A Systematic Approach for the design of Metallic Delay Lenses

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***Abstract*—A major disadvantage of natural dielectric lenses is the excessive physical weight of the dielectric material. Artificial dielectric lenses are proposed to replace the actual dielectric and overcome this disadvantage. In this paper, we introduce a systematic and comprehensive method for the design of metallic delay lenses. Previous approaches suggest analytical formulas based on effective medium theories for the evaluation of the effective electromagnetic properties of artificial dielectrics. The method presented in this paper goes beyond the applicability of the theoretical methods, since it is applicable for periodic structures with larger metallic elements that are desired in practice. To validate this method, a metallic delay lens comprising of copper spheres is used as a proof of concept demonstrator and favorably compared with the solid lenses.**

I. Introduction

Microwave lenses made of natural dielectrics are used to focus electromagnetic energy from a point source into a sharp beam. The excessive physical weight may prohibit the use of solid dielectric lenses. The so-called artificial dielectrics were introduced by Winston E. Kock in 1948 [1] to replace the actual dielectric material for weight reduction. Artificial dielectrics usually consist of a lattice of conducting elements within a host dielectric material that imitates the electromagnetic response of natural dielectrics. A *metallic delay lens* consisting of such a medium is capable of demonstrating a behavior almost identical to the natural dielectric lens, but with the advantage of greatly reduced weight.

Several authors have attempted to conceptually replace the artificial dielectric by a continuous medium with effective electromagnetic parameters. The dependence of the effective permittivity ϵ_{eff} and permeability μ_{eff} on the shape, size and concentration of the conducting elements has been investigated [2]–[4]. Theoretical formulas offer important physical insight into the nature of the problem; however, analytical expressions for the expected permittivity and permeability are not consistent with experimental values as the wavelength becomes shorter, the element sizes larger and the spacings smaller. This is the case of microwave lenses with an index of refraction that is desired in practice.

In this paper, we propose a systematic method for the design of metallic delay lenses. Section II presents the method for the determination of the effective permittivity and permeability of an artificial dielectric. In section III, simulations show that a sphere array lens is capable of performance almost identical to that of the solid lens of the same electromagnetic properties. For the sake of brevity, we would include only selected results here while other metallic delay lens examples will be presented during the conference.

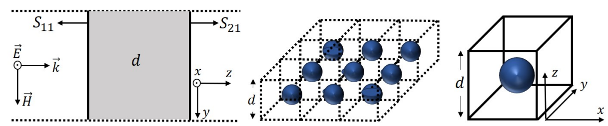

Fig. 1. (a) Slab of the unknown sample under a plane wave excitation. The thickness of the sample is d. S_{11}, S_{21} are the scattering parameters. (b) Periodic array of metallic spheres. (c) The unit cell of the periodic structure of (b).

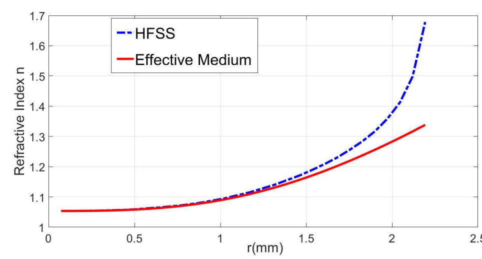

Fig. 2. Comparison of the refractive index n obtained by the electromagnetic parameter retrieval method of Section II and the effective medium theory for unit cells with different sphere radius r. The blue dashed curve is the extracted data from HFSS simulation, the red curve is the effective medium theoretical values, using the relations of [3].

II. Electromagnetic Parameter Retrieval

In this section, a systematic approach for the determination of the effective electromagnetic properties of an artificial dielectric is presented. The unknown sample of Fig. 1(a) has thickness d and the S parameters under a normally incident plane wave can be determined. The sample can be conceptually replaced by a hypothetical continuous material of parameters ϵ_{eff}, μ_{eff} and equal scattering parameters under the same plane wave excitation. The effective permittivity ϵ_{eff} and permeability μ_{eff} can be calculated from the S parameters using the following relations [5]:

$$n = \frac{1}{k_0 d} \cos^{-1}\left[\frac{1}{2S_{21}}\left(1 - S_{11}^2 + S_{21}^2\right)\right] \tag{1}$$

$$\zeta = \sqrt{\frac{(1+S_{11}^2)^2 - S_{21}^2}{(1-S_{11}^2)^2 - S_{21}^2}} \tag{2}$$

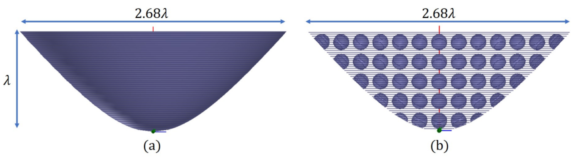

Fig. 3. (a) Side view of the simulated natural homogeneous convex lens with $\epsilon_r = 1.65$, $\mu_r = 1$ and $n = 1.28$. (b) Side view of the simulated metallic delay lens. The lens comprises copper spheres supported by a dielectric foam of $\epsilon_r = 1.11$. The surface of the lens at the feed side is hyperbolic and the aperture plane surface is flat. The WR-75 waveguide feed is at a focal length $F = 2\lambda_0$ from the hyperbolic surface.

$$\epsilon_{eff} = \frac{n}{\zeta} \tag{3}$$

$$\mu_{eff} = n\zeta. \tag{4}$$

In the above equations, $k_0 = 2\pi/\lambda_0 = \omega/c$ is the wavenumber of the incident wave, $\zeta = \sqrt{\mu_{eff}/\epsilon_{eff}}$ and $n = \sqrt{\mu_{eff}\epsilon_{eff}}$ are the wave impedance and refractive index of the hypothetical equivalent continuous material, respectively. In general, n, ζ, ϵ_{eff} and μ_{eff} are complex numbers. For the cases studied hereafter, the imaginary part is negligible and therefore neglected.

An artificial dielectric which is formed by an array of spheres is shown in Fig. 1(b). This example was motivated by Kock [1] who proposed a sphere array lens made of metallic spheres supported by a polystyrene foam. The unit cell of the periodic structure is defined in Fig. 1(c) and modelled in ANSYS HFSS. The operating frequency is $f = 13.4$GHz, the cubic unit cell's size is $\lambda_0/5$ and the relative permittivity of the dielectric foam is $\epsilon_r = 1.11$. Periodic boundary conditions are imposed on the right, left, front and rear sides. The structure is excited by a TE plane wave. The refractive index is obtained by the electromagnetic parameter retrieval method and compared to the effective medium theoretical values formulas of [3] for different values of the sphere radius r in Fig. 2. For example, for a sphere radius $r = 1.8$mm, $\epsilon_{eff} = 3.06$, $\mu_{eff} = 0.54$ and $n = 1.28$. Note that there is fairly good agreement only for small r since the effective medium theory is accurate for small element dimensions.

III. Application to Sphere Array Lens

A natural dielectric convex lens with $\epsilon_r = 1.65$, $\mu_r = 1$ and $n = 1.28$ is used to collimate the beam from a WR-75 waveguide at a focal length $F = 2\lambda_0$, as shown in Fig. 3(a). The diameter of the lens is $D = 2.68\lambda_0$, the subtended angle is 48^o, and the maximum thickness of the lens is $1\lambda_0$. An artificial dielectric lens with identical geometrical properties is shown in Fig. 3(b). A unit cell of this structure is shown in Figure 1(c). The dimensions are chosen using the design curve of Fig. 2 so that the metallic delay lens possesses identical refractive index $n = 1.28$. In particular, the spheres are supported by a dielectric foam of $\epsilon_r = 1.11$, the spacing of the cubical array in each direction is $\lambda_0/5$ and the sphere radius is 1.8mm. Using the results of section II, the artificial dielectric has $\epsilon_{eff} = 3.06$ and $\mu_{eff} = 0.54$. Another solid lens with identical electromagnetic properties has $\epsilon_{eff} = 3.06$, $\mu_{eff} = 0.54$, $n = 1.28$.

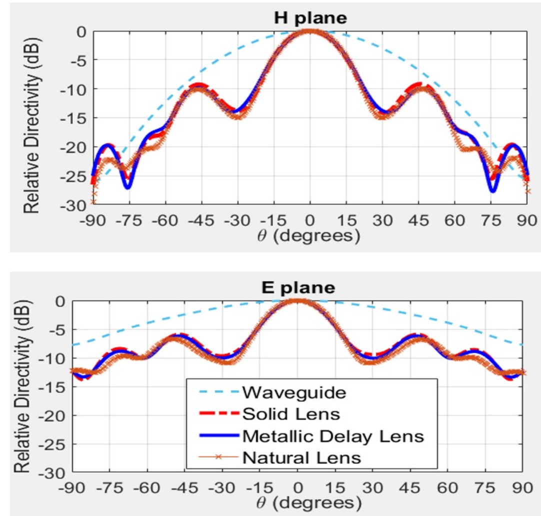

Fig. 4. Simulated relative directivity for the lens antennas of section III at $f = 13.4$GHz ($\lambda_0 = 2.24$cm). The natural dielectric lens has $\epsilon_r = 1.65$, $\mu_r = 1$ and $n = 1.28$. The metallic delay lens has $\epsilon_{eff} = 3.06$, $\mu_{eff} = 0.54$ and $n = 1.28$. The solid lens has the same electromagnetic properties with the metallic delay lens. The directivities are 12.40dB, 11.75dB and 11.79dB, respectively. The feed directivity is 7.45dB. The patterns are in excellent agreement for the entire angular range for both E and H planes.

The three lenses are simulated using ANSYS HFSS finite element simulation software. The resemblance of the simulated far-field results for the lenses is illustrated in Fig. 4. The patterns are in excellent agreement for the entire angular range for both E and H plane. There exist no significant differences for the $\phi = 45^o$ cut and the cross polarization too. Note that the feed type and position are not chosen for an optimal performance. The objective is to validate the electromagnetic parameter retrieval method of section II for the effective properties of an artificial dielectric and highlight that metallic delay lenses can perform as well as natural solid lenses.

IV. Conclusion

A systematic method for the design of metallic delay lenses has been presented. This approach involves the evaluation of the effective electromagnetic properties of artificial dielectrics. Simulation results of a sphere array lens highlight that metallic delay lenses can perform as well as solid lenses. Future work includes the design, prototyping and measurement of metallic delay lens antennas of practical interest.

References

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