A Fano-Reflection Metafilm Composed of Metamaterial-Lined Discs

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ABSTRACT This work presents a compact metafilm, which provides frequency-selective reflection and is based on subwavelength metallic discs lined using \( \mu \)-negative and near-zero (MNNZ) metamaterial liners. It is shown that such particles undergo resonance at sizes of \( \lambda/7 \) or smaller and exhibit interesting transmission/reflection behaviour. It is further demonstrated that when an array of these resonators is illuminated using a normally or obliquely incident plane wave, a Fano-shape reflection profile is obtained, exhibiting a high degree of reflection at resonance followed by strong transmission. These resonators may be closely packed since the resonance mechanism does not rely on diffraction effects. We present simulation data and experimental results demonstrating 98.4\% (18-dB) decreased transmission at resonance using a polarization-insensitive compact metafilm measuring 1.7\( \lambda \) by 2.3\( \lambda \), as well as near-transparency at other frequencies. This novel unit cell provides compact solutions for applications such as switching owing to its miniaturized size and Fano-shape reflection response.

INDEX TERMS Metasurfaces (MTSs), metafilms, \( \mu \)-negative (MNG) metamaterials (MTMs), resonance.

I. INTRODUCTION

Metasurfaces (MTSs) are the two-dimensional equivalents of metamaterials (MTMs) and can replace them in modifying and transforming electromagnetic waves [1]. They occupy less physical space than bulk, volumetric (3D) MTMs, and can be practically fabricated in a wide frequency range from the microwave to the optical [2]–[12]. By judiciously choosing the shape of their constituent scatterers, MTSs can be made to exhibit many interesting field transformations, including, but not limited to, wavefront manipulation and the design of flat lenses [13]–[19], linear to circular polarization conversion [20]–[23], polarization rotation [23]–[26], the realization of zero-index properties [27], [28], shielding [29], [30], and switching [31], [32].

MTSs may be classified into two topologies: a fishnet topology referring to apertures placed periodically in a metallic screen, which are called metascreens, or a cermet topology, referring to a 2D array of isolated metallic scatterers, called metafilms [33]. Other kinds of MTSs might be designed that lie somewhere between these two extremes [1].

In this work, a novel miniaturized metafilm unit cell is introduced. This design is motivated by a complementary metascreen technology previously presented in [34], where the miniaturization of a circular aperture in a metallic screen was achieved by means of lining the aperture using a thin layer of an epsilon-negative and near-zero (ENNZ) MTM. It was shown that the resonance frequency of the fundamental \( HE_{11} \) mode of the lined aperture can be reduced when the permittivity of the liner lies in the ENNZ regime, resulting in enhanced resonant transmission. The ENNZ property of the liner was achieved using inductively loaded, radially directed copper traces, as shown in Fig. 1(a). Here, we show that if the metallic and gap regions in Fig. 1(a) are interchanged, which causes the shunt (radially directed) loading inductors to be replaced with series (azimuthally directed) loading capacitors as shown in Fig. 1(b), a metafilm is obtained that demonstrates dual transmission/reflection behaviour. Based on the notion of duality, the metafilm structure consists of a metallic disc lined using a \( \mu \)-negative and near-zero (MNNZ) MTM liner, and supports modes with interchanged transverse electric- and magnetic-field distributions as compared to the metascreen design. This technology, like its metascreen counterpart [34], lends itself to a variety of applications ranging from shielding to imaging to switching to antenna...
In general, highly miniaturized resonators are poor radiators and hence possess low scattering loss and narrow bandwidth. The miniaturized resonators proposed in this work exhibit strong fields localized at the sites of the resonators, which implies strongly reduced coupling levels between adjacent resonators under low-loss conditions. Although broader bandwidth may be obtained by operating subwavelength elements away from resonance [35], this additional bandwidth may come at the expense of other performance criteria, such as stability with respect to the angle of incidence. The use of subwavelength, resonant elements provides a stable response with respect to the angle of incidence, while this is not necessarily true for subwavelength, nonresonant unit cells. The narrowband response and insensitivity to positioning/orientation of the array proposed in this work is advantageous in multiple applications where fine control over the spectral response is required without the need for careful alignment, such as filtering unwanted electromagnetic interference in wireless LAN applications, GSM/LTE mobile networks [36], and satellite communication systems [37].

