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Transmission-line lens antenna with embedded source

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Abstract—We demonstrate how the recently proposed approach to create artificial “materials” with so-called transmission-line networks can be used in microwave lens antenna design. A two-dimensional transmission-line network is designed in such a way that wave propagation inside the network is nearly isotropic, and furthermore, the network is well coupled to the surrounding medium, which in this case is free space. Using the well-known equations for dielectric lens design, we choose the profile of our transmission-line lens in such a way that a line source placed inside the lens creates a plane-wave field outside the lens. Therefore the lens, excited with an embedded source, acts as a highly directive antenna.

I. INTRODUCTION

Artificial dielectrics are well-known in lens antenna design, see, e.g., [1], [2]. Recently, the use of so-called transmission-line (TL) networks [3], [4] as artificial volumetric lenses with a possibility of impedance matching with the surrounding medium has been proposed [5]. The basic principle of this approach to the lens design is that a transmission-line network, for which we can independently control both the refractive index n and the matching of the network with the surrounding medium, can provide lens focusing properties with suppression of unwanted reflections. This opens a possibility for obtaining structures effectively behaving as homogeneous media having a certain index of refraction and, ideally, perfect coupling with the surrounding medium, without using any natural or artificial magnetic materials [5].

In [5], a lens that focuses TE-polarized plane waves propagating in free space to a line in free space was designed and simulated. It was shown that the well-known equations for dielectric lens design (see, e.g., [6]), can be used effectively also in the design of these TL-based artificial “materials.” In this paper, we show that the same design procedure can be also used for the design of more advanced lenses that can include embedded sources and therefore be applied to create highly directive antennas.

II. LENS ANTENNA DESIGN

We start by designing a “traditional” dielectric lens, that is excited by a line source in free space and creates a plane wave

on the other side of the lens. In this case, we choose to use a lens that has a cylindrical surface on the side of the source, and on the other side, a surface defined by [6]

$$y^2 = \frac{[x + (n - 1)(F + T)]^2}{n^2} - x^2, \quad (1)$$

where x is the distance from the source in the direction parallel to the lens axis, F is the focal distance, and T is the thickness of the lens. See Fig. 1 for the lens profile in the case $F = 15.5d$, $T = 13.5d$, $d = 8$ mm, and $n = \sqrt{4.66} \approx 2.16$.

There is a definite advantage in using a lens whose near-source surface is cylindrical: The space between the source and the lens can be filled with any homogeneous material, without affecting the refraction at the outer surface of the lens (all waves emitted by the source will impinge on the inner lens surface with normal incidence). It is therefore obvious,

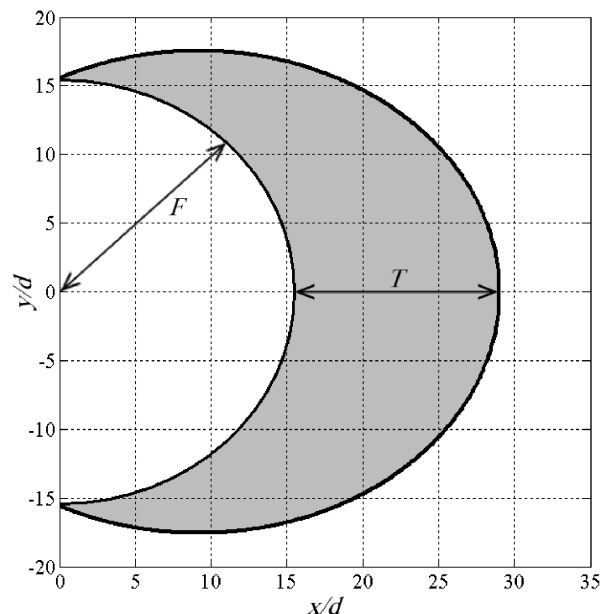


Fig. 1. Lens profile calculated with (1), having $F = 15.5d$, $T = 13.5d$, $d = 8$ mm, and $n = \sqrt{4.66}$. The source location is at $x = 0$, $y = 0$.

