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Flat Lens Design Using Artificially Engineered Materials

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Abstract—In this work, we present a new systematic technique for the design of a flat lens using modified commercial off-the-shelf (COTS) materials, as opposed to metamaterials (MTMs) that are often required in lens designs based on the Transformation Optics (TO) approach. While lens designs based on Ray Optics (RO) do not suffer from the drawback of having to use metamaterials, they still require dielectric materials that may not be commercially available off-the-shelf. This paper describes a systematic procedure for realizing the desired materials by modifying the COTS types, and illustrates its application with some practical examples.

1. INTRODUCTION

In recent years, a variety of techniques have been proposed by researchers to design flat lenses [1–9] that are based on Transformation Optics (TO) as well as other techniques. The TO approach, which is very elegant and systematic, often leads to designs based on metamaterials that can be difficult to realize because they require ϵ_r and μ_r values that are either less than 1, or very large, or both. Novel approaches to circumventing theses problems and developing ϵ-only designs have recently been proposed by a number of workers, though this is still regarded as "work in progress".

In this work, we discuss ways to mitigate some of the problems encountered with MTMs, and present strategies for artificially synthesizing dielectric materials that are broadband as well as low-loss; hence, they are useful for real-world antenna applications involving low-profile flat lenses and reflectarrays, for example. The key to circumventing the difficulties with MTM, which we have identified above, is to steer clear of the common practice of using resonant inclusions or "particles" to achieve extreme material properties, such as $\gg 1$; $\ll 1$; negative index; and, zero index. Our strategy is to develop antenna designs that only call for material parameters that are realistic, so that they can either be acquired off-the-shelf, or by slightly tweaking the available materials by embedding small patches or apertures, often referred to as "particles", whose dimensions are far removed from the resonance range. This obviates the problems of dispersion, narrow bandwidths and losses that plague the MTMs, at least those that fall in the "exotic" category, e.g., the double-negative or DNG type. The RO approach, although it leads to dielectric-only designs without the need to use magnetic materials, still typically requires dielectric materials that may not be available off-the-shelf.

The paper will present several examples to illustrate the procedure for synthesizing artificial dielectrics — both the single-layer and multilayer types — the latter to achieve better control including matching. It will also include the designs of flat lenses and a comparison of their performances with those of some of the existing designs.

Although the 3D-printing technology is becoming widespread and affordable day-by-day, the current 3D printers can only work with certain materials with limited range of material parameters. Hence, the current work can be very helpful for designing dielectric materials which cannot be directly handled

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in 3D printers. Typically, it is difficult to realize the dielectric materials with permittivities that are higher than what is available for 3D-printing. In contrast to this, the infill approach or similar methods can be employed to create materials with lower values [10]. Hence, we will concentrate on the former in this work, namely to increase the effective permittivities of available materials.

2. LENS DESIGN

2.1. RO and RO(ZP) Lens Design

We begin with the RO-lens design by using the methodology described in [7]. The design parameters of the lens (see Fig. 1) are: center frequency $f = 30\,\text{GHz}$; focal length $F = 12.7\,\text{mm}$; thickness $h = 9\,\text{mm}$; and specified gain. The diameter D of the lens is chosen to be 63.5 mm on the basis of the gain requirements. We use 10 discrete rings for the lens, each with a width of 3.175 mm though the number of rings can be increased, if desired, to achieve a design with a finer discretization. The dielectric parameters chosen to satisfy the path-length condition of these rings are shown in Table 1. We also modify these dielectric parameters to design a Zone-Plate (ZP) version of the lens by using modulo 2π for the phase variation, and the parameters of this lens are listed in Table 2. For completeness, we include the dielectric parameters of most commonly available COTS materials in Table 3. A quick check shows that many of the desired materials that are tabulated in Tables 1 and 2 are not commercially available from vendors such as Rogers. We also note that the zone-plating has helped to bring the dielectric parameters of the lens to lower values. It eases the process to find the available COTS material as RO(ZP) lens demands lower dielectric parameters as compared to RO lens.

Table 1. Material parameters for RO lenses.