An application of this unit cell for the design of single-layer dual-band metafilm unit cells has been shown in [38], where a novel MNNZ liner is combined with a meandered loop to create two independent, copolarized electric dipolar resonances with identical scattering response at two independent and closely-spaced frequencies in a single subwavelength unit cell. This normally requires introducing multipolar resonances or multiple layers, which negatively impacts the scattering patterns and increases fabrication complexity. That work exclusively proposes a polarization-sensitive dual-band unit cell, which is a special case of the polarization-insensitive unit cell studied in this work. Given the large number of applications that may benefit from the proposed metafilm technology, this work presents the detailed study of its unit-cell design and resonance mechanism.

This paper is organized as follows: Sec. II provides a brief overview of the application of complementarity to create an MNNZ-lined disc from an ENNZ-lined aperture (for more details, see [34]). A practical, fully printed liner design that exhibits the desired $\mu$-negative behaviour is described in Sec. III, and transmission/reflection simulation studies are presented for an infinite 2D metafilm. The field distributions of the two lowest-order modes are then obtained through eigenmode simulation studies for comparison to a circular PMC waveguide. The impact of changing various design parameters as well as oblique angles of incidence are also investigated through full-wave simulations. A fabricated prototype is then presented in Sec. IV, for which the measured transmission is compared to that obtained from simulations, demonstrating a strong agreement following the incorporation of fabrication tolerances. Applications that can benefit from this technology are discussed in Sec. V.

II. THEORY

It was shown in [34] that the fundamental resonance frequency of a circular aperture in a metallic screen can be
are replaced with discrete, in Fig. 1(a), and discrete, radially directed loading inductors are interchanged as compared to the aperture design shown in Fig. 1(b), where metal and vacuum/dielectric regions including its ENNZ frequency regime.

and it was noted that this resonance frequency can be further reduced simply by increasing the amount of inductive loading. This controls the effective permittivity of the liner, including its ENNZ frequency regime.

The complementary metafilm unit-cell design is shown in Fig. 1(b), where metal and vacuum/dielectric regions are interchanged as compared to the aperture design shown in Fig. 1(a), and discrete, radially directed loading inductors are replaced with discrete, azimuthally directed capacitors, which affect the MNNZ response. To design a polarization-insensitive metafilm, the MTM liner needs to exhibit a high degree of azimuthal symmetry. As such, a total number of 2^n capacitors where n is an integer, greater than or equal to 2 may be used, as it provides a highly symmetric response for orthogonal polarizations of incidence. Whereas n should be sufficiently large as to justify description of the liner as an effective “medium”, increasing the number of series capacitors in the MTM liner reduces the overall capacitance, and therefore, degree of miniaturization. A total number of 8 capacitors is chosen to achieve a high degree of polarization insensitivity while satisfying the effective-medium condition, without sacrificing miniaturization.

It will be shown that the response of the metafilm is the dual of that of the metascreen design; that is, the presence of an MNNZ liner reduces the resonance frequency of the metallic disc in the same way that the ENNZ liner loading reduces the resonance frequency of an aperture. The apertures presented in [34] showed increased transmission at resonance, with a Fano lineshape exhibiting a maximum followed by a minimum. Hence, the same behavior may be expected for the reflection parameter of the complementary metafilm design. Fano resonance occurs when two mechanisms of transmission interfere with one another [39]. One of these two mechanisms is required to be discrete (i.e., resonant), and the other should be continuous (i.e., nonresonant). The sharp phase change at the resonance frequency of the discrete spectrum can cause the two mechanisms to interfere constructively at one frequency and destructively at another nearby frequency, producing a peak followed by a minimum or vice versa in the frequency response. In this work, the nonresonant mechanism is offered by the background transmission, while the resonant behavior is provided by the miniaturized MNNZ-lined discs.

