A Review of Recent Advances in Designing True-Time-Delay Microwave Lenses Exploiting Metamaterials with Non-Resonant Constituting Unit Cells

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Abstract **─** This paper presents a review of recent developments in the design of planar microwave lenses capable of operating over broad bandwidths in a true-time-delay fashion. The lenses discussed in this paper consist of planar apertures populated with miniature, sub-wavelength time-delay units. Each time delay unit is the unit cell of an appropriately-designed Frequency Selective Surface (FSS) with non-resonant, sub-wavelength constituting unit cells and is designed to provide a constant time-delay unit over the frequency range at which the lens operates. Designs that exploit both band-pass and low-pass FSSs are presented and discussed. Because of the non-resonant nature of their constituting unit cells and their small dimensions, such lenses can operate over broad bandwidths with wide fields of views. When used in conjunction with appropriately designed feed antennas, these lenses can be used in multi-beam, high-gain, broadband antenna apertures.

Index Terms **─** Frequency selective surfaces, microwave lenses, multi-beam antennas, phased-array antennas.

I. INTRODUCTION

Microwave lenses have been used in a variety of applications ranging from imaging and radar systems [1]-[2], to high-gain phased arrays [3]. A microwave lens generally acts as a transformer converting a spherical wave front generated by a feed antenna located on its focal point to a planar wave front at the output aperture of the lens. This transformation, however, is frequency dependent and generally works perfectly fine at only one frequency in most microwave lenses reported in the literature. In broadband, pulsed applications, a microwave lens must preserve the temporal characteristics of the transmitted pulse and pass it through with minimal distortion. Alternatively, in the receiving mode, all the frequency components of a broadband pulse incident on the aperture of the lens must be focused to the same focal point and chromatic aberrations must be minimized. In such applications, microwave lenses that act in a True Time Delay (TTD) fashion and satisfy Fermat's principle at every point on the aperture are highly desired.

Over the past several decades, numerous different types of microwave lenses and collimating structures have been reported. Examples include dielectric lenses [4]-[5], planar microwave lenses consisting of an array of transmitting and receiving antennas coupled together using a phase shifting or a time-delay mechanism [6]-[9], and Frequency Selective Surface (FSS) based microwave lenses [10]. Planar microwave lenses that use antenna arrays tend to suffer from poor scanning performance. This is primarily due to the relatively large spacing between the different phase shifting (or time delay) units that occupy the aperture of such lenses [6]-[9]. This behavior is also observed in FSS-based microwave lenses that exploit traditional frequency selective surfaces. Such FSSs are essentially identical to antenna arrays where the elements of the array are terminated with reactive elements. They too tend to suffer from poor scanning performances [10]. Additionally, the great majority of the planar microwave lenses reported in the literature are designed based on the phase

Submitted On: March 25, 2014
Accepted On: July 25, 2014

matching condition, where the lens aperture is designed to collimate a spherical incident wave into a planar output wave only at a single frequency. Therefore, such lenses are not well-suited for broadband operation where pulses with wide instantaneous bandwidths are used.

In recent years, several new classes of frequency selective surfaces that consist of sub-wavelength periodic structures with primarily non-resonant constituting unit cells were reported [11]-[13]. Since these FSSs do not use antenna elements as their constituting unit cells, their unit cells can be made extremely small. This feature leads to very stable responses for a wide range of incidence angles and polarizations of the incident wave. These FSSs, referred to as Miniaturized-Element FSSs (MEFSSs), have also been used to design planar microwave lenses [14]-[16]. In [14], the unit cells of appropriately-designed MEFSSs with band-pass frequency responses were used as spatial phase shifters to design a broadband planar lens. This lens demonstrated a wide field of view with a good scanning performance in the ±60° range. However, the lens reported in [14] satisfied Fermat's principle only at one single frequency and suffered from chromatic aberrations. Subsequently, the same types of unit cells were used in [15] to design Time-Delay Units (TDUs) capable of operating over a broad frequency band with minimal frequency dispersion. Using these TDUs, an MEFSS-based true-time-delay lens was reported in [15]. It was demonstrated that such MEFSS-based lenses can operate over very wide bandwidths without introducing any significant distortion in the temporal content of the incident pulse. Planar microwave lenses based on low-pass MEFSS were introduced in [16]. Such lenses tend to operate over an even wider frequency band than those based on band-pass MEFSSs, and they are particularly well suited for applications that work at lower microwave frequencies. The primary aim of this article is to provide a concise review of MEFSS-based true-time-delay microwave lenses and discuss their design procedures and methods for fabrication and characterization. This article reviews the recent developments in this area and it is based on the materials presented at the 2013 Harbin Engineering University Computational Electromagnetics and Applications Workshop.