Ring No.	**RO Lens**	**RO COTS Lens**	**RO DaD Lens (without patches)**		**RO DaD Lens (with patches, $b = 1.58\,\text{mm}$)**		
	ϵ_r ($t_1 = 9\,\text{mm}$, t_2=0)	ϵ_r ($t_1 = 9\,\text{mm}$, $t_2 = 0$)	ϵ_1/ϵ_2	t_1/t_2 (mm)	ϵ_r	a	t_1/t_2 (mm)
1	11.2	10.2	$\epsilon_1 = 10.2$ $\epsilon_2 = 1$	$t_1 = 9$ $t_2 = 0$	$\epsilon_1 = 10.2$ $\epsilon_2 = 1$	1.25	$t_1 = 9$ $t_2 = 0$
2	10.6	10.2	$\epsilon_1 = 10.2$ $\epsilon_2 = 1$	$t_1 = 9$ $t_2 = 0$	$\epsilon_1 = 10.2$ $\epsilon_2 = 1$	0.98	$t_1 = 9$ $t_2 = 0$
3	9.8	9.8	$\epsilon_1 = 9.8$ $\epsilon_2 = 1$	$t_1 = 9$ $t_2 = 0$	$\epsilon_1 = 9.8$ $\epsilon_2 = 1$	N/A	$t_1 = 9$ $t_2 = 0$
4	8.7	9.2	$\epsilon_1 = 9.2$ $\epsilon_2 = 6.15$	$t_1 = 8$ $t_2 = 1$	$\epsilon_1 = 9.2$ $\epsilon_2 = 6.15$	N/A	$t_1 = 8$ $t_2 = 1$
5	7.45	6.15	$\epsilon_1 = 9.2$ $\epsilon_2 = 6.15$	$t_1 = 4.3$ $t_2 = 4.7$	$\epsilon_1 = 9.2$ $\epsilon_2 = 6.15$	N/A	$t_1 = 4.3$ $t_2 = 4.7$
6	6.15	6.15	$\epsilon_1 = 6.15$ $\epsilon_2 = 1$	$t_1 = 9$ $t_2 = 0$	$\epsilon_1 = 9.2$ $\epsilon_2 = 6.15$	N/A	$t_1 = 9$ $t_2 = 0$
7	4.88	4.7	$\epsilon_1 = 6$ $\epsilon_2 = 4.7$	$t_1 = 1.58$ $t_2 = 7.42$	$\epsilon_1 = 9.2$ $\epsilon_2 = 6.15$	N/A	$t_1 = 1.58$ $t_2 = 7.42$
8	3.7	3.66	$\epsilon_1 = 4.5$ $\epsilon_2 = 3.66$	$t_1 = 0.78$ $t_2 = 8.22$	$\epsilon_1 = 9.2$ $\epsilon_2 = 6.15$	N/A	$t_1 = 0.78$ $t_2 = 8.22$
9	2.64	2.75	$\epsilon_1 = 2.75$ $\epsilon_2 = 2.5$	$t_1 = 5.4$ $t_2 = 3.6$	$\epsilon_1 = 9.2$ $\epsilon_2 = 6.15$	N/A	$t_1 = 5.4$ $t_2 = 3.6$
10	1.73	1.96	$\epsilon_1 = 1.96$ $\epsilon_2 = 1$	$t_1 = 7.25$ $t_2 = 1.75$	$\epsilon_1 = 9.2$ $\epsilon_2 = 6.15$	N/A	$t_1 = 7.25$ $t_2 = 1.75$

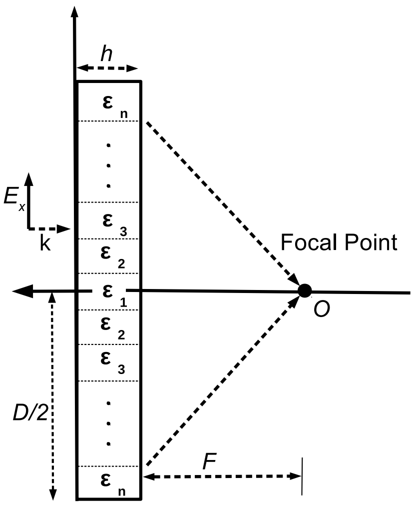


Figure 1. RO lens design principle.

