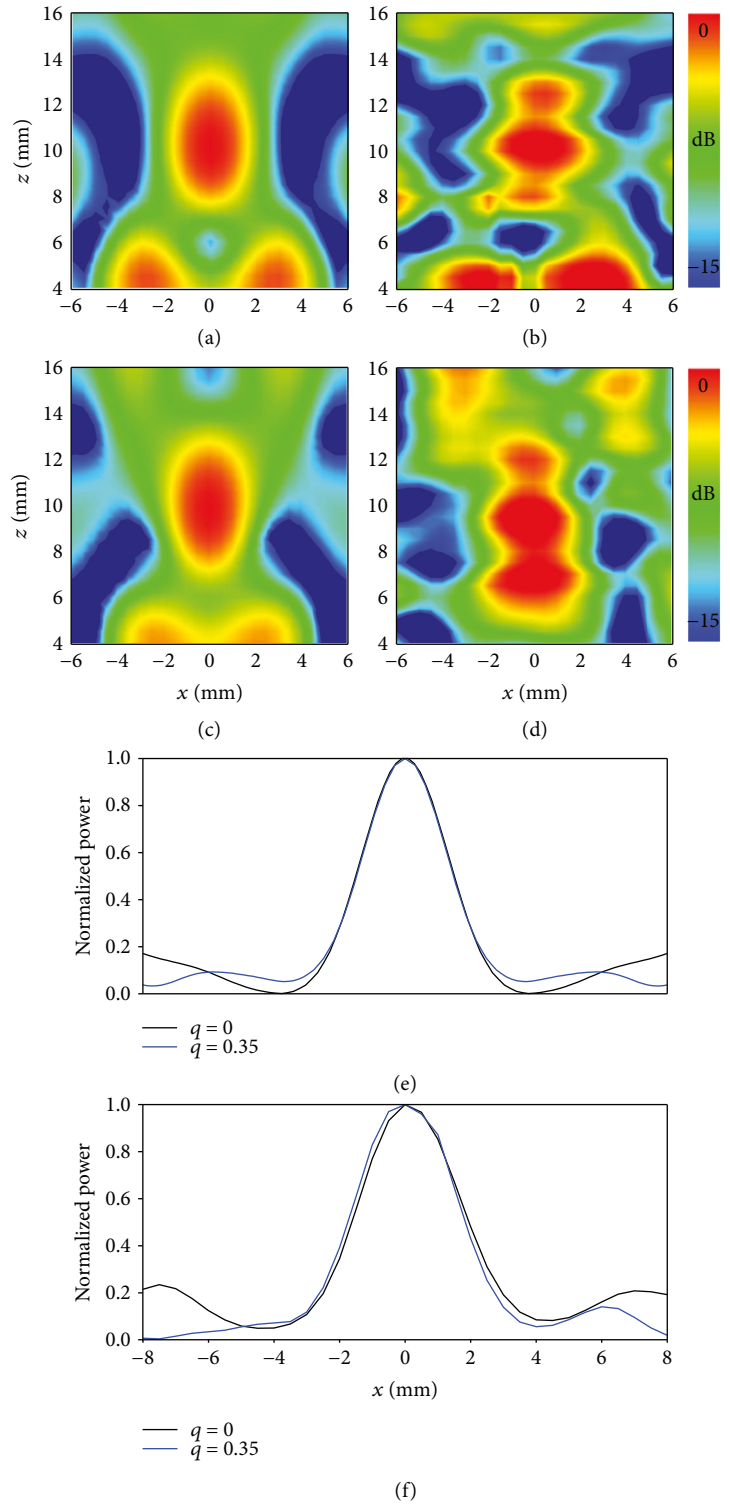

FIGURE 4: Focusing performance. Numerical (a, c, e) and experimental results (b, d, f) of the power distribution in the xz plane (H-plane) for the designs with phase reversal and reference phase with a value of $q = 0$ (a, b) and $q = 0.35$ (c, d). Numerical (e) and experimental (f) values of the normalized power along the transversal x-axis at each FL for the prototypes with phase reversal and $q = 0$ (black) and $q = 0.35$ (blue).

chromatic dispersion is reduced (i.e., the shifting of the focus when changing the operational frequency), as compared with the concave profiles, with the focus emerging at the same position even when the frequency is changed from 54 to 56 GHz which is a relatively broad bandwidth of 2 GHz (~4%) considering the intrinsic narrow band response of the fishnet MTM [33, 45, 46]. Moreover, in the simulation, the peak of maximum power (focus) appears at the operation frequency (55 GHz) with FL = 10.25 mm ($1.87\,\lambda_0$) and FL = 9.8 mm ($1.79\,\lambda_0$) for $q = 0$

Table 1: Results of the focusing properties of the metalenses with reference phase and phase reversal. The experimental and numerical values are given at frequencies of 55.5 GHz and 55 GHz, respectively.