II. MEFSS-BASED MICROWAVE LENSES

Figure 1 shows the topology of an MEFSS-based microwave lens. The lens is illuminated with a feed antenna located at its focal point. The spherical wave front generated by the feed antenna is converted to a planar wave front at the output aperture of the lens. The lens' aperture is populated with a number of pixels. Each pixel has sub-wavelength dimensions and acts as a time-delay unit providing a desired, constant time-delay value across the entire frequency of operation of the lens. This way, if a broadband pulse is radiated by the feed antenna, all of the frequency components of the broadband pulse will arrive at the output aperture of the lens at the same time, ensuring that no temporal distortion is introduced in the radiated pulse. Alternatively, if a plane wave arrives at the input aperture of the lens, all of the components of the incident pulse are focused at the same focal point and chromatic aberrations in the lens are minimized.

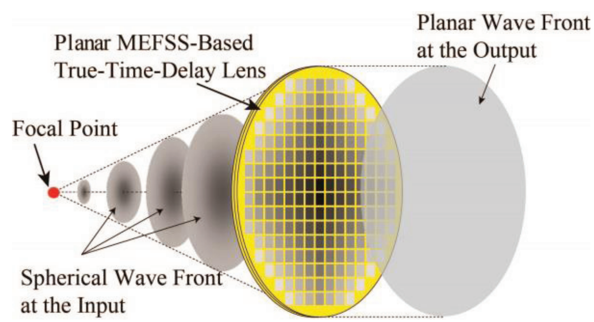


Fig. 1. Topology of a miniaturized-element frequency selective surface based microwave lens illuminated with an antenna located at its focal point.

Figure 2 (a) shows the side view of a typical MEFSS-based TTD lens. In this case, a point source is assumed to be located at the focal point of the lens generating a perfect spherical wave. The lens is conceptually illustrated with multiple metallic layers separated from each other by thin dielectric slabs. To work in a true-time-delay fashion, all the rays that leave the point source in different directions and are intercepted by the input aperture of the lens, must arrive at the output aperture of the lens at *the same time*. Let us assume that the aperture of the lens is divided into a number of circular concentric zones with different inner and outer radii. Let us further assume that each zone of the lens is populated with identical time-delay units. In this case, the mathematical condition that needs to be satisfied to ensure that all of the rays departing the feed point arrive at the output aperture of the lens at the same time is given by the following:

$$T_1 + TD_1 = T_2 + TD_2 = \cdots = T_M + TD_M, \quad (1)$$

where T_i is the time that it takes an electromagnetic wave to travel the distance between the feed point and the center of the i^{th} zone, and TD_i is the time-delay provided by the pixels occupying the i^{th} zone of the lens. Since the value of T_i increases as we move away from the center of the lens towards its outer periphery, TD_i should decrease to ensure the output aperture of the lens remains and equal-time surface. Assuming that the TD_i values are constant over the desired frequency band of the lens, the phase response of each pixel will be a linear function of frequency. The higher the TD_i value is, the steeper the slope of the phase versus frequency function will be. This behavior is illustrated in Fig. 2 (b), where the ideal phase responses of TDUs occupying different zones of a typical MEFSS-based planar lens are shown. As can be seen, as the zone number increases, the slope of the phase response increases as well, which indicates a larger time delay value.

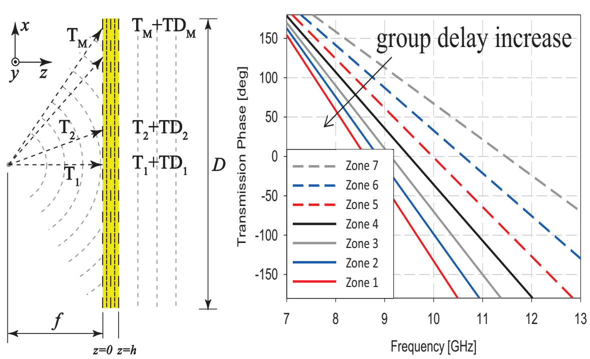


Fig. 2. (a) Side view of an MEFSS-based true-time-delay microwave lens and (b) the phase response of the different spatial time delay units occupying the aperture of the lens.