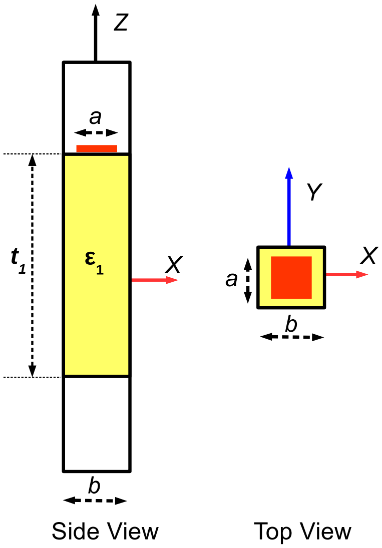


Figure 2. Unit cell for designing higher permittivity materials from low permittivity COTS material.

Table 2. Material parameters for RO(ZP) lenses.

Ring No.	RO(ZP) Lens	RO(ZP) COTS Lens	RO(ZP) DaD Lens (without patches)	
	ϵ_r $(t_1 = 9\,\text{mm},\, t_2 = 0)$	ϵ_r $(t_1 = 9\,\text{mm},\, t_2 = 0)$	ϵ_1/ϵ_2	t_1/t_2 (mm)
1	4.96	4.7	$\epsilon_1 = 6$ $\epsilon_1 = 4.5$	$t_1 = 3.1$ $t_1 = 5.9$
2	4.62	4.7	$\epsilon_1 = 4.7$ $\epsilon_1 = 4.5$	$t_1 = 5.8$ $t_1 = 3.2$
3	4.08	3.66	$\epsilon_1 = 4.5$ $\epsilon_1 = 3.66$	$t_1 = 4.7$ $t_1 = 4.3$
4	3.38	3.27	$\epsilon_1 = 3.55$ $\epsilon_1 = 3.27$	$t_1 = 4.3$ $t_1 = 4.7$
5	2.62	2.5	$\epsilon_1 = 3$ $\epsilon_1 = 2.5$	$t_1 = 2.52$ $t_1 = 6.48$
6	1.88	1.96	$\epsilon_1 = 1.96$ $\epsilon_1 = 1$	$t_1 = 8.25$ $t_1 = 0.75$
7	1.21	1	$\epsilon_1 = 1.96$ $\epsilon_1 = 1$	$t_1 = 2.3$ $t_1 = 6.7$
8	3.7	3.66	$\epsilon_1 = 4.5$ $\epsilon_1 = 3.66$	$t_1 = 0.78$ $t_1 = 8.22$
9	2.64	2.75	$\epsilon_1 = 2.75$ $\epsilon_1 = 2.5$	$t_1 = 5.4$ $t_1 = 3.6$
10	1.73	1.96	$\epsilon_1 = 1.96$ $\epsilon_1 = 1$	$t_1 = 7.25$ $t_1 = 1.75$

Table 3. COTS dielectric materials used for lens design.

1.96	2.17	3	4.5	6	9.2	10.2
	2.2	3.02	4.7	6.15	9.8	
	2.33	3.2				
	2.5	3.27				
	2.75	3.55				
	2.94	3.6				
		3.66				

We employ a novel technique, referred to herein as dial-a-dielectric (DaD), for engineering artificial materials by enhancing COTS or COTS materials to achieve the dielectric parameters we need for implementing our design. The DaD approach synthesizes the desired artificial material by placing the metallic patches either on top or sandwiched between dielectric layers, as explained below in Sec. 2.2, to achieve the desired dielectric parameters. Alternatively, we can use a combination of two or more dielectric layers of different materials to realize the desired permittivity values. The novelty of this method is that it does not depend on resonance properties of patches to realize the desired dielectric parameters; hence it does not suffer from the issues of bandwidth and losses that often plague other available approaches. The underlying concept of the low-loss design is to choose patch sizes whose dimensions are relatively small, because they are only used to make minor adjustments to the available COTS materials.

2.2. Design of Artificially Engineered Materials

RO/RO(ZP) lenses are realized by using different dielectric materials as explained earlier in Sec. 2.1 where we have pointed out that not all the requisite materials are available commercially, consequently we need to use the DaD strategy to realize these materials.

Once we have determined the desired dielectric parameters by following the design strategy shown in Fig. 1, we encounter three different possibilities:

(i) Desired permittivity value is same as that available commercially. In this event, we go ahead and use the COTS material.
(ii) Desired dielectric constant is higher than available COTS material. For this case we use the approach presented in Sec. 2.2.1 or 2.2.2.
(iii) Desired permittivity value is lower than available COTS material. For this case we follow Sec. 2.2.3.