Fig. 1(c) exhibits the representative behaviour of the simulated vector magnetic fields that this unit cell supports at its frequency-reduced resonance. Strong transverse-magnetic-field magnitudes in the liner region along with the change in the direction of the radial fields between the disc and liner regions confirm the negative and near-zero properties of the permeability in the liner region.

III. DESIGN AND SIMULATIONS

A. TRANSMISSION STUDIES

Fig. 2 shows the practical implementation of the metafilm unit cell previously seen in Fig. 1(b), where the lumped capacitors are replaced by their fully printed interdigitated counterparts. There are multiple benefits in using fully printed loading elements including lower cost, easier single-step fabrication (as soldering of surface mount components would not be required), precise control of the resonance frequency by simply varying the capacitor’s span and/or number of interdigitations, and larger resonance contrast [38]. Important design parameters are labeled in this figure, and their values are chosen as follows: b = 8.5 mm, a = 5.15 mm, θ = 40°, w = 0.1 mm, p = 18 mm, and t = 0.1 mm, so that the fully printed metafilm unit cell resonates at 2.45 GHz.

Fig. 3 shows transmission and reflection parameters obtained through full-wave HFSS simulations for an infinite array of the following two unit cells, each illuminated using a normally incident plane wave: i) the fully printed MNNZ-loaded disc shown in Fig. 2(a), and ii) an unloaded metallic disc unit cell with an outer radius of b = 8.5 mm, plotted for reference. The screen used in each array is a Rogers/Duroid 5880 substrate (εr = 2.2, tan δ = 0.0009) of 1.524-mm thickness, metallized on one side with copper of thickness 17 µm. As is evident from the data in Fig. 3, no resonance effect is observed for the unloaded metallic-disc array (dot markers),
single polarization of excitation. Such a resonance can be to miniaturizing a disc is the creation of a meandered-loop parameter of the complementary ENNZ-liner structure [34].

metafilm, where the discs are highly subwavelength and 44 GHz in the curves corresponding to the fully printed liner loading is introduced. A resonance effect is observed since these frequencies are far below the first structural resonance of the metallic disc or grating anomalies of the array. It is important to note here that an alternative approach to miniaturizing a disc is the creation of a meandered-loop resonator, where the resonance occurs for a loop length of \( \lambda / 2 \) corresponding to the formation of two \( \lambda / 2 \) dipoles for a single polarization of excitation. Such a resonance can be supported by a loop similar to a liner, but with or without an inner disc [38]. However, the novel resonance mechanism presented here relies on applying an MNNZ liner to a metallic disc and, in fact, does not occur in the absence of the inner disc, as shown in Fig. 4 [38].

B. EIGENMODE STUDIES

To confirm the MNNZ property of the liner, the effective plasma frequency of the effective permeability of this liner was calculated using a transmission-line (TL) model in [38]. Here, we will characterize the MNNZ liner through independent eigenmode studies, which yield effective plasma-frequency and permeability values that are very consistent with those obtained from the TL studies presented in [38].

Eigenmode studies are performed on the fully printed design shown in Fig. 2. Whereas the transverse fields of the ENNZ-lined aperture resonances were described in terms of the modal cutoffs of an equivalent ENNZ-lined PEC waveguide, here, the dual analogy (an MNNZ-coated PEC rod) does not hold: we deal with resonances in which the discs support electric fields perpendicular to the inner disc (metallic) region. To facilitate description, we refer to these modes as the hybrid modes of an analogous, inhomogeneously filled PMC circular waveguide, which essentially exchanges the roles of the electric and magnetic fields and, therefore, the hybrid-mode descriptors EH and HE, while retaining the mode indices. It is worth noting that the reduced-frequency resonant modes occur in a reverse order compared to the natural modes of a PMC waveguide, as was the case with the ENNZ-lined PEC waveguide [40]. In analogy to the \( HE_{11} \) and \( EH_{01} \) resonances of the ENNZ-lined metascreen apertures, we concentrate on the \( EH_{11} \) and \( HE_{01} \) resonances of the MNNZ-lined metafilm discs, for which the reduced resonance frequencies obtained through eigenmode studies are \( f_{01} = 3.26 \) GHz and \( f_{11} = 2.39 \) GHz.

Fig. 5 demonstrates the vector magnetic (H-) and electric (E-) fields of the fully printed metafilm unit cell at \( f_{01} \) and \( f_{11} \), respectively. The resonances are classified by comparing the expected dual modal indices to the observed resonant field profile. A generally radial transverse-field distribution for vector H-fields can be observed in Fig. 5(a) at \( f_{01} \), which exhibits the expected zero azimuthal variation. Vector E-fields are expectedly perpendicular to the metallic disc region and are all co-directed, as suggested by the distribution shown in Fig. 5(b). Figs. 5(c) and 5(d) show the modal H- and E-field distributions at \( f_{11} \). Vector H-fields are strongly collimated in the inner disc region, which is consistent with the collimation of vector E-fields at the reduced \( HE_{11} \) mode of the ENNZ-lined complementary aperture design [34]. Vector E-fields possess the expected purely normal distribution on the inner disc, and the direction of these fields switches in the middle of the metallic region.

It was argued in [41] that the \( EH_{01} \) cutoff frequency of an ENNZ-lined circular waveguide coincides with the plasma frequency of the Drude dispersion profile of the liner. The permittivity of the liner approaches zero at the plasma frequency,

![FIGURE 3. Scattering parameters of an infinite 2D array of metafilm unit cell shown in Fig. 2 with design values \( b = 8.5 \) mm, \( a = 5.15 \) mm, \( w = 0.1 \) mm, \( t = 0.1 \) mm, \( \theta = 40^\circ \), and \( p = 18 \) mm. The scattering parameters of an array of unloaded metallic discs with the same outer radius \( b \) are plotted in curves with dot makers as reference (adapted from [38]).](image1)

![FIGURE 4. Transmission parameter for the unit cell shown in Fig. 2, with and without the inner metallic disc. Resonance does not occur without the disc.](image2)
FIGURE 5. (a) Vector magnetic fields of the $HE_{01}$ mode, (b) vector electric fields of the $HE_{01}$ mode, (c) vector magnetic fields of the $EH_{11}$ mode, and (d) vector electric fields of the $EH_{11}$ mode of the fully printed design obtained through eigenmode studies.

FIGURE 6. Dispersion profile of the permeability of the liner obtained through TL and eigenmode studies.

FIGURE 7. $S_{11}$ of the metafilm design when periodicity ($p$) is varied from 18 mm to 22 mm in 2-mm steps.

which implies no azimuthal variation. This condition is satisfied by the resonant field distribution of the $EH_{01}$ mode. Based on the duality observed in the resonance mechanism as well as the modal field distributions between the metafilm and metascreen unit cells, it is proposed that $f_{01}$ in this work corresponds to the effective magnetic plasma frequency of the MNNZ liner. Assuming a lossless Drude-like dispersion (i.e., $\mu = \mu_0(1 - f_{mp}^2/f^2)$) for the effective permeability of the liner with $f_{mp} = f_{01} = 3.26$ GHz suggests $\mu_r = -0.78$ at the resonance frequency of 2.44 GHz, which are very close to the values of $f_{mp} = 3.19$ GHz and $\mu_r = -0.83$ obtained through TL studies [38]. As shown in Fig. 6, the permeability values extracted through the two different studies follow Drude-like dispersions that match very well throughout the frequency band.

C. PARAMETRIC STUDIES

Parametric studies are performed on the design parameters of the proposed metafilm unit cell to establish a better understanding of the underlying mechanism of the observed resonance. Furthermore, these studies help to provide insight into controlling the resonance frequency of this unit cell.

1) PERIODICITY

In this study, the element-to-element spacing $p$ is varied from 18 mm to 22 mm in 2-mm steps, while the unit cell design is kept unchanged. The corresponding $S_{11}$ data presented in Fig. 7 show that there is only a small frequency upshift when $p$ is increased. This suggests a weak interaction between neighbouring unit cells, which is a result of strongly confined
2) DISC SIZE
The data presented in Fig. 8 are obtained when the outer radius $b$ is decreased from 8.5 mm to 6.5 mm in 1-mm steps. A decrease in $b$ (keeping liner thickness unchanged) shifts the resonance frequency up for two different reasons: i) a smaller overall resonator size, and ii) a decrease in the amount of printed capacitive loading, which will push the $f_{mp}$ of the liner to higher frequencies. This study reveals that $b$ is a major design parameter to control the operating frequency of the metafilm.

3) CAPACITIVE LOADING
Next, the effect of capacitive loading is studied independently of the disc size by changing the printed capacitor’s span $\theta$ from $32^\circ$ to $40^\circ$ in $4^\circ$ steps. As evident from the data in Fig. 9, the amount of capacitive loading controls the resonance frequency as well as the degree of miniaturization (as outer radius $b$ and unit-cell size $p$ are kept constant). These data also emphasize that capacitor span ($\theta$) is another major parameter for controlling the resonance frequency of the proposed metafilm design. By increasing $C$, the effective plasma frequency in the Drude-like dispersion model of the permeability of the liner is reduced, resulting in lower MNNZ frequency regimes, and therefore, lower resonance frequencies (i.e., higher degrees of miniaturization). Utilizing fully printed capacitors provides precise control over the operating frequency.

D. OBLIQUE INCIDENCE STUDIES
Figs. 10(a) and 10(b) show the reflection parameters of the proposed metafilm for TE- and TM-polarized incident waves, respectively, when the angle of incidence is swept from normal to $60^\circ$ in steps of $15^\circ$. As the unit cells presented in this work are miniaturized and resonant (measuring $\lambda/7$ at resonance), they show a stable response when the angle of incidence is increased towards grazing angles. This behaviour would not be achieved through arrays with electrically large unit cells. Notice that the return loss away from resonance increases for grazing TE incidence, but decreases for grazing TM incidence. This is due to the metafilm being excited by in-plane electric fields.

E. BANDWIDTH CONTROL STUDIES
The response of the proposed metafilm unit cell is typically narrowband, making it suitable for narrow-band shielding/filtering applications. Nevertheless, it is shown in Fig. 11 that some control may be obtained over the bandwidth as well as the degree of miniaturization of the proposed MNNZ-coated disc unit cell by changing the liner thickness (i.e., $t = b − a$) and/or capacitor span (i.e., $\theta$), while keeping...
FIGURE 11. Effect of different values of liner thickness and/or capacitor span on the bandwidth of the proposed metafilm design.

TABLE 1. A comparison of various properties of the proposed MTS versus other MTSs/miniaturized-element FSSs.

| Ref  | Size in free space | Size in dielectric | BW (-10dB) | Angular Stability |
|------|--------------------|-------------------|------------|------------------|
| [42] | λ/11.3             | λ_d/6             | ~ 50%      | Stable for TE, less stable for TM |
| [43] | λ/5                | λ_d/3.4           | ~ 50%      | not shown        |
| [44] | λ/11.3             | λ_d/5.4           | ~ 20%      | Very Stable      |
| [45] | λ/12.5             | λ_d/6.77          | ~ 40%      | Stable           |
| [46] | λ/12.2             | λ_d/5.88          | ~ 13%      | Very Stable      |
| [47] | λ/6.4              | λ_d/2.6           | ~ 33%      | Stable           |
| [48] | λ/3.2              | λ_d/3.2           | ~ 21%      | Stable           |
| [49] | λ/2.4              | λ_d/1.2           | ~ 22%      | not shown        |
| [50] | λ/7.3              | λ_d/4.5           | ~ 28%      | Very Stable      |
| This work | λ/6.8              | λ_d/4.6           | ~ 2.4%     | Very Stable      |

the outer radius (b) fixed. The transmission curves presented in Fig. 11 demonstrate the possibility of designing for a larger bandwidth, if desired, by the use of a thicker liner and/or a smaller capacitor span.

Table 1 contains a comparison between the proposed design and other state-of-the-art MTSs in terms of electrical size in free space but also the electrical size in the corresponding dielectric substrate in order to more fairly account for miniaturization contributed by the dielectric environment. In addition, the table compares bandwidth and qualitative measures of stability with respect to the angle of incidence. For brevity and to maximize relevance, this comparison has been limited to single-layer designs introduced for the purposes of shielding.

It can be concluded from Table 1 that the degree of miniaturization in this work is generally comparable to the existing MTSs when compared to the wavelength in the corresponding dielectric substrate, and can be further improved simply by the use of higher capacitive loading in the design of the MTM liner region, which may be realized through discrete loading capacitors. Furthermore, this design provides an advantage over existing MTSs for narrow-band filtering applications. Additionally, the proposed design demonstrates a highly stable response for oblique angles of incidence for both TE and TM incident polarizations. The characteristic Fano-profile resonance offered by the proposed unit cell is an interesting feature that allows for the design of inhomogeneous, highly decoupled resonators in an array, which may be useful for sensing/imaging applications such as the one suggested in [51], where isolation of adjacent unit cells is important. Other advantages of the proposed design lie in its simple theory and design versatility, allowing for the design of subwavelength single- or dual-band metafilm unit cells without the need for increasing the electrical size or adding more layers.

IV. FABRICATION AND MEASUREMENT

To verify the shielding response of the proposed metafilm design, a 16 × 12 array was fabricated using an LPKF Protolaser U3 laser-milling machine. Fig. 12 shows the fabricated prototype, along with an inset in the top-right corner magnifying one fabricated unit cell. The number of unit cells in the array was chosen to maximize the use of space on an available 9-in × 12-in substrate panel. The substrate used for fabrication is Rogers RT/Duroid 5880 with 17-μm copper cladding thickness, which matches that used in simulations. The fabricated structure measures 1.7λ × 2.3λ at the resonance frequency.

Fig. 13 depicts the experimental setup in an ETS-Lindgren shielded fully anechoic chamber, picturing the double-ridged
horn (DRH) antenna probe on the left-hand side and the WR-340 standard-gain horn (SGH) antenna on the right-hand side, placed at a distance of 166 cm (i.e., 14λ) from each other. The metafilm array is inserted at a distance of 39 cm from the DRH antenna (implying a distance of 127 cm from the SGH antenna). These distances are chosen as close to the far-field distances of the two antennas as possible within the space afforded by the chamber, so as to realize a plane-wave-like excitation. This experimental setup has been designed for measuring the $S_{21}$ parameter of the proposed metafilm, as this parameter proves easier to experimentally validate. As the simulation data in Fig. 3 demonstrate that this metafilm is generally low-loss, it can be concluded that a reduction in $S_{21}$ implies an increase in $S_{11}$. Furthermore, these data need to be properly normalized prior to comparison with the simulation data due to the finite size of the fabricated array versus the infinite array modeled in simulations. To do this, a large screen covered with absorbers was built with a window of the same size as the fabricated MTS in the center. The transmission parameter was then obtained with the fabricated design inserted into the window, and normalized to the corresponding values measured in its absence.