The time-delay units of an MEFSS-based microwave lens are unit cells of appropriately-designed miniaturized element frequency selective surfaces. Since these MEFSSs are designed to be impedance matched, the microwave lenses are also impedance matched. The response of an MEFSS is identified by its transfer function. In the design of MEFSS-based lenses, all pixels of the lens operate within the pass band of the MEFSSs that constitute them. Under this operational condition, each pixel introduces a minimal insertion loss and the magnitude of the transmission coefficient of the MEFSS that constitutes the pixel becomes irrelevant. In other words, only the phase response of the MEFSS and the variations of its phase response with frequency become relevant in the design of MEFSS-based microwave lenses. The design process of these lenses is based on designing MEFSSs with linear phase responses within the desired frequency band of operation. Such an MEFSS will have a constant group delay (time delay) across the frequency range where its phase response remains linear. The group delay of the MEFSS is a function of the order of its response function and the bandwidth of the FSS. For a given fixed FSS bandwidth, the group delay can be increased by increasing the order of the filter response. For a fixed filter response order, the group delay can be increased by decreasing the bandwidth of the filter. These two mechanisms can be used to design the pixels that go into the different zones of an MEFSS-based microwave lens. In the next section, we will discuss doing this in practice using MEFSSs with band-pass and low-pass responses.

III. DESIGN OF TRUE-TIME-DELAY LENSES USING BAND-PASS MEFSSs

A. Design and simulation

Figure 3 shows the unit cell topology of a band-pass MEFSS with a fourth-order response. Band-pass MEFSSs of this type are composed of a number of sub-wavelength capacitive patches and sub-wavelength inductive wires separated from one another by thin dielectric substrates. Using the design procedure presented in [12], MEFSSs of arbitrarily high orders can be designed to demonstrate a wide range of different response types, including filter responses with maximally flat group delays or linear phase types. Such MEFSSs with N^{th} order band-pass responses are composed of N capacitive layers and N-1 inductive layers. The detailed design process for MEFSSs of this type is presented in [12] and will not be repeated here for brevity.

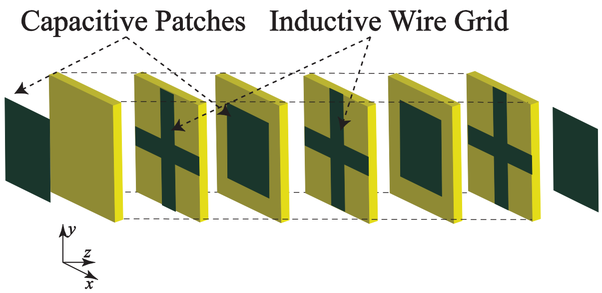
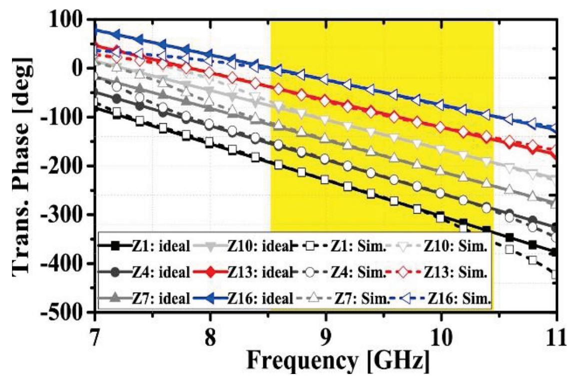


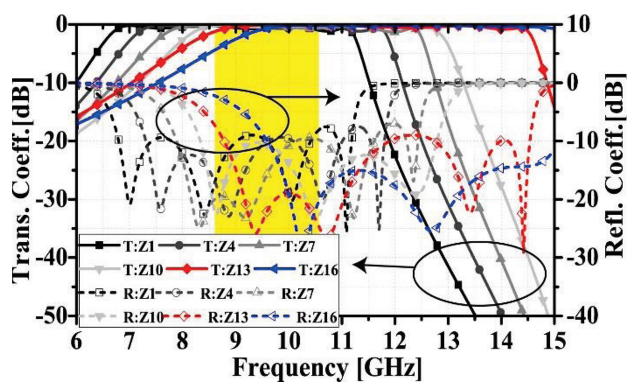
Fig. 3. Topology of a unit cell of a band-pass MEFSS of the type reported in [12]. This MEFSS has a fourth-order bandpass response and is composed of 7 metal layers and six dielectric layers.

An MEFSS-based microwave lens using band-pass MEFSSs of the type shown in Fig. 3 was presented in [15]. This lens has a circular aperture with a diameter of D=18.6 cm and a focal length of f=19 cm. This corresponds to an $f/D\approx1$. With such aperture dimensions and f/D ratio, the maximum time delay variation over the aperture of the lens is limited to approximately 63 ns. Such a time-delay range can be achieved with an MEFSS with a fourth-order bandpass response similar to the one shown in Fig. 3. In this case, the different pixels of the lens can provide linear phase responses over the frequency band of 8.5-10.5 GHz. Figure 4 shows the simulated frequency responses of the different MEFSSs that constitute the pixels of this lens. For clarity, only a subset of the responses is shown. Figure 4 (a) shows the phase responses of the different pixels that occupy different zones of the lens. The desired phase responses that will result in an ideal true-time-delay lens are also shown for each of the 16 zones of this lens. As can be observed, the pixels provide an excellent approximation of these ideal phase responses over the highlighted frequency range. Within this frequency range, the pixels act as equivalent time-delay units.

In this lens, all of the different pixels that occupy the different zones of the lens are implemented with MEFSSs with fourth-order band-pass responses. To achieve different group delays, the bandwidth of the response of each of the MEFSSs is changed. This scenario is shown in Fig. 4 (b), where the magnitudes of the transmission and reflection coefficients of the MEFSSs that were used to design the pixels occupying each of the 16 different zones of the lens are shown. As can be seen, these MEFSSs have different transmission coefficients. However, over the highlighted frequency range in Fig. 4 (b), all of their transmission coefficients overlap with one another. Within that range, each of the MEFSSs act simply as a spatial time-delay unit providing a time-delay characterized by the negative of the derivative of the phase response of the device shown in Fig. 4 (a), with respect to the frequency.



(a)



(b)

Fig. 4. (a) The simulated phase responses of the time delay units occupying the different zones of the MEFSS-based microwave lens discussed in Section III and (b) the magnitudes of the transmission and reflection coefficients of the different pixels of the lens.

B. Fabrication and measurement

The lens discussed in Section III-A is fabricated using standard Printed-Circuit-Board (PCB) fabrication and substrate bonding techniques [15].

Figure 5 shows a photograph of the fabricated prototype. The performance of the lens is characterized using a number of different measurements. First, the lens is illuminated with a plane wave from the normal direction, and the focal point of the lens is determined after the received power intensity is measured in the near field region of the lens and the location of the maximum field intensity is determined. This procedure is performed at different frequencies to experimentally determine the focal length of the antenna as a function of frequency. One of the characteristics of lenses with chromatic aberration is that their focal lengths change with frequency. Figure 6 shows the measured focal length of this lens versus frequency. As can be observed, the focal length of the lens does not change significantly with frequency, indicating minimal chromatic aberrations. For comparison, the measured focal lengths of two other MEFSS-based microwave lenses, which are not true-time-delay lenses, are also presented in Fig. 6 (these lenses are reported in [14]). Both of these lenses were designed to operate at 10.0 GHz and have bandwidths exceeding 20%. As can be observed, in both cases, the focal lengths of the lenses varies significantly with frequency, indicating that a considerable amount of chromatic aberration is present in each of them.

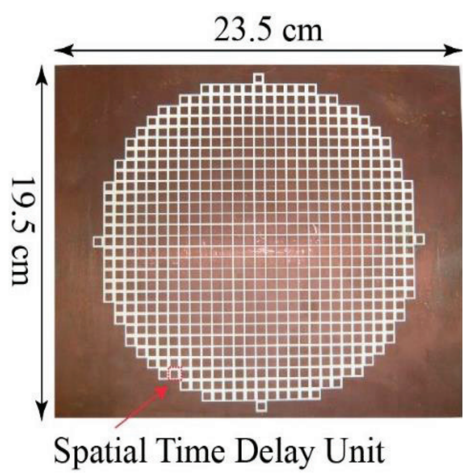


Fig. 5. Photograph of the fabricated prototype of an MEFSS-based planar microwave lens using band-pass MEFSSs (after [15]).

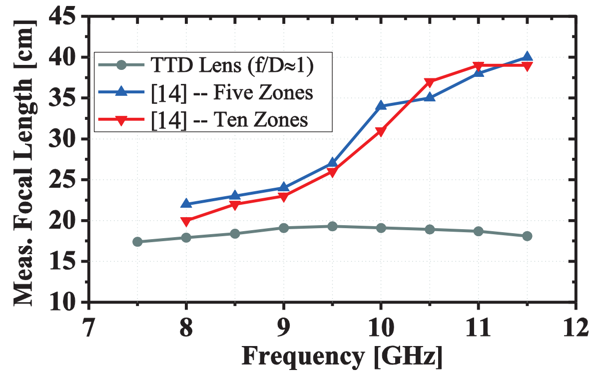


Fig. 6. Measured focal length of the lens discussed in Section III vs. frequency. For comparison the measured focal lengths of two non-TTD lenses reported in [14] are also presented.

The scanning performance of this lens is characterized using the system shown in Fig. 7. In this case, the lens is illuminated with a transmitting antenna at various incidence angles to generate plane waves arriving at the aperture of the lens from different directions. The received power pattern is then measured on the focal arc of the antenna. Because of reciprocity, if a feed antenna is placed at the location of maximum field intensity on the focal arc, a far field beam in the direction of the incoming plane wave would be excited. The measured power patterns on the focal arc of the lens are shown in Fig. 8 for three different frequencies and incidence angles in the 0°-60° range. These measured results suggest that this lens is expected to be able to operate with fields of views in the range of ±60°.

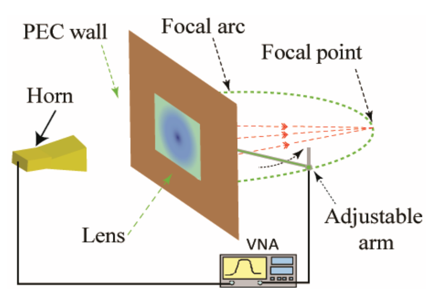


Fig. 7. The measurement setup used to measure the scanning performance of the lens under receiving conditions.

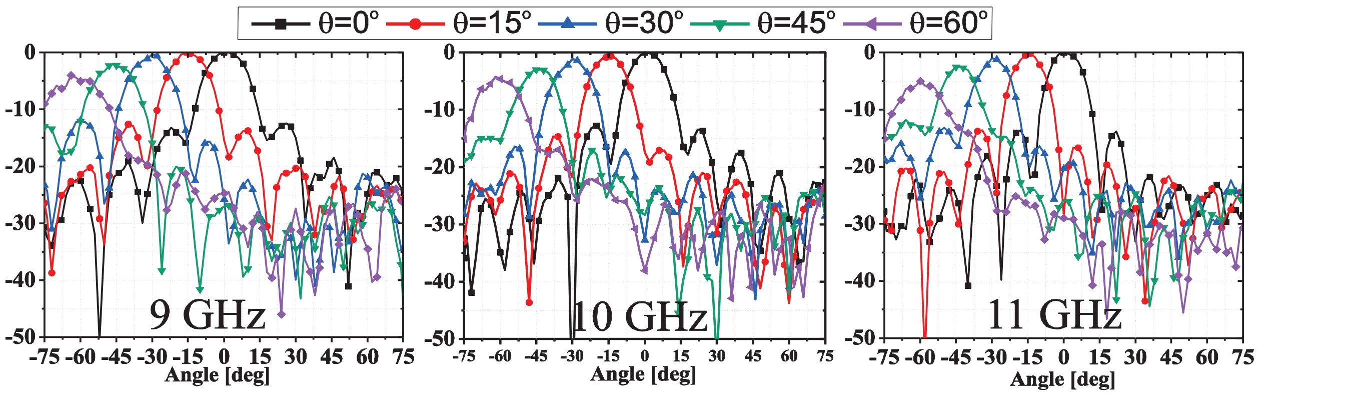


Fig. 8. Measured power patterns on the focal arc of the lens at different frequencies across its entire band of operation for different incidence angles in the 0°-60° range.