2.2.1. Designing Higher Permittivity Materials from Low Permittivity COTS Material: Method-1

In this section, we present the technique for engineering the COTS (commercial off-the-shelf) materials to realize the dielectric parameters we desire by implementing the "dial-a-dielectric," scheme [10–13]. To tweak the COTS materials, we use square patches (other shapes can be used as well), arranged in a circular pattern as shown in Fig. 5, and print them on top of the dielectric rings to realize the desired ϵ_r values. Alternatively, we can print them on a mylar sheet and then place the sheet above the rings. To carry out the simulation, the concerned ring is discretized in the unit cells of appropriate periodicity (b, here $b = 1.58\,\mathrm{mm}$). The periodicity is decided on the basis of phase value needed to compensate across the unit cell. In our tests, we found that the unit cell with periodicity around $\lambda/10$ gives satisfactory results. We use unit cell of COTS material and patch combination (see Fig. 2) to realize the artificial dielectric. We start this process by placing patch of very small side dimension on COTS material layer. Phase of S_{21} for COTS material covered with small patch will be close to COTS-only material layer. After confirming this behavior, we increase patch dimensions. The dimensions of the patches are chosen such that the phase of S_{21} of a dielectric-only layer, if available would match the S_{21} of the COTS materials covered by the patch. Since the incremental change is relatively small, the patch-size needed to accomplish this phase shift behavior is such that it is far from its resonance, and this is key to realizing a wideband low-loss design.

2.2.2. Designing Higher Permittivity Materials from Low Permittivity COTS Material: Method-2

As mentioned in the previous section, there is limit to the dielectric permittivity value we can achieve by following the approach presented therein. If we find that the required patch size becomes comparable to the local periodic of the unit cell, insertion loss of the achieved material becomes too high to be unacceptable. In that scenario, we can modify the above approach as we will now explain. We use two dielectric blocks with permittivity values higher and lower than the desired dielectric value and place the patch above the stack as shown in Fig. 3. Since commercially available dielectric materials only come with pre-set thicknesses, we can use the patches to fine-tune the effective dielectric constant of the stack.

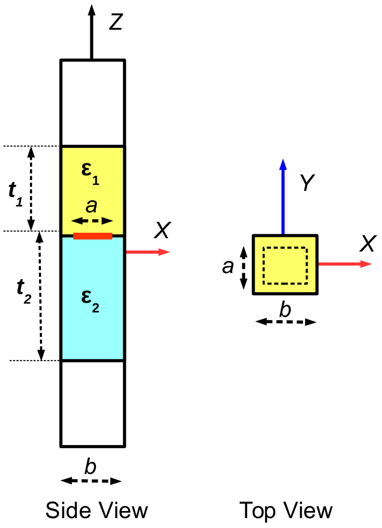


Figure 3. Unit cell for designing higher permittivity materials from low permittivity COTS materials.

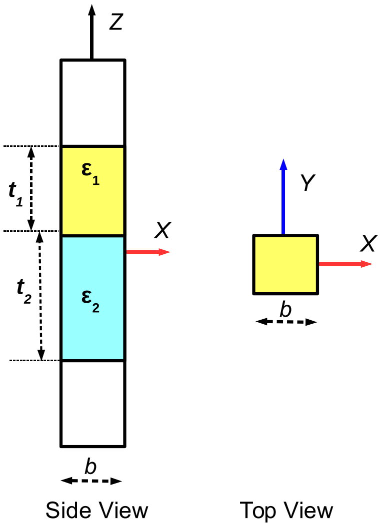


Figure 4. Unit cell for designing lower permittivity materials from high permittivity COTS material.

2.2.3. Designing Lower Permittivity Materials from High Permittivity COTS Material

It is not uncommon to find that the desired value of permittivity is lower than that of the available COTS material which is closest to the desired one. In this event, we can use the following approach.

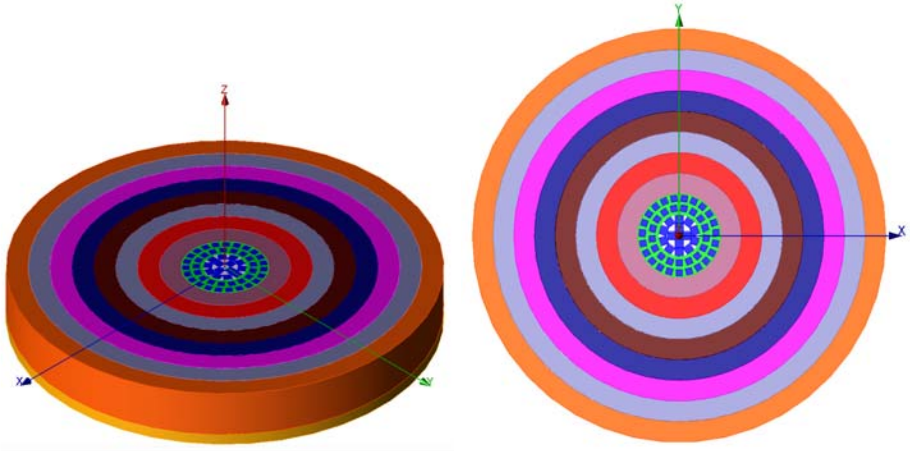
Take two COTS dielectrics, one with a lower and the other with a higher permittivity value than the desired one. Stack them and adjust the height of both the dielectric materials (see Fig. 4) until the desired phase of S_{21} is realized.

Above methods can be sometimes combined with each other to obtain the desired dielectric permittivity. We have also observed that stacking multiple layers gives flexibility to achieve higher dielectric permittivity. We were able to get desired dielectric permittivity to be 2–3 times of the COTS material with reasonable S_{21} magnitude.

2.3. DaD Lens Design

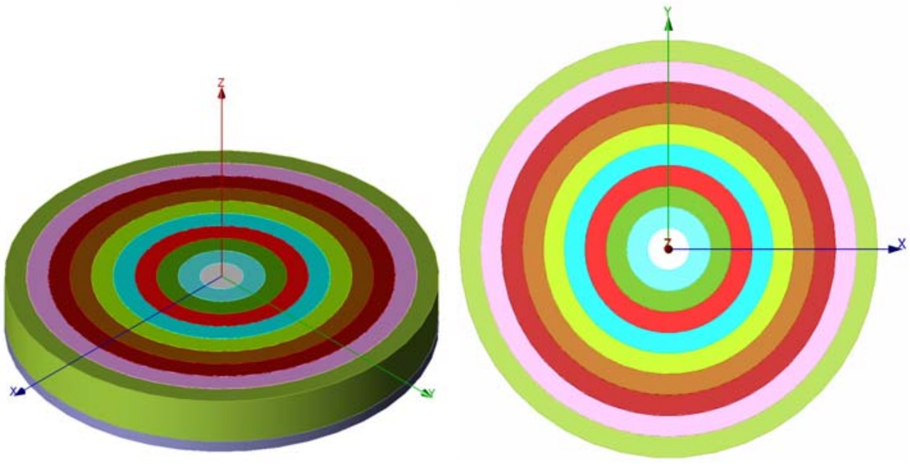
2.3.1. RO/DaD Lens Design

For the DaD lens design, we begin with a COTS material and follow Sec. 2.2 to design the local unit cells for the rings for which COTS materials with desired permittivity values are not available, by using one of the techniques presented in Sec. 2.2. For the current design, we choose the periodicity to be



(a) (b)

Figure 5. Designed RO/DaD lens (with patches). (a) Isometric view. (b) Top view.



(a) (b)

Figure 6. Designed RO(ZP)/DaD lens (without patches). (a) Isometric view. (b) Top view.

1.58 mm and designed RO/DaD lens (see Fig. 5) whose parameters are given in Table 1. Note that we only need to add patches in the rings 1 and 2, and not in the other rings, to achieve the desired permittivity values.

2.3.2. RO(ZP) DaD Lens Design

For the RO(ZP) lens, we note that the required permittivity values in certain rings are lower than those of the RO lens. We can take advantage of this and achieve the desired permittivity values by using the methods described in Sec. 2.2.2 as well as Sec. 2.2.3, depending upon the values of the COTS materials we use. We found that patches are not needed in this design since all the permittivity values for RO(ZP) lens can be achieved without the patches. The material parameters realized for the RO(ZP)/DaD lens (see Fig. 6) are listed in Table 2.