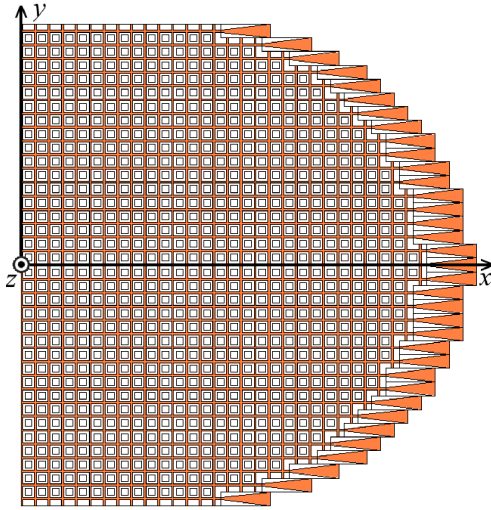


Fig. 2. Model of the proposed TL lens antenna, having the same surface profile (outer surface) as the lens in Fig. 1. The source location is at $x = 0$, $y = 0$. The antenna is symmetrical with respect to the yz -plane, i.e., only half of the antenna is illustrated here. The period d of the network is equal to 8 mm, and the size of the antenna in the transversal (y -) direction is $35d = 280$ mm.

that in order to realize an embedded-source lens using the transmission-line approach, we can fill the space between the source and the lens with the same transmission-line network that makes the lens itself.

See Fig. 2 for the simulation model of a transmission-line lens with the outer surface defined by (1) and having the same design parameters as the lens of Fig. 1. In the case of the TL lens, the parameter $d = 8$ mm is the period of the TL network. The transmission lines at the side edges of the lens are terminated with lumped resistors to mitigate reflections from the sides. The optimal resistance value is determined later by conducting simulations of the whole lens structure. The transmission-line network that is used is the same as proposed in [5], i.e., a 2-D network having effectively $n = \sqrt{4.66}$, composed of parallel-strip transmission lines embedded in a dielectric with $\varepsilon_{r,TL} = 2.33$. The effective refractive index of this lens can be calculated using the previously derived dispersion equation [5], and in the case of a two-dimensional network (under the assumption $d \ll \lambda$) the refractive index is simply the square root of two times the relative permittivity of the background dielectric, i.e.,

$$n = \sqrt{2 \times \varepsilon_{r,TL}} = \sqrt{2 \times 2.33}. \quad (2)$$

Although the impedance of the transmission lines composing the network is far from the ideal value of 585Ω [5] (the characteristic impedance of the transmission lines used here is $Z_{TL} \approx 179 \Omega$, which can be calculated using well-known equations), the transition layer effectively couples the electromagnetic waves between the network and the surrounding free space. In principle the coupling could be further improved by increasing Z_{TL} , but this study is out of the scope of this paper.

As in [5], also here we simulate an infinitely high volumetric

structure which is periodic in the vertical (z -) direction. To achieve this, we place perfect electric conductor (PEC) walls on the top and bottom of the simulation model, which includes only one layer of a two-dimensional TL network and the transition layer connected to this network. The simulation is further simplified by placing perfect magnetic conductor (PMC) walls to the xz - and yz -planes.

We have conducted full-wave simulations (with the Ansoft HFSS software) of the proposed TL lens antenna, together with two lens antennas having a similar surface profile and the same index of refraction, but composed of conventional homogeneous dielectrics. One of the dielectric lenses has the same step-wise surface profile as the TL lens, while the other one has a smooth surface profile. The inner lens surface is removed also from the dielectric lenses by filling all the space between the source and the outer lens surface with the dielectric. For the case of the TL lens, the source is a port connected between the parallel-strip transmission lines at $x = 0$, $y = 0$. For the dielectric lenses, the source is a vertical line current. The embedded source of the TL lens can be realized in a periodic structure by using power dividers.

In the lens studied in [5] there was no material in the space between the adjacent sections of transmission line, except the dielectric. Also for the lens studied in this paper this was the case at first. By conducting full-wave simulations for this lens, it was noticed that at certain frequencies the power fed into the network can couple to the space that is between the adjacent layers of two-dimensional TL networks. We suspect that these frequencies where such coupling occurs depend on the electrical size of the lens. Note that in the case of the previously studied lens with different geometry and size the fields were confined inside the transmission lines for all the studied frequencies [5].