To examine the time-domain performance of the lens, its fidelity factor was measured when the lens was excited with broadband Gaussian pulses. The fidelity factor is a measure to quantify the correlation between the signal incident on the surface of the lens and the transmitted one. The procedure for calculating the fidelity factor is described in [15]. A fidelity factor of 1 means that the transmitted signal is a perfect copy of the incident signal and no temporal distortion is introduced in the signal by the lens. Fidelity factors lower than 1 indicate the level of distortion caused by the variations of the response of the lens from a perfect true time delay one. For the lens discussed in this section, the fidelity factor was measured when the Gaussian incident pulse had a center frequency of 9.5 GHz with fractional bandwidths of 10%, 20%, and 30%, and was found to be respectively equal to 0.985, 0.972, and 0.96. The fact that the fidelity factor is very close to 1.0 further confirms the true-time-delay nature of this lens. As the bandwidth of the incident pulse increases, however, the fidelity factor decreases. This can be explained by examining the phase responses shown in Fig. 4 (a). As can be observed, the responses of the spatial TDUs of this lens start to deviate from those of ideal TDUs as we approach the edge of the band. This cases the fidelity factor to deteriorate as the bandwidth of the incident pulse increases.

IV. DESIGN OF TRUE-TIME-DELAY LENSES USING LOW-PASS MEFSSs

A. Design and simulation

The TTD lens shown in Fig. 1 can also be designed if low-pass MEFSSs are used. The unit cell of such a low-pass MEFSS is shown in Fig. 9. This structure is composed of a number of sub-wavelength non-resonant capacitive patches separated from one another by thin dielectric substrates. If the dielectric substrates have small thicknesses and relatively low dielectric constants, they act as series inductors in the path of the propagating EM wave. Therefore, this structure can act as a classical low-pass filter of order $2N$-1, where N is the number of capacitive patches used. Similar to the design methodology described in Section III, the phase responses of these low-pass MEFSSs can be fitted to those of ideal true-time-delay units to synthesize the TDUs needed to populate the aperture of an MEFSS-based of the type depicted in Fig. 1.

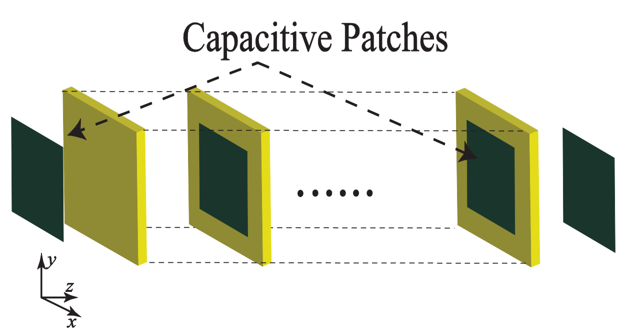
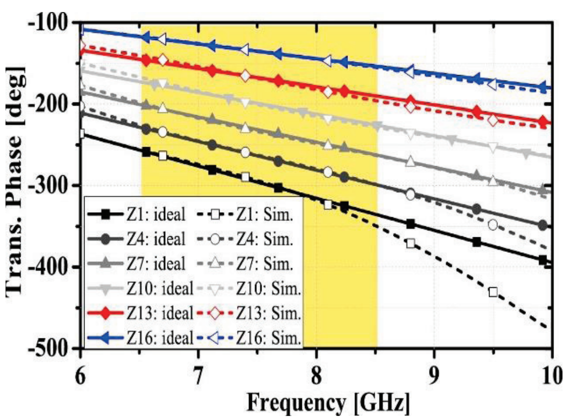
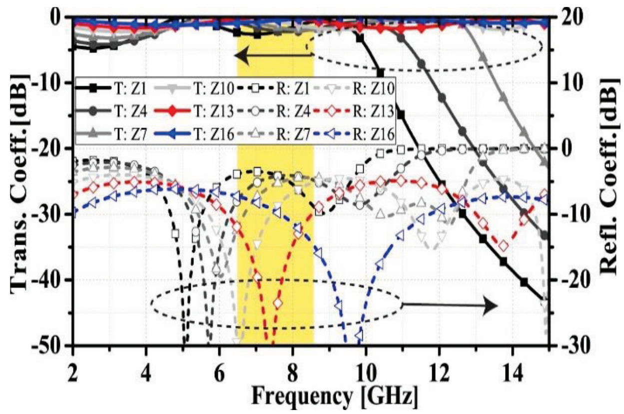


Fig. 9. Topology of a unit cell of a low-pass MEFSS. The structure is composed of a number of non-resonant metallic patches separated from each other by thin dielectric substrates.

To illustrate this in practice, let us consider an MEFSS-based lens with an aperture diameter of 19 cm and a focal length of 19 cm (i.e., *f/D*=1). The aperture of this lens is divided into 17 concentric zones and each zone is populated with identical low-pass type TDUs. Similar to the previous case, the maximum time delay variation over the lens aperture is 63 ns. This time-delay variation over the aperture of the lens can be compensated using a seventh-order low-pass MEFSS composed of four metallic layers separated from one another with three dielectric substrates. Figure 10 (a) shows the simulated phase responses of the TDUs occupying several different zones of this lens. To allow for easy comparison, the desired phase responses needed from TDUs occupying the aperture of an ideal TTD lens are also plotted in that figure. As can be seen, over the frequency range of 6.5-8.5 GHz, the TDUs provide linear phase responses and approximate the desired ideal response very well. Figure 10 (b) shows the magnitudes of the transmission and reflection coefficients of the different TDUs occupying the different zones of the lens. Similar to the previous case, the operational frequency band of the lens (6.5-8.5 GHz) falls within the pass bands of all low-pass MEFSSs used in this design. Therefore, within this operational band, the lens is expected to be completely impedance matched with no significant reflection and low insertion loss.



(a)



(b)

Fig. 10. (a) The simulated phase responses of the time delay units occupying the different zones of the MEFSS-based microwave lens discussed in Section IV and (b) the magnitudes of the transmission and reflection coefficients of the different pixels of the lens.

B. Fabrication and measurement

A prototype of this lens is also fabricated using the standard PCB lithography and substrate bonding techniques. Figure 11 shows the photograph of the fabricated prototype. The lens' response is characterized experimentally using the procedures discussed in Section III-B. Figure 12 shows the measured focal length of the lens as a function of frequency. As can be observed, the focal length of the antenna remains constant in the 7.0-9.0 GHz frequency range, which indicates that over this band, the lens does not suffer from chromatic aberrations. This frequency band is slightly different from the 6.5-8.5 GHz frequency range predicted by the simulations (see Fig. 10). This can be primarily attributed to the fact that the simulations shown in Fig. 10 are conducted when the unit cells are placed in periodic structures with infinite dimensions; whereas, the unit cells of the low-pass MEFSSs are actually used in a non-periodic environment (the lens). Nevertheless, the lens does operate over the expected bandwidth of 2.0 GHz. The fidelity factor of this lens is also measured using the procedure described in the previous section. In this case, the lens was excited with a Gaussian pulse with a center frequency that coincides with that of the lens and bandwidths of 10%, 20%, and 30%, and the fidelity factors were measured to be respectively 0.974, 0.96, and 0.95. This further confirms the true-time-delay nature of the lens.

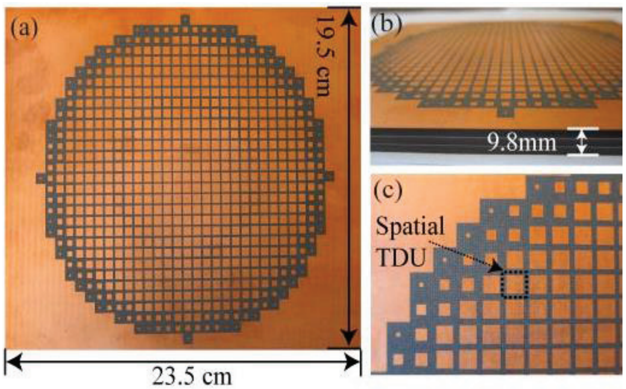


Fig. 11. Photograph of the fabricated prototype of an MEFSS-based planar microwave lens using low-pass MEFSSs (after [16]).

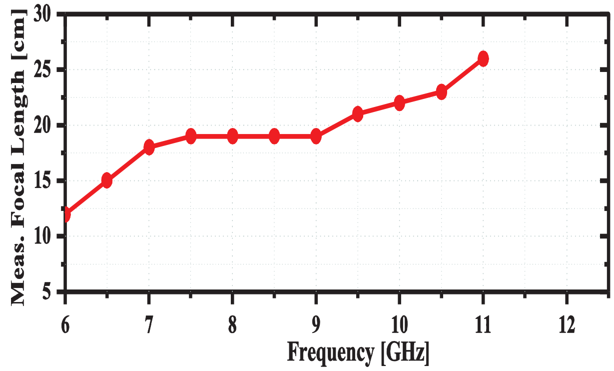


Fig. 12. Measured focal length of the low-pass-MEFSS-based planar lens described in Section IV. Over the frequency range of 7-9 GHz, the focal length of the lens remains the same, indicating very small levels of chromatic aberrations in this band.

The scanning properties of this MEFSS-based lens were measured using the setup shown in Fig. 7, and the results are presented in Fig. 13. As can be seen, over its entire band of operation, the lens can perform well when illuminated with incidence angles in the range of ±60°. Based on these results, it is expected that when lenses of this type are used in scanning antennas or multiple-beam antennas, fields of views in the ±60° range can be easily obtained.

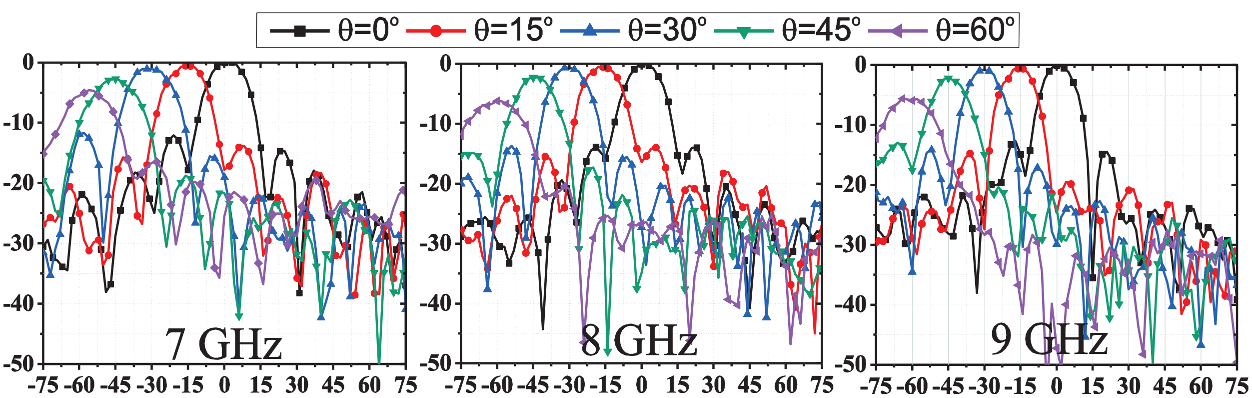


Fig. 13. Measured power patterns on the focal arc of the lens at different frequencies across its entire band of operation for different incidence angles in the 0°-60° range.

V. CONCLUSIONS

A review of the recent developments in the design of planar, true-time-delay microwave lenses exploiting the concept of miniaturized-element frequency selective surfaces was presented. TTD planar microwave lenses can be designed using either band-pass MEFSS of the type reported in [12], or using low-pass MEFSSs as described in [16]. In both cases, lenses with relatively broad bandwidths and minimal or no chromatic aberrations can be obtained. The use of low-pass MEFSSs in designing TTD lenses has the certain advantages in terms of the simplicity of the design process and its amenability to the operation at lower frequency bands. Nevertheless, both techniques can conveniently be used at microwave frequencies to design low-profile, broadband, TTD microwave lenses. The small sub wavelength dimensions of the spatial time-delay units used in these planar lenses enhances their responses when they are illuminated with oblique incidence angles. These planar microwave lenses can be useful in broadband, multi-beam, true-time-delay scanning antenna arrays.

ACKNOWLEDGMENT

This material is based upon work supported by the Air Force Office of Scientific Research under AFOSR Award No. FA9550-11-1-0050. This work is also supported in part by the National Science Foundation under NSF Awards No. ECCS-1101146.

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