	$q = 0$		$q = 0.35$	
	Sim	Exp	Sim	Exp
FL	1.87 λ_0	1.94 λ_0	1.79 λ_0	1.75 λ_0
FWHMx	0.55 λ_0	0.555 λ_0	0.54 λ_0	0.55 λ_0
DF	0.93 λ_0	0.925 λ_0	0.94 λ_0	0.97 λ_0
Enh	5.7 dB	4.5 dB	8.2 dB	6.5 dB

and $q = 0.35$, respectively. In the experiment, the focus appears at 55.5 GHz with a FL = 10.5 mm (1.94 λ_0) and FL = 9.5 mm (1.75 λ_0), for each design, respectively. The slight deviation of the FL, ~0.3 λ_0 from the designed value (1.5 λ_0), along with the small frequency deviation (0.9%) in all the metalenses could be attributed to experimental misalignments and fabrication tolerances. Additionally, this small error could be due to the fact that the waves emerging from the furthest zones (along the x-axis) of a convex profile reach the focal plane at different positions along the z-axis, that is, spherical aberrations of the lens. However, we can consider that this deviation is small taking into account that the FL for each metalens is close to the design value. For the sake of completeness, the numerical and experimental results of the power distribution spectra at each FL are shown in Figures 3(e) and 3(f), respectively, demonstrating that the operational bandwidth is increased with these designs compared with the concave profiles.

For the sake of completeness, the impedance matching between the lenses and free space was numerically evaluated using the frequency domain solver of the commercial software CST Microwave Studio (not shown). In this study, the fishnet metamaterial was modeled using an infinite array of holes along the x- and y-axes considering 9 perforated plates along the propagation z-axis (which corresponds to the maximum number of plates used in the proposed lenses as shown in Figure 1). The effective ε and μ and normalized impedance η of the fishnet metamaterial were calculated from the S-parameters, giving as a result Re $\{\varepsilon\} = -0.7$, Re $\{\mu\} = -0.38$, and $\eta = 0.75$ at the operation frequency of 55 GHz. Note that despite the fact that the proposed lenses are not perfectly matched with free space ($\eta = 1$), small reflections are still expected.

In the next study, the power distribution in the xz plane at the operation frequency and FL position for each metalens is found. In the simulation analysis, the results were found by defining a power density monitor at the operation frequency. In the experiment, a similar procedure was carried out to measure the focal plane: the receiving probe was placed on a translation stage and then moved from −6 to 6 mm and from 4 to 16 mm along the x-axis and z-axis with a step of 0.25 mm at the operation frequency. The results are shown in Figure 4. For the naked eye, the good agreement between both results with a clear focus produced by each structure is evident. To better compare the focal properties, the numerical and experimental values of the power distribution along the transversal axis at each FL are presented in Figures 4(e) and 4(f), respectively, where again a good agreement is observed. Moreover, it is shown that the lateral lobes in the focal plane are reduced when $q = 0.35$ and the phase reversal technique is used, as expected [42]. A summary of the focal properties of these metalenses is shown in Table 1 in terms of the full width at half maximum (FWHM), FL, depth of focus along the z-axis (DF), and power enhancement at the FL.

As it is shown, the best performance is obtained for the design with $q = 0.35$ and phase reversal with a higher power enhancement, reduced FWHM, and an FL closer to the design value. By comparing these results with the concave counterparts [42], the metalenses with phase reversal suffer from spherical aberrations because the DF is increased compared with that in the concave structures, as explained before. However, these results demonstrate that convex metalenses with small FL can be also designed using the fishnet MTM. Moreover, they can be used in applications where a wideband response is needed due to the fact that these designs have a reduced chromatic aberration of the FL.

4. Conclusions

The profile of the zoned fishnet metalenses using the reference phase technique has been changed from a concave profile to a convex profile in order to evaluate their performance when the phase distribution inside of them is reversed. From the results of the spectral response, it has been shown that the chromatic dispersion is reduced with the reversed convex fishnet metalenses compared with the concave profiles. In this respect, it has been demonstrated that the position of the focus does not change for a relatively broadband frequency range of ~4% around the design frequency (considering the intrinsic narrow band response of the fishnet metamaterial) without affecting the overall performance of the metalenses. The best performance in terms of the power enhancement, reduced FWHM, and FL close to the design value has been achieved with the design with $q = 0.35$ which combines both the reference phase and phase reversal techniques. The metalenses designed here may find applications where a wideband response and low side lobes are needed due to the reduced chromatic aberrations of the focus.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

Acknowledgments

The authors would like to thank Dr. V. Torres for the fabrication of the prototypes. This communication is based on the research conducted within the PhD thesis developed by Victor Pacheco-Peña. This work was partially supported by the Spanish Ministerio de Economía y Competitividad with European Union Fondo Europeo de Desarrollo Regional (FEDER) funds (TEC2014-51902-C2-2-R). Victor Pacheco-Peña is supported by Newcastle University (Newcastle University Research Fellow). Igor V. Minin and Oleg V. Minin were partially supported by the Mendeleev scientific fund of Tomsk State University.

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