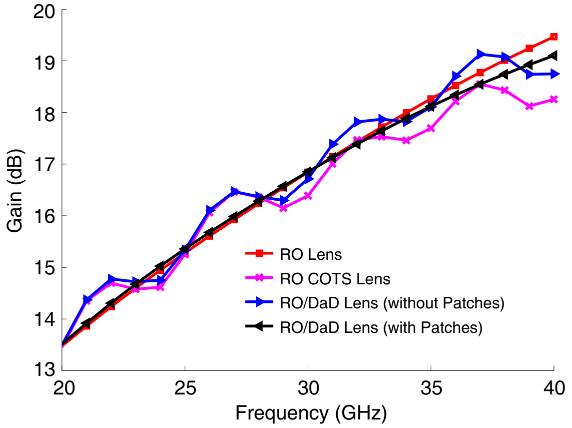


Figure 7. Gain response for RO lenses.

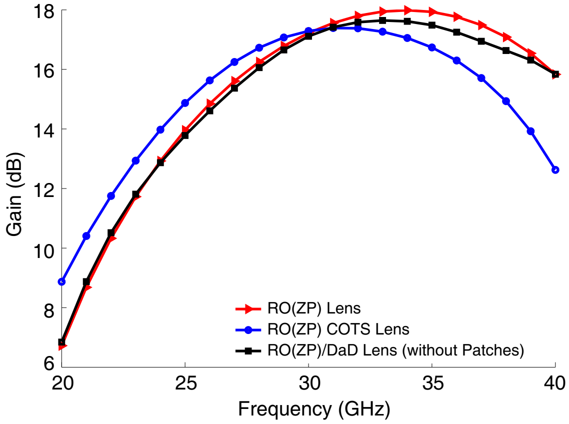


Figure 8. Gain response for RO(ZP) lenses.

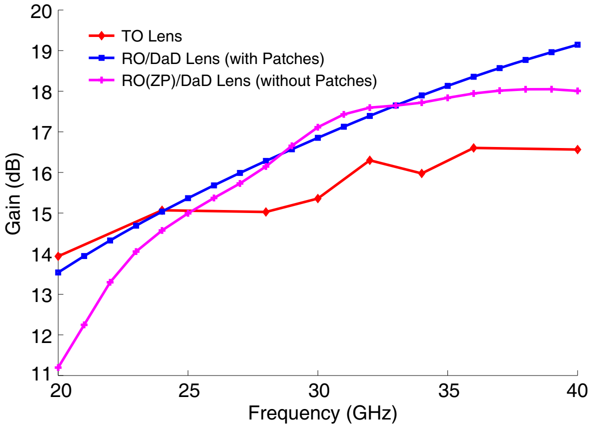


Figure 9. Gain response for designed lenses.

3. RESULTS

We have carried out a comparative study of different types of RO lenses and we will now present the results of this study. We used commercial finite element method (FEM) and finite-difference time-domain (FDTD) softwares to simulate these lenses. We show the gain results in Fig. 7 for: (i) RO lens; (ii) RO COTS lens (we use only COTS materials for this design); (iii) RO/DaD lens without using patches for its design; and (iv) RO/DaD lens that uses patches for its design. The material parameters of these lenses are listed in Table 1.

Figure 8 shows the gain results for (i) RO(ZP) lens; (ii) RO(ZP) COTS lens; (iii) RO/DaD lens without using patches for its design. Recall that there was no need to use patches for the RO (ZP)/DaD lens design, since all the desired values of permittivities can be realized by using Sec. 2.2.3. The material parameters of these lenses are listed in Table 2.

We observe that the RO(ZP) lens has a narrower bandwidth than when zone plating is not used. The narrowband behavior is attributable to the fact that, strictly speaking, zone plating design achieves the desired phase only at the single design frequency, since it adjusts the phase values modulo 2π.

It is obvious from these results that the lens designs based on DaD technique perform very well, and realize the highest gain value. We also compare these lenses with TO Lens [7] and see that DaD lenses perform very favorably when compared to the TO lens (see Fig. 9).

4. COMMENTS AND CONCLUSIONS

We have shown in this paper how we can systematically design ray-optics-based zone-plate planar lenses using artificial dielectrics synthesized by implementing the "dial-a-dielectric" or DaD approach. The designed lenses have the desirable characteristics of low-loss as well as low reflection. Also, the synthesized lens has been shown to perform well in the entire 20–40 GHz frequency band.

Before closing we mention that the present technique is also useful for designing reflectarray antenna designs that are both low-loss and wideband.

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