Aperture Antenna Embedded Notched Parallel Plate Waveguide and Its Application to Dual-Polarized 3-D Absorptive Frequency-Selective Transmission Structure

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ABSTRACT

This paper introduces an angular-insensitive dual-polarized 3-D absorptive frequency-selective transmission structure (AFST), which has a transmission window and an upper absorption band. The transmission band is produced by lossless resonators implemented using an aperture antenna embedded notched parallel plate waveguide with a metalized via hole in the center. The absorption band is obtained by lossy resonators constructed by the single resistor embedded bent metallic strips. In addition, the whole structure is constructed without backing discontinuous metallic ground plane, which overcomes the fabrication difficulty of conventional 3-D structures. Physical mechanism of the proposed AFST is explained with the aid of an equivalent circuit model, as well as current and electric field distributions. A prototype of the designed AFST is fabricated and measured, and experimental results show that a fractional transmission bandwidth of 20.5\% and an upper absorption bandwidth of 28.8\% with absorptivity around 90\% for both TE- and TM-polarizations are achieved under oblique incident wave up to 50\°.

INDEX TERMS

Absorptive frequency-selective transmission structure (AFST), 3-D frequency selective structure (FSS), rasorber, RCS reduction.

I. INTRODUCTION

Frequency selective structures (FSSs) are widely known as a spatial filter for electromagnetic waves, which have been used in a large range of applications for their attractive frequency filtering characteristics [1]–[3]. However, traditional FSSs are often designed as bandpass structures transmitting the in-band waves while reflecting the out-of-band waves, which prevent interference but results in a large radar cross section (RCS). With the development of information detection technique, it is necessary to improve the communication security and stealth performance of the platform with FSS installed. A new kind of structures termed as absorptive frequency-selective transmission structure (AFST) was reported in [4]. The AFSTs perform unique characteristic of being transparent to incident EM waves in the passband and absorptive outside the passband, thus out-of-band RCS can be reduced.

Multitudinous AFSTs were reported recently [5]–[21], which were usually constructed by cascading a lossy layer above a slot-type FSS. In order to obtain expectable transmission and absorption performances, various lossy resonant structures are utilized in the lossy layer to realize the absorption band, while a lossless resonance is built to generate the transmission band. However, these multilayer based AFSTs often suffer from large unit cell size and unstable filtering response over a large incident angle of waves. Moreover, most of the existing AFSTs have the feature of narrow transmission band and relatively large insertion loss.
Three dimensional frequency selective surfaces (3-D FSSs) consisting of a two dimensional periodic array of multimode resonators, which resonate in the wave transmitting direction, were proposed [22]–[25], and they can readily achieve low insertion loss, high selectivity and stable angular incidence wave performance although the implementation of these 3-D FSSs are more complicated compared with multilayer FSSs. 3-D AFSTs, deriving from 3-D FSSs, separate the transmission and absorption propagation paths, and then attractive AFSTs with low insertion loss, easy controllable bandwidth and angular-insensitive can be obtained [26]–[29].

Loading an array of lumped resistors at one side of a microstrip-line based bandpass FSS is a classical structure to build multiple resonators of 3-D AFSTs, including lossy resonators, and absorption band is realized in the upper side of the passband [26]. Another attempt is realized by employing two lossy resonators and one lossless resonator in the unit cell to produce two absorption and one transmission bands, although the lower absorption band is very narrow [27]. Then, two kinds of AFSTs with two wide absorption bands are constructed by a tailoring methodology through introducing a transmission window in an ultra-wideband absorber [28], and utilizing the intrinsic reflection band and higher-order absorption band of a wideband 3-D absorber [29].

However, all of aforementioned 3-D AFSTs only operates under single polarization. Because encircle metallic plates are required for the dual-polarization 3-D AFSTs, it will form the waveguide pattern and bring the cut-off frequency to intercept incident wave in the operating band. It is imperative to realize a dual-polarized AFST while maintaining the wide passband and stable angular response.

Fortunately, there is a clear sign showing that the researchers have realized the problem of the 3-D AFSTs working under single polarization only. An AFST based on parallel plate waveguides is designed for dual-polarization with two absorption bands located at both sides of the transmission window [30], and the absorption bands are achieved by loading of lumped resistors at the entry port of short-circuited waveguides. However, the structure needs a discontinuous ground plate in each unit cell to assure a good absorption performance, which is extremely difficult to be implemented, especially for the 3-D configuration.

A 3-D AFST operating under dual-polarization is proposed in this paper, which performs a relatively wide transmission window and one upper wide absorption band. In addition, the discontinuous ground plates, which bring lots of troubles to process the 3-D structures, are inexistent in the proposed one. The unit cell consists of a lossless propagation path implemented using a parallel plate waveguide (PPW) with a metalized via hole in the center and a lossy propagation path constructed by the resistor-embedded bent metallic strips encircled by the metallic plates of the PPW. In order to obtain the dual-polarization performance, a receiving aperture antenna is embedded in the front of each metallic plate, which removes the cut-off frequency from the waveguide pattern. The equivalent circuit model and current and electric field distributions are utilized to reveal the operating principle, and the corresponding theoretical formulation is provided to guide the design of the proposed 3-D AFST. The designed AFST is fabricated and measured, and the simulation and measurement results verify that the proposed 3-D AFSTs exhibit stable transmission and absorption performance for the wave incident angle up to 50°.

II. OPERATING PRINCIPLE

A. CONFIGURATION OF THE UNIT CELL

Fig. 1 presents the unit cell of the proposed 3-D structure with the thickness $H$ along the $z$-direction and period $p$ along both the $x$- and $y$-directions. Fig. 1(b) shows the top view of the proposed structure, which shows a square topology in the $xy$-plane, considering its advantages in analysis and processing [32], [33]. Two aperture antenna embedded notched metallic plates are utilized to build the boundary of PPW, which is filled with dielectric substrate with a relative permittivity $\varepