

# Second-Order Terahertz Bandpass Frequency Selective Surface With Miniaturized Elements

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**Abstract**—In this paper, a second-order frequency selective surface (FSS) made of miniaturized elements is proposed and designed for terahertz applications. The FSS is composed of two layers of metallic arrays separated from each other by a polymer dielectric spacer. The unit cells on the front and back layers are smaller than  $\lambda_0/5$ , where  $\lambda_0$  is the free space wavelength. The operation principle of the proposed FSS is described through a circuit model, and a synthesis procedure is presented for designing a desired filtering response. A prototype of the FSS is synthesized to operate at a center frequency of 0.42 THz with 45% fractional bandwidth. The designed FSS is fabricated by using microfabrication process. The performance is evaluated by using terahertz time-domain spectroscopy. Measurement results show a low sensitivity of the FSS response to oblique angles of incidence for both of the TE and TM polarizations.

**Index Terms**—Bandpass filter, frequency selective surface (FSS), periodic structures, spatial filters, terahertz (THz), THz filter.

## I. INTRODUCTION

RAPID development of terahertz applications in recent years has been underpinned by numerous designs of passive and active devices and circuits operating over millimeter-wave and terahertz frequencies [1]–[5]. Potential applications of the terahertz radiation include remote sensing [6], imaging [7], chemical and biological sensing [8], [9], etc. Terahertz frequency selective surfaces (THz-FSSs) are key components in many of these applications [10], [11]. A range of FSSs have been reported for remote sensing [12], absorbers or polarization converters in terahertz systems [13]–[15], sensing and imaging applications [16].

Several FSS structures have been proposed for bandpass filtering at terahertz and millimeter-wave frequencies [17]–[21]. A

common specification among these conventional FSS structures is that their unit cell dimensions are comparable to half of the operational wavelength. As a result, their frequency response is sensitive to the angle of incidence [22]. In order to circumvent this problem, a new class of FSS structures called miniaturized-element FSSs (MEFSSs) has been introduced in [23]. These structures are composed of multilayer arrays of non-resonant metallic elements with dimensions much smaller than the operation wavelength. The sub-wavelength unit cells provide a more consistent response of the whole structure with respect to non-planar phase fronts. Since then, a large number of MEFSS structures for higher-order spatial filtering have been designed and proposed at microwave frequencies [24]–[33]. However, they have not been demonstrated for sub-millimeter-wave and terahertz applications yet. Recently, a MEFSS has been proposed by Moallem and Sarabandi for suppressing an image component provided by a harmonic mixer in MMW radars [34]. The structure in [34] is composed of metallic patches and I-shaped wires that provide a first-order bandpass response with an adjacent transmission zero. Higher-order filters with wide out-of-band rejection are required in certain applications to enhance the spectral selectivity [17]–[21]. Particularly, FSSs with these specifications can reduce the radar cross section (RCS) of antennas, and reduce undesirable strong background noise in spectroscopy [35]. Based on this requirement, this article introduces a MEFSS with a second-order filter response for sub-millimeter-wave and terahertz applications with a wide rejection band and large angular tolerance. The proposed structure is composed of two layers of metallic arrays each having a first-order filter response. Since the structure is made of miniaturized unit cells, its electromagnetic response can be modelled through a lumped element equivalent circuit [36]–[38]. Therefore, an analytical procedure can be developed for the proposed FSS structure by using the standard filter theory leading to a straightforward design. This article is organized as follows. The design procedure and the operation principle of the proposed FSS is presented in Section II. Section III explains the fabrication process of the designed FSS. Experimental results for the fabricated sample are presented and discussed in Section IV and finally, Section V provides the conclusion.

## II. FSS TOPOLOGY AND DESIGN PROCEDURE

### A. FSS Structure and Equivalent Circuit Model

A three-dimensional view of the proposed terahertz FSS is shown in Fig. 1(a). The structure is composed of two periodic metallic arrays that are separated from each other by a dielectric

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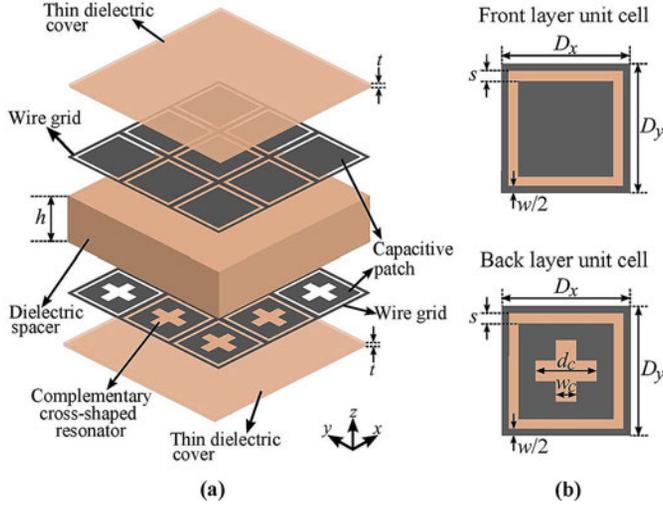


Fig. 1. Topology of the proposed second-order terahertz FSS. (a) 3-D view of the FSS with the gray regions showing the metallization and the light brown regions showing the dielectric spacer. (b) Unit cells on the front and back layers along with their geometric parameters.

spacer having a subwavelength thickness of  $h$ . Fig. 1(b) shows the unit cells for the front and back layers. The dimensions of each unit cell are  $D_x$  and  $D_y$  ( $D_x = D_y = D$ ) along the  $x$  and  $y$  directions, respectively. The front layer unit cell is made of a wire loop surrounding a non-resonant capacitive square patch. The back layer unit cell is very similar to the front layer excepting a complementary cross-shaped resonator (CCSR) that is embedded into the capacitive patch. Both of the front and back 2-D metallic arrays are covered by a very thin protective layer (thickness =  $t$ ) made of the same dielectric material as the spacer.

As mentioned before, since the structure is composed of miniaturized unit cells, it can be modeled by a lumped-element equivalent circuit. The equivalent circuit model of this FSS is depicted in Fig. 2(a), which is valid for a normally incident plane wave. In this model,  $L_1$  and  $L_2$  account for the inductive behavior of the front and back layers wire grids. The capacitors  $C_{L1}$  and  $C_{L2}$  model the capacitive effect between the square patch and the inductive wire grid in the front and back layers, respectively. The CCSR in the back layer is modelled by a  $L_3C_3$  resonator. The dielectric spacer that separates the two layers is modelled through a section of transmission line with a characteristic impedance of  $Z_T$  and length of  $h$ . It should be mentioned that  $Z_T = Z_0/\sqrt{\epsilon_r}$ , where  $Z_0 = 377 \Omega$  is the free space impedance and  $\epsilon_r$  is the relative permittivity of the spacer. And finally, the Ohmic loss associated with the front and back wire grids and CCSR are modeled by resistors  $R_1$ ,  $R_2$  and  $R_3$  respectively. These losses are related to the surface resistivity of the metallization and the current distribution therein [34]. The combination of the complementary cross-shaped resonator ( $L_3C_3$ ) and  $C_{L2}$  adds a transmission zero to the filter response and improves its out of band behavior. In fact, this transmission zero appears at the frequency when the combination of  $C_{L2}$  and  $L_3C_3$  is short-circuited. Thus, this frequency is given by

$$f_z = \frac{1}{2\pi\sqrt{L_3(C_3 + C_{L2})}}. \quad (1)$$

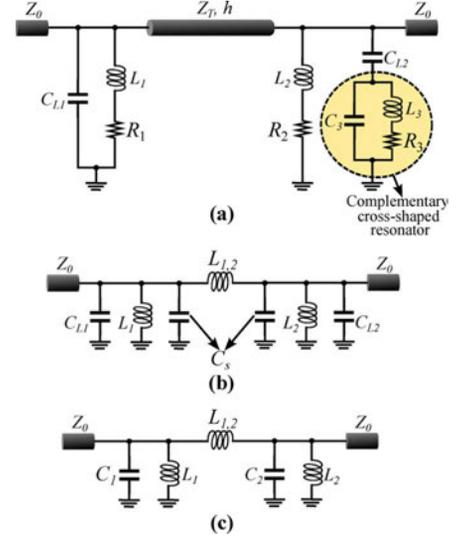


Fig. 2. Equivalent circuit model of the proposed FSS for the normally incident EM wave. (a) A full circuit model for normal incidence. (b) A simplified model with the transmission line section replaced with equivalent lump elements and the loss  $R$  neglected. (c) Standard circuit model of a second-order bandpass coupled resonator filter. This circuit is equivalent to the circuit in Fig. 2(b) with  $C_1 = C_{L1} + C_s$  and  $C_2 = C_{L2} + C_s$ .

This transmission zero can be tuned by varying the dimensions of the complementary cross-shaped resonator ( $d_c, w_c$ ), which in turn translates to the variation of  $L_3$  and  $C_3$  values.

Since the values of  $L_3$  and  $C_3$  are designed to be much smaller than  $L_2$  and  $C_{L2}$ , the parallel combination of  $L_3C_3$  has a very small impedance around the passband frequencies of the FSS. So,  $L_3C_3$  can be considered as a short circuit at these frequencies. In addition, the transmission line section can be replaced with its equivalent lumped-element circuit model by using the telegrapher's equation [39]. Fig. 2(b) illustrates the FSS equivalent circuit around the passband by considering  $L_3C_3$  as a short circuit and replacing the transmission line with its circuit model ( $L_{1,2}$  and  $C_s$ ). The losses are not considered in Fig. 2(b) for simplicity. The values of  $L_{1,2}$  inductor and  $C_s$  capacitors can be obtained by using the following relations [22]

$$L_{1,2} = \mu_0\mu_r h, \quad (2)$$

$$C_s = \frac{\epsilon_0\epsilon_r h}{2} \quad (3)$$

where  $\mu_0$  and  $\mu_r$  are the permeability of the free space and the relative permeability of the spacer, respectively. Likewise,  $\epsilon_0$  and  $\epsilon_r$  are the permittivity of the free space and the relative permittivity of the spacer, respectively. The circuit of Fig. 2(b) can be converted into the one in Fig. 2(c) that shows a standard basic circuit model of a second-order bandpass filter [40]. In this form,  $C_1 = C_{L1} + C_s$  and  $C_2 = C_{L2} + C_s$ , and the circuit can be considered as coupled input and output resonators of  $L_1C_1$  and  $L_2C_2$ , respectively.

### B. Synthesis Procedure of the Proposed FSS

As discussed above, the frequency response of the considered FSS around its passband can be described by the circuit model in Fig. 2(c). By using this circuit model, a desired second-order

filtering response can be synthesized and then, the equivalent circuit parameters can be converted into the corresponding geometrical parameters of the proposed FSS. The lumped-element values of the equivalent circuit in Fig. 2(c) can be determined by applying the concept of coupled-resonator filter with inductive coupling [36], [40]. Supposing that  $f_0$  is the center frequency of the filter and  $\delta = \text{BW}/f_0$  is the fractional bandwidth, the values of the circuit elements in Fig. 2(c) can be obtained based on the following steps:

- 1) The values of the  $C_1$  and  $C_2$  capacitors can be determined from the following relation:

$$C_i = \frac{q_i}{\omega_0 r_i Z_0 \delta}, \quad i = 1, 2. \quad (4)$$

In (4),  $Z_0 = 377 \Omega$ ,  $q_1$  and  $q_2$  are the normalized quality factors of the input and output resonators, and  $r_1$  and  $r_2$  are the normalized source and load impedances of the filter in Fig. 2(c) [40].

- 2) The values of  $L_1$  and  $L_2$  inductors can be obtained by

$$L_i = \frac{1}{\omega_0^2 (C_i - k_{1,2} \delta \sqrt{C_1 C_2})}, \quad i = 1, 2 \quad (5)$$

where  $k_{1,2}$  is the normalized coupling coefficient between the input and output resonators.

- 3) The coupling inductance  $L_{1,2}$  can be calculated from

$$L_{1,2} = \frac{1}{\omega_0^2 k_{1,2} \delta \sqrt{C_1 C_2}}. \quad (6)$$

The normalized quality factors and coupling coefficient for some different filter types are extracted from [40] and presented in Table I.

After calculating the values of the circuit elements in Fig. 2(c), the thickness of the dielectric spacer that separates the front and back metallic arrays can be obtained from (2). Then the spacer capacitance  $C_s$  can be derived from (3), and the values of  $C_{L1}$  and  $C_{L2}$  capacitors can be found from (7).

$$C_{Li} = C_i - \frac{\epsilon_0 \epsilon_r h}{2}, \quad i = 1, 2. \quad (7)$$

In order to convert the calculated lumped element values into the geometrical parameters, the method presented in [36]–[38] can be used. The effective inductance of an infinite wire grid shown in Fig. 3(a) with a period of  $l$  and a wire width of  $w$  is given by [22]

$$L = \mu_0 \mu_{\text{eff}} \frac{l}{2\pi} \ln \left( \frac{1}{\sin \frac{\pi w}{2l}} \right) \quad (8)$$

where  $\mu_0$  is the permeability of the free space and  $\mu_{\text{eff}}$  is the effective permeability of the substrate. Equation (8) can be used for calculating the wires width in the front and back layer metallization of the proposed FSS. The period of the wire grid is considered to be equal to the unit cell size in Fig. 1 ( $l = D$ ) and the unit cell size can be chosen arbitrarily. However, choosing very small unit cell size leads to a very thin wire that might not be practical due to fabrication limits. It is worth mentioning that (8) is valid when the wire grid is away from any metallic objects such as capacitive patches in Fig. 2 or scatterers [36], [38]. So, the value of  $w$  calculated from (8) can only be used as an approximation. A more accurate value of  $w$  can be obtained

TABLE I  
NORMALIZED QUALITY FACTOR AND COUPLING COEFFICIENTS FOR DIFFERENT FILTER TYPES EXTRACTED FROM [40]

Filter Type	$q_1$	$q_2$	$k_{12}$	$r_1$	$r_2$
Gaussian	0.4738	2.185	0.9828	1	1
Butterworth	1.4142	1.4142	0.70711	1	1
Chebyshev (0.01 dB ripple)	1.4829	1.4829	0.7075	1	1.1007
Chebyshev (0.1 dB ripple)	1.6382	1.6382	0.7106	1	1.3554
Chebyshev (0.5 dB ripple)	1.9497	1.9497	0.7225	1	1.9841

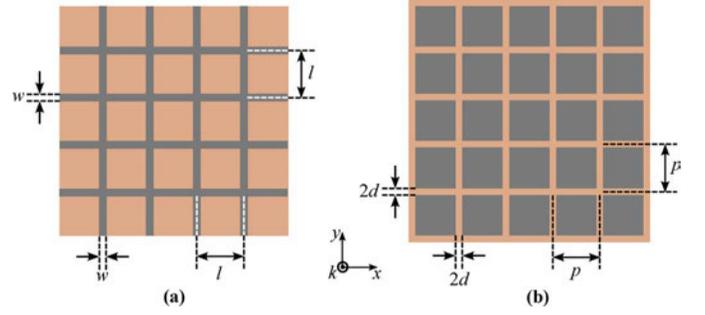


Fig. 3. (a) Infinite metallic wire grid. (b) Infinite metallic square patch array. The wire grid shows an inductive behavior whereas the patch array shows a capacitive effect with respect to the incident electromagnetic wave. Metallization is indicated with gray colored regions.

by fitting the full-wave simulation result to the analytical circuit calculation.

The effective capacitance of an infinite array of sub-wavelength capacitive square patches shown in Fig. 3(b) can be obtained by using [22]

$$C = \epsilon_0 \epsilon_{\text{eff}} \frac{2p}{\pi} \ln \left( \frac{1}{\sin \frac{\pi d}{2p}} \right). \quad (9)$$

In (9),  $\epsilon_0$  is the permittivity of free space and  $\epsilon_{\text{eff}}$  is the effective permittivity of the dielectric spacer,  $p$  is the period of the array and  $2d$  is the gap spacing between the adjacent patches. Although for the proposed structure, the capacitive patches are surrounded by the wire grid, (9) can still be used as an approximation if the capacitive effect between the edges of the metallic square patches and the wire grid is approximated by a corresponding patch array in Fig. 3(b). To this end, the gap spacing between the adjacent metallic patches in Fig. 3(b) is assumed to be equal to the space between a capacitive patch and the wire grid in Fig. 1(b) ( $2d = s$ ). By this assumption, the period of the corresponding patch array of Fig. 3(b) will be

$$p = D - w - s, \quad (10)$$

where,  $D = D_x = D_y$  is the unit cell size in Fig. 2(b) and  $w$  is the width of the wire grid surrounding each capacitive patch. Based on (9) and (10), the spacing between the patches in Fig. 3(b), that corresponds to the spacing between the patches and the wire grid in Fig. 2 can be determined.

### C. Design of Terahertz FSS

Based on the synthesis procedure in Section II-B, this section demonstrates a design of a second-order bandpass FSS at terahertz frequencies. The design starts by considering a center fre-

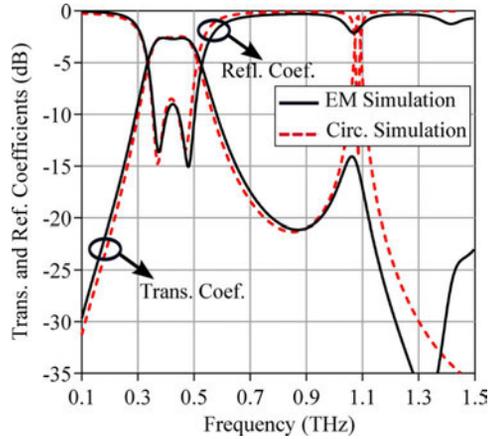


Fig. 4. Simulation results of the proposed FSS for the normal incident angle. The parameters used in simulations are:  $C_{L1} = C_{L2} = 4.2$  fF,  $L_1 = L_2 = 45$  pH,  $R_1 = R_2 = 6.5$   $\Omega$ ,  $D_x = D_y = 130$   $\mu\text{m}$ ,  $h = 100$   $\mu\text{m}$ ,  $t = 10$   $\mu\text{m}$ ,  $w = 10$   $\mu\text{m}$  and  $s = 5$   $\mu\text{m}$ .

frequency of  $f_0 = 0.42$  THz and a  $-3$  dB fractional bandwidth of  $\delta = 35\%$  for the circuit model in Fig. 2(c). This frequency band is chosen to match the capabilities of most terahertz time-domain spectroscopy (THz-TDS) systems. Polydimethylsiloxane (PDMS) is considered for the dielectric spacer since it has a low dielectric constant of  $\epsilon_r = 2.35$  causing a low impedance mismatch with free space [34]. The front and back metallic layers are made of 200 nm thick gold (Au) with the DC conductivity of  $4.1 \times 10^7$  S/m and the sheet resistance of around  $0.2 + j0.22$   $\Omega/\text{square}$  at the passband of the FSS. In order to improve the mechanical strength of the filter, two encapsulating PDMS layers with a thickness of 10  $\mu\text{m}$  are applied to the front and back metal layers. The relative permeability of the PDMS is  $\mu_r = 1$ . By assuming a Butterworth filter response, the values of the circuit elements in Fig. 2(a) are calculated using the synthesis method described in Section II-B. The calculated values are  $C_1 = C_2 = 4.23$  fF,  $L_1 = L_2 = 45$  pH and  $L_{1,2} = 130$  pH. The unit cell size is considered as  $D_x = D_y = D = 130$   $\mu\text{m}$ , which is slightly smaller than the  $\lambda_0/5$ , where  $\lambda_0$  is the free space wavelength at 0.42 THz. By using the procedure described in Section II-B, the circuit parameters can be mapped into the geometrical dimensions of the FSS:  $w = 14.8$   $\mu\text{m}$ ,  $s = 4.5$   $\mu\text{m}$  and  $h = 103$   $\mu\text{m}$ . Now,  $w$  and  $s$  can be optimized in simulation for obtaining more accurate values. Equation (9) is reasonably accurate since the capacitance between the patches in Fig. 3(b) corresponds directly to the capacitance between the patches and grid in Fig. 1. On the other hand, the presence of those square metallic patches in the vicinity of the wire grid affects the magnetic field and hence reduces the inductance. So, the final optimized value of  $w$  is expected to be smaller than the value obtained from (8). For optimization, we first consider the calculated value of  $w$  from (8) based on the synthesized value of  $L_1$  and  $L_2$ . Now, by having  $D$  and  $w$ , the value of  $s$  will be determined from (9) to satisfy the synthesized value of  $C_1$  and  $C_2$ . The unit cell is then simulated to obtain the  $L$  and  $C$  values. If the inductance of the wire grid obtained from the simulation is smaller than the synthesized value, the previous steps are then repeated with a smaller value for  $w$ , until

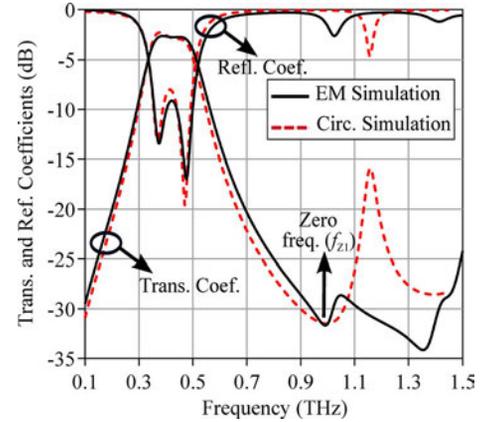


Fig. 5. Simulation results of the proposed FSS for the normal incident angle by considering the effect of the complementary cross-shaped resonator. The complementary cross shaped resonator dimensions are:  $w_c = 20$   $\mu\text{m}$ ,  $d_c = 65$   $\mu\text{m}$  and  $L_3 = 3$  pH,  $C_3 = 2.9$  fF,  $R_2 = 1.2$   $\Omega$  and  $R_3 = 4.25$   $\Omega$  are considered in circuit model simulations. The rest of parameters are the same as the Fig. 4.

desired consistency between the simulation results and the synthesized values is achieved. The optimized equivalent circuit and geometrical parameters of the designed FSS are listed in the caption of Fig. 4. As seen, the optimized value for  $s$  is very close to the value obtained from (9) but, the optimized value of  $w$  is smaller than the value predicted by (8).

After mapping the synthesized values of the  $L$  and  $C$  parameters to the geometrical parameters of the FSS, the values of the resistances in Fig. 2 can be determined by curve fitting of the EM and circuit simulation results. Fig. 4 shows a comparison between the results obtained from the circuit simulation with ADS and from the full-wave electromagnetic simulation with CST Microwave Studio. Both of the transmission and reflection coefficients are shown. As can be observed in Fig. 4, there is a good agreement between the circuit model and the full-wave electromagnetic simulation of the FSS. The good agreement confirms that the circuit based synthesis procedure offers an efficient analytical method for designing the proposed FSS configuration.

The results in Fig. 4 are obtained without considering the effect of the CCSR. As explained in Section II-A, the combination of CCSR ( $L_3$ ,  $C_3$ ) and  $C_{L2}$  adds a transmission zero that can be used to improve the out of band response of the FSS. The frequency of this zero can be calculated from (1) and can be tuned by varying  $w_c$  and  $d_c$ . Fig. 5 shows the transmission response of the FSS by considering  $w_c = 20$   $\mu\text{m}$  and  $d_c = 65$   $\mu\text{m}$ . As seen, the out of band response in Fig. 5 is improved with respect to Fig. 4 since the transmission coefficient stays below  $-27$  dB up to 1.45 THz.

The values of  $L_3$  and  $C_3$  elements that represent the effect of the CCSR can be determined by a semi-analytical procedure described as follows: the zero frequency provided by  $L_3$ ,  $C_3$  and  $C_{L2}$  can be calculated from (1). The value of  $C_{L2}$  as listed in caption of Fig. 5 is already designed by the synthesis procedure. On the other hand, the zero frequency is obtained from EM simulation in CST Microwave Studio ( $f_{z1}$  in Fig. 5). By putting arbitrary capacitors of  $C_{ar}$  between the capacitive square patches and the wire grid in the back layer of the FSS in CST Microwave Studio, the capacitance between the wire grid

and square patches will be increased to  $C_{L2} + C_{ar}$ . This will shift down the zero frequency to

$$f_{Z2} = \frac{1}{2\pi\sqrt{L_3(C_3 + C_{L2} + C_{ar})}}. \quad (11)$$

So, by solving (1) and (11), the unknown values of  $L_3$  and  $C_3$  are determined. The calculated  $L_3$  and  $C_3$  for the designed FSS are given in Fig. 5. It should be noted that the circuit model in Fig. 2(a) and the results in Fig. 5 are only valid for normal incidence. For oblique incidence, both of the free-space equivalent impedance  $Z_0$  and the dielectric spacer impedance  $Z_T$  need to be changed to

$$Z_{0,TE} = \frac{Z_0}{\cos \theta} \quad (12)$$

$$Z_{0,TM} = Z_0 \cos \theta \quad (13)$$

$$Z_{T,TE} = \frac{Z_{0,TE}}{\sqrt{\epsilon_r}} \quad (14)$$

$$Z_{T,TM} = \frac{Z_{0,TM}}{\sqrt{\epsilon_r}} \quad (15)$$

where  $Z_0 = 377 \Omega$  is the free-space characteristic impedance. In addition, the front and back layers equivalent impedance need to be modified for the oblique incidence [41]. A model describing the effect of oblique incidence on the impedance of the layers and the couplings in higher order Floquet modes is available for the square patch array [41], [42]. This model gives an insightful understanding of the FSS response under oblique incidence and in higher order Floquet modes.

### III. FABRICATION PROCESS

The FSS structure is fabricated to experimentally validate the simulation results by utilizing standard microfabrication techniques. The FSS is composed of alternating three layers of PDMS and two layers of patterned metal. In the first step, as a supporting substrate, a 3 inch silicon wafer is coated with 20 nm aluminium (Al), which enables final release of the multi-layer structure from silicon in a freestanding form. A 10  $\mu\text{m}$  PDMS layer acting as encapsulation is spin-coated on the Al-coated silicon wafer. First metallization step is performed with 200 nm gold (Au) with a 20 nm adhesion layer of chromium (Cr) deposited by electron beam evaporation (PVD75, Kurt J. Lesker) at a rate of 0.1 nm/s. Metal layers are patterned by photolithography followed by wet chemical etching [2], [3]. Photoresist is then stripped off with acetone, rinsed with isopropanol and dried with high purity nitrogen.

Then, a second PDMS layer of 100  $\mu\text{m}$  thickness, acting as dielectric spacer, is spun-on and cured on a leveled surface at room temperature to ensure thickness uniformity. Subsequently, the second layer of metallization followed by photolithography with alignment and etching is performed. To encapsulate the second level of metallization, a third PDMS layer of 10  $\mu\text{m}$  is spun-on to complete the fabrication. The resulting structure is then peeled off from the supporting silicon and transferred onto a 3 inch clamp for testing. Fig. 6 shows micrographs of the front and back metal layers and the fabricated structure supported in a clamp for testing.

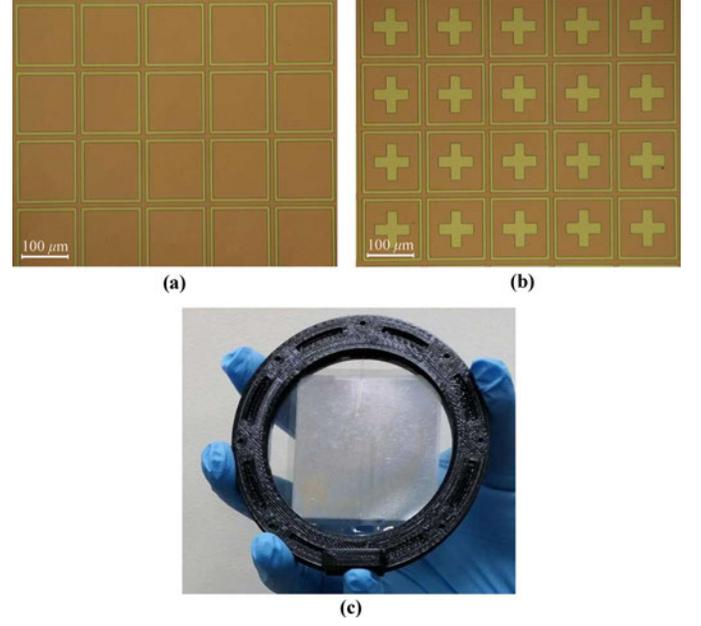


Fig. 6. Fabricated second-order terahertz FSS. Optical micrographs of the (a) front and (b) back layers. (c) Frame-supported MEFSS after release.

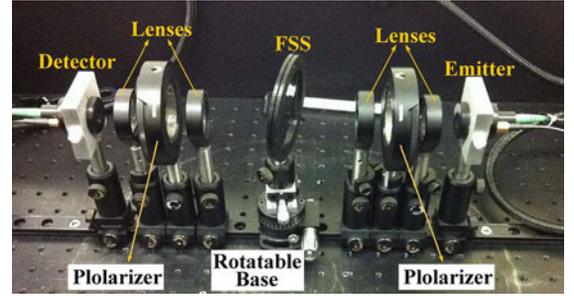


Fig. 7. Free-space measurement setup. A rotatable base is considered for measuring the FSS performance at oblique angles of incidence.

### IV. RESULTS AND DISCUSSION

This section presents the simulation and experimental measurement results to evaluate the performance of the designed FSS under different conditions. The free-space measurement is performed using the Menlo Systems GmbH Tera K15. The measurement setup is shown in Fig. 7. The setup is composed of Tera 15-SL25-FC and Tera 15-DP25-FC antenna modules acting as emitter and detector respectively that provide 2-port S-parameter measurement. The four identical lenses are made of polymer with a diameter of 50 mm, an effective focal length of 54 mm, and a working distance of 46 mm. A rotatable base is used for the FSS to evaluate its response for different oblique angles of incidence. The emitter and detector can be rotated around the propagation axis to obtain TE and TM polarizations. Two polarizers are placed between the lenses to have better polarization purity in TE and TM mode measurements. A broadband terahertz pulse is radiated from the emitter through the FSS to the detector. The four lenses collimate and focus the beam onto the FSS. The transmission response is then normalized with a response obtained from free-space measurement.

In Fig. 8, the measured transmission response of the fabricated FSS is plotted together with the electromagnetic and

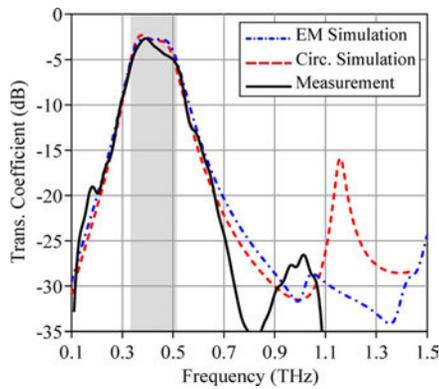


Fig. 8. Comparison between the simulation and measurement results of the FSS transmission coefficient under normal angle of incidence. The  $-3$  dB bandwidth is shaded with gray.

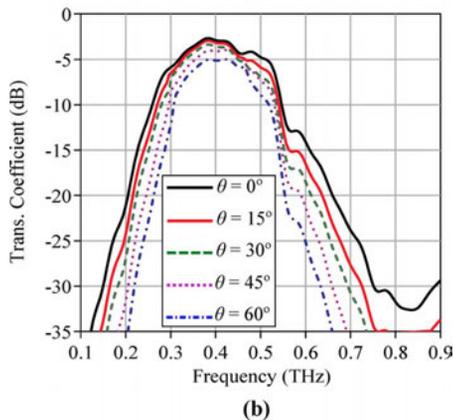
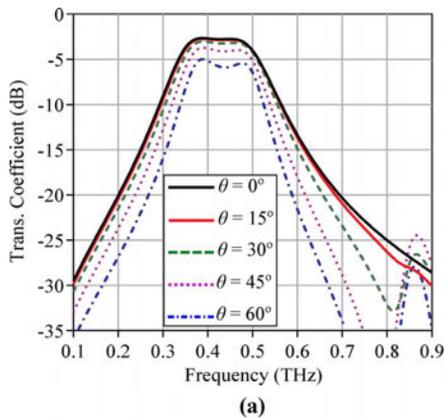


Fig. 9. Transmission responses of the proposed FSS for oblique angles of incidence with TE polarization. (a) Simulated transmission responses in CST Microwave Studio. (b) Measured transmission responses.

equivalent circuit simulation results at normal angle of incidence. As seen in this figure, a good agreement between the simulation and measurement results is achieved within the measurement bandwidth. The center frequency is 0.42 THz and the  $-3$  dB bandwidth of the passband is around 45%. This is wider than the designed 35% bandwidth because the dissipation losses decrease the quality factor ( $Q$ ) of the front and back layers and hence increase the bandwidth. A wide out-of-band rejection is obtained up to 1.5 THz below  $-25$  dB. The maximum loss in the passband is less than 5 dB. This loss is mainly attributed to the dielectric loss in the PDMS layers. Additional simulations (not

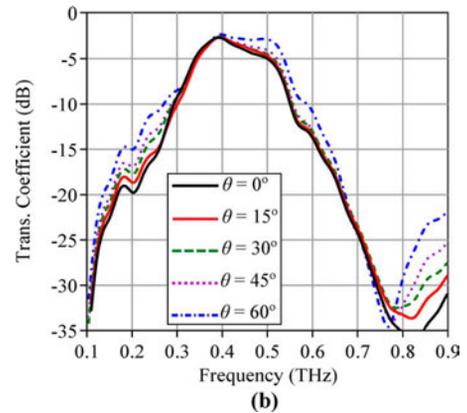
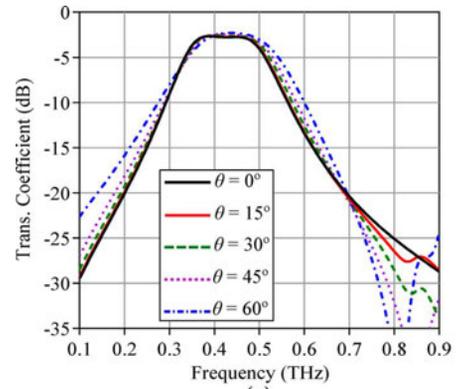


Fig. 10. Transmission responses of the proposed FSS for oblique angles of incidence with TM polarization. (a) Simulated transmission responses in CST Microwave Studio. (b) Measured transmission responses.

shown) reveal that by replacing PDMS layers with a lower loss material such as cyclo-olefin copolymer (COC), the insertion loss in passband is reduced to 1 dB. The discrepancies between the measured and EM simulation results in the out-of-band response is attributed to the limited dynamic range of the measurement system.

The performance of the proposed FSS for the oblique angles of incidence is also investigated through simulation and measurement. The simulated and measured transmission coefficients of the FSS for the TE polarization are shown in Fig. 9. In addition, Fig. 10 presents the simulated and measured transmission coefficients for the TM polarization. In both cases, the results are presented for  $0^\circ$ – $60^\circ$  incidence angles. As observed, the FSS can reasonably sustain its original response at very large incidence angles. However, the fractional bandwidth (FBW) is decreased for the TE polarization response as the angle of incidence increases. On the contrary, for the TM polarization, the FBW is increased as the incidence angle increases. This is mainly due to a change in the wave impedance for the two modes as described through (12)–(15) [43]. So, as the angle of incidence increases,  $Z_{0,TE}$  will be increased resulting in a larger loaded quality factor in the input/output resonators that causes a smaller fractional bandwidth. On the other hand, in the TM mode,  $Z_{0,TM}$  will be decreased by increasing  $\theta$ , and thus leads to a smaller loaded quality factor in the input/output resonators and a larger fractional bandwidth. A small discrepancy between the measured TE and TM transmission responses under normal

incidence is possibly caused by a small difference in the system alignment and by a small anisotropy in the sample.

## V. CONCLUSION

A second-order bandpass FSS based on miniaturized elements has been proposed and implemented for terahertz applications. An equivalent circuit is considered for modelling the FSS response. A simple synthesis procedure has been developed based on the equivalent circuit and the standard filter theory for designing the proposed FSS. The presented synthesis procedure has been verified through both simulation and experimental results. The results show a wide out-of-band rejection below  $-25$  dB up to 1.5 THz. In addition, the spectral responses of the FSS are consistent over a wide range of incidence angles for both the TE and TM polarizations. The transmission level of the FSS in the passband can be improved significantly by a low loss polymer such as COC for dielectric layers.

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