In order to make sure that these unwanted modes cannot be excited at the frequencies of interest we have introduced vertical PEC rods (parallel to the z -axis), having the square cross section of $4 \text{ mm} \times 4 \text{ mm}$, inside the TL network. These PEC rods are placed periodically in the whole area of the lens, as can be seen from Fig. 2. The PEC rods have the same height as the whole simulation model, i.e., they are effectively infinitely high. The PEC rods act as an impenetrable wall to the unwanted modes, making sure that the fields are confined inside the transmission lines at all the studied frequencies. The reader should note that placing of objects, such the PEC rods here, inside the transmission-line network, has been also proposed as a way of achieving efficient electromagnetic cloaking of these objects [7].

The resistance of the lumped resistors placed on the side edges of the TL lens was found by conducting a coarse tuning of this value in the range from 100Ω to 400Ω , to maximize the directivity of the lens in the frequency range from 2.5 GHz to 3.5 GHz. A suitable value of the resistance was found to be $R = 200 \Omega$, with which the sidelobes are clearly mitigated as compared to other tested resistance values. A full optimization of the value of R was not possible due to the limited computing power available.

III. FULL-WAVE SIMULATION RESULTS

We compare the radiation properties of the TL lens antenna and the dielectric antennas with the one of an idealized aperture antenna of the same transversal size, having a uniform illumination and therefore the normalized magnitude of the (far-field) electric field distribution E/E_{Max} defined by [8]

$$\frac{E}{E_{\text{Max}}} = \frac{\sin[(\pi a/\lambda) \sin(\phi)]}{(\pi a/\lambda) \sin(\phi)}, \quad (3)$$

where a is the size of the aperture of the antenna and ϕ is the angle (in radians) in the xy -plane.

See Fig. 3 for the simulated radiation patterns at the frequency $f = 3$ GHz, produced by the TL lens antenna and the two dielectric lenses, all having the same surface profile defined by (1) and the volume between the source and the lens filled with the same material as composes the lens itself (as in Fig. 2).

Dielectric lens antenna #1 has the same step-wise profile as the TL lens antenna, whereas the dielectric lens antenna #2 has a smooth profile. The curve marked “ideal” presents the directivity pattern given by (3), with $a = 280$ mm, i.e., an aperture antenna with the same transversal size as the simulated antennas. Fig. 3 demonstrates the benefit of the TL lens, as compared to the dielectric lenses: the radiation pattern of the TL lens is much closer to the ideal, uniform-illumination pattern due to reduced reflections at the lens surface. Also a great improvement in the sidelobe level is achieved with the TL lens antenna, as compared to the dielectric ones. This is of course due to the resistors placed at the edges of the TL network.

As the studied TL lens antenna is of non-resonant type, it is expected that this antenna would operate in a large frequency band. What limit the operation are the impedance-matching of the network, which varies as a function of the frequency, as well as the operation of the transition layer that is used to couple the network with the surrounding medium. Although this layer is inherently non-resonant due to its small electrical size, it affects the frequency response of the whole lens. For various lens and cloak structures using this type of transition layer, it is necessary to verify the structure’s operation, i.e., good coupling with the surrounding medium, with numerical simulations. Based on the previous results [5], the network studied here and the corresponding transition layer are expected to offer good coupling of TE-polarized waves (with electric field \vec{E} parallel to the z -axis) between the network comprising the lens and the surrounding free space in a relatively broad frequency band with the center frequency around 3 GHz [5].

By conducting full-wave simulations at frequencies from 2 GHz to 4 GHz, we have found that the TL lens antenna studied here exhibits a directivity pattern very close to the one of an ideal, uniformly lit aperture antenna [eq. (3)] at least in the frequency band from 2.5 GHz to 3.5 GHz. This is expected to be a consequence of the mitigation of the reflections at the outer surface of the lens, as well as a result of the absorption of power at the sides of the lens, which reduces the sidelobes.