The measured $S_{21}$ is presented in Fig. 14 (solid curve) along with the simulated data (dashed curve). Although the two sets of data are in strong agreement in terms of trend and contrast, the measured data demonstrate a 95 MHz (3.9%) frequency upshift compared to the simulation data. This upshift may be attributed to an effective reduction in the value of the interdigitated capacitors caused by fabrication tolerances. In fact, a precise study of one unit cell through white-light interference profilometry demonstrates an effective trace width of 95 µm (i.e., a gap width of 105 µm) instead of the desired value of 100 µm caused by the Gaussian beam shape of the milling laser, as well as an effective copper thickness of 13 µm instead of the simulated value of 17 µm. The original simulation was repeated according to these measured parameters, and the resulting data are shown in the dotted black curve in Fig. 14. The new data show much better agreement with the measured data. A bandstop response is observed at approximately 2.5 GHz, providing better than 18-dB decrease in transmission.

V. APPLICATIONS

The degree of miniaturization in this work is generally comparable to that of existing MTSs, and can be further improved if desired simply by the use of higher capacitive loading in the design of the MTM liner region, which may be realized through discrete loading capacitors. This property can be exploited through the design of inhomogeneous partially transmitting/reflecting surfaces for beam-shaping with high-spatial-resolution control of the transmitted and reflected fields. This metafilm is also beneficial for selective shielding/filtering applications that require a compact array due to a limited available space, or need the array to remain transparent outside a narrow shielding band [37]. Furthermore, the characteristic Fano-profile resonance offered by the proposed unit cell is an interesting feature that allows for the design of inhomogeneous, highly decoupled resonators in an array, which may be useful for sensing/imaging applications such as the one suggested in [51], where isolation of adjacent unit cells is important. Moreover, the proposed unit cell is very amenable to integration of lumped tunable elements such as varactor diodes, which may be utilized to provide varied degrees of capacitive loading in the MTM liner region, and therefore, a tunable response. Another advantage of the proposed design, which was studied in [38], is that it may be made polarization-selective simply by reducing the number of series capacitors from 8 to 2 in the design of the MTM liner, which is beneficial in linear-polarization wireless applications for shielding the cross-polarized electromagnetic radiation. Such a modification also allows for much higher degrees of miniaturization ($\lambda/10$ or smaller), as a lower number of series capacitors means a higher overall loading capacitance in the MTM liner region. Reducing the number of loading elements from 8 to 2 also frees up one axis of the unit cell, which allows the addition of different loading elements for a dual-band operation without the need for adding multiple layers. The sharp Fano lineshape of the resonance may prove very useful for switching applications through the integration of nonlinear materials/elements [39].
The circular-shaped geometry of this unit cell along with its subwavelength size provides maximum adaptability for applications that require conformal MTSs [52].

VI. CONCLUSION
In this work, a novel, miniaturized metafilm unit cell was introduced through lining a metallic disc with a thin MNNZ MTM liner. It was shown that the resulting unit cell is strongly resonant while being subwavelength (smaller than λ/7) in the regime where the MTM liner exhibits an MNNZ frequency response. A Fano-like profile was observed in the S_{11} of the proposed metafilm array, providing a 4.7-dB increase in return loss compared to the unlined metallic disc array at the resonance frequency of 2.44 GHz, and a 1.2-dB reduction in return loss compared to the unlined metallic disc array at the antiresonance frequency of 2.52 GHz. The unit cell was shown to be among the smallest in the literature and provides high degrees of controllability of the resonance frequency/bandwidth through adjusting the parameters of the MTM liner. Parametric studies were presented to provide further insight into the resonance mechanism and to introduce various design parameters. Frequency insensitivity with respect to the periodicity and the angle of incidence were also studied, which are advantageous for many applications. A 16 × 12 array was fabricated and measured in an antenna anechoic chamber, confirming the expected bandstop response of the metafilm array. Finally, a list of applications based on the design versatility of this unit cell were proposed.

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