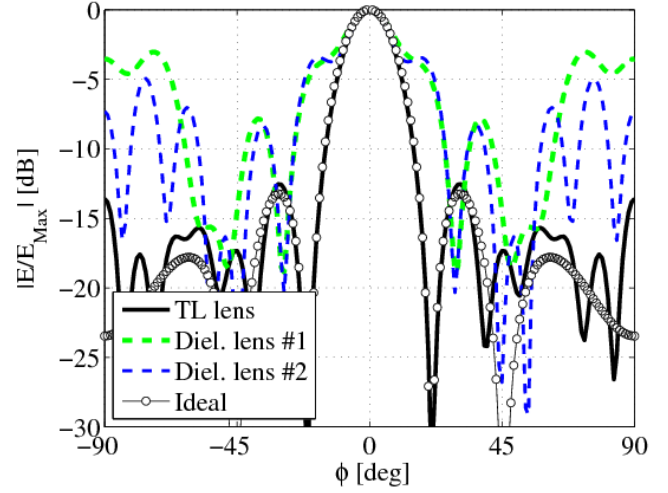


Fig. 3. Normalized magnitude of the radiated electric field at $f = 3$ GHz (in the far-field of the TL lens and the dielectric lenses), simulated with Ansoft HFSS software. The radiation from a uniformly lit aperture (“Ideal” case) is calculated using (3).

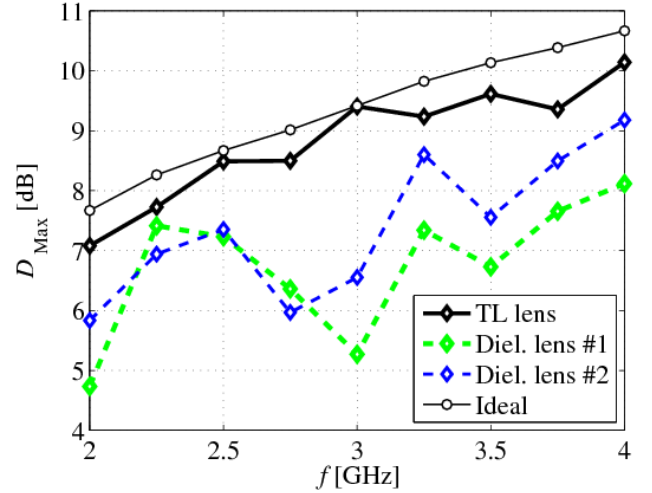


Fig. 4. Maximum directivities of the studied antennas, simulated with Ansoft HFSS software. The maximum directivity of a uniformly lit aperture antenna (“Ideal” case) is calculated analytically.

The maximum directivities of the simulated antennas, as well as that of the idealized uniform-illumination aperture antenna described above, are presented in Fig. 4. Here it can be observed that the maximum directivity of the TL lens antenna varies relatively smoothly as a function of the frequency, and is in the studied frequency range only slightly lower than the maximum directivity of the ideal aperture antenna. The maximum directivities of the two dielectric antennas on the other hand vary quite strongly as the frequency changes, and they are both lower than in the case of the TL lens antenna. The reader should keep in mind that the considered antennas exhibit a bidirectional radiation pattern, with main lobes in $\phi = 0^\circ$ and $\phi = 180^\circ$.

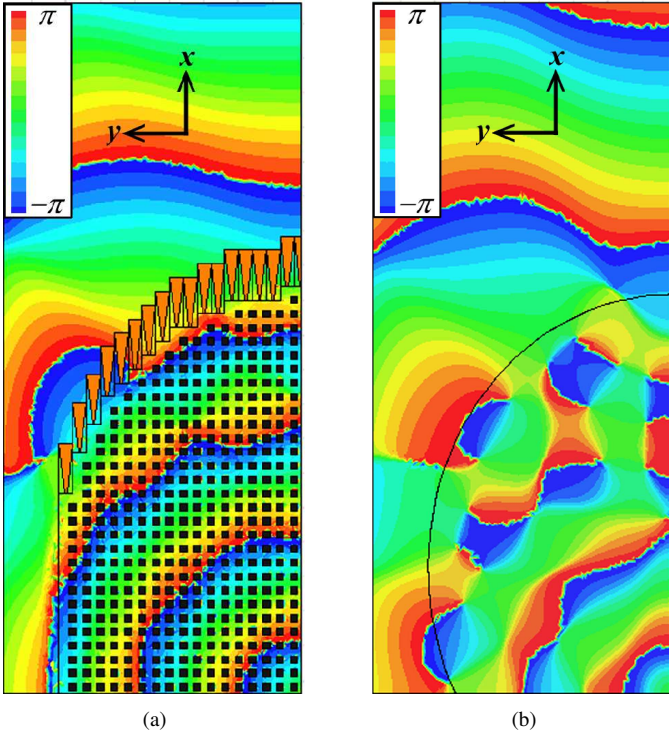


Fig. 5. Full-wave simulated electric field phase distribution at $f = 2.5$ GHz. (a) TL lens antenna. (b) Dielectric antenna with $\epsilon_r = 4.66$.

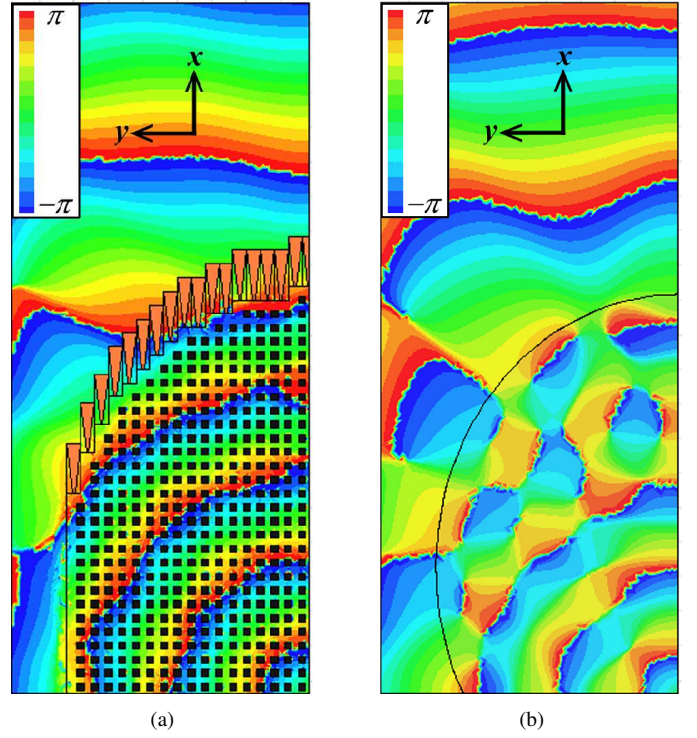


Fig. 6. Full-wave simulated electric field phase distribution at $f = 3.0$ GHz. (a) TL lens antenna. (b) Dielectric antenna with $\epsilon_r = 4.66$.

To have more verification on the reduction of the reflections as well as on the refraction effect itself, we have plotted the simulated electric field phase distributions of the TL lens and the dielectric lens #2 (lens with a smooth surface profile) at the frequencies 2.5 GHz, 3.0 GHz, and 3.5 GHz. See Figs. 5-7 for the results. In Figs. 5a-7a the transmission lines of the network are not shown for clarity, but the transmission lines of the transition layer are displayed to illustrate the surface profile of the lens. The black squares illustrate the PEC rods placed inside the TL lens (the fields are not solved inside PEC). In Figs. 5b-7b the surface profile of the dielectric lens is illustrated with a black line. The plots in Figs. 5-7 verify the mitigation of reflections at the outer surface of the TL lens: The cylindrical wave patterns in Figs. 5a-7a are well preserved, as compared to Figs. 5b-7b, where the reflections from the lens surface severely disturb the wave patterns.

IV. MATCHING OF THE ANTENNA TO A 50Ω CABLE

The matching of the proposed TL lens antenna to a 50Ω feeding cable was studied. The matching is considered for a single layer of the proposed volumetric structure. For a practical realization of this type of volumetric structure, with a finite number of layers, it is possible to feed each layer of the lens from a single feed port by using a network of power dividers. As the lens has a lot of available space inside it (the volume between the transmission lines is effectively “cloaked” [7]), which in the current model is filled with the vertical PEC rods, it is not a problem to introduce transmission lines of the feed network running vertically inside the lens.

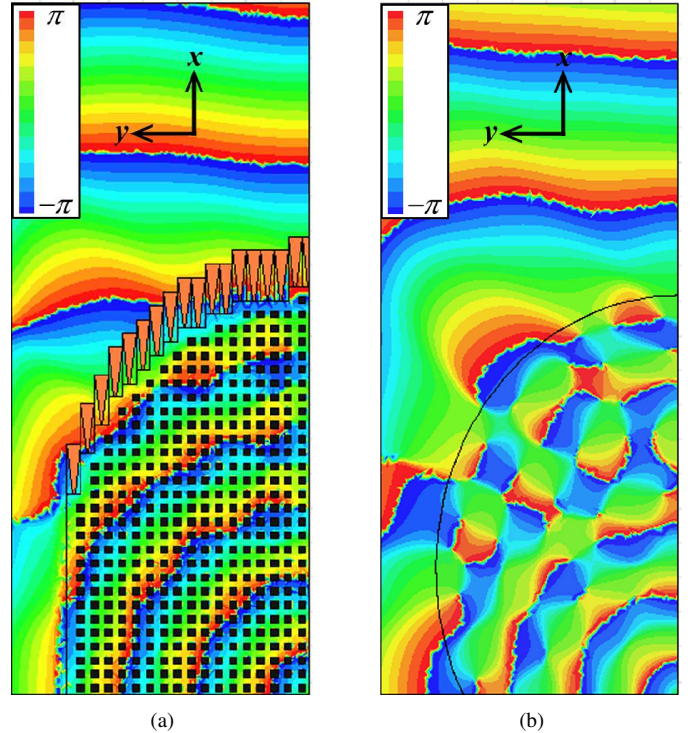


Fig. 7. Full-wave simulated electric field phase distribution at $f = 3.5$ GHz. (a) TL lens antenna. (b) Dielectric antenna with $\epsilon_r = 4.66$.

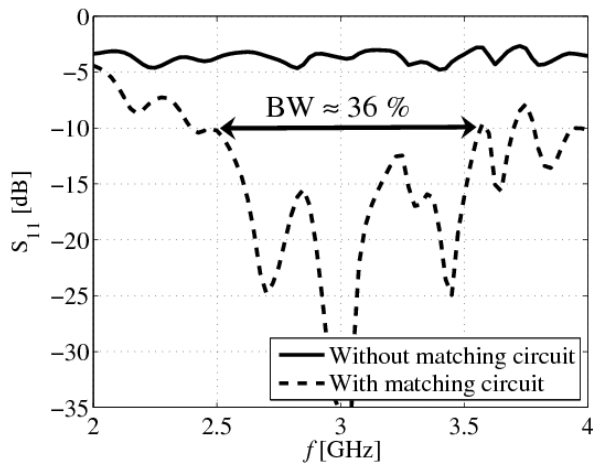


Fig. 8. Simulated reflection from a port feeding the TL lens antenna. The solid line is the S_{11} calculated directly at the position of the port. The dashed line represents the S_{11} obtained by using a matching circuit.

See Fig. 8 for the simulated S_{11} of the TL lens antenna (solid line). To illustrate the achievable matching level and bandwidth, we have designed a matching circuit to match the antenna better in the operational frequency band, i.e., in the range from $f = 2.5$ GHz to $f = 3.5$ GHz. To achieve this with a simple matching circuit, we have used a series connection of a 54Ω quarter-wave transformer (length 25 mm) and a lumped series capacitor, having the capacitance of 0.58 pF. The matching circuit was designed for the optimal operation at 3 GHz and the achieved relative bandwidth at -10 dB level is approximately 36 %, as shown in Fig. 8 (dashed line).

V. CONCLUSIONS

A lens antenna composed of periodically stacked two-dimensional transmission-line networks is proposed and analyzed numerically. By using a lens antenna design having a cylindrical surface profile on the side of the illuminating source, we are able to fill the volume between the source and the lens with a similar transmission-line network as composes the lens itself and use a source embedded in this network for exciting the lens. The directivity of the proposed transmission-line lens antenna is studied with full-wave simulations and the results are compared with similar lens antennas made of conventional dielectrics, and with the directivity pattern of an idealized uniformly lit aperture antenna having the same size. The results indicate that the proposed antenna has better matching with the surrounding free space than the dielectric antennas, thus resulting in mitigation of unwanted reflections at the lens surface. Also the sidelobe level of the transmission-line lens antenna is shown to be improved as compared to the dielectric antennas, due to the introduction of lumped resistors at the side edges of the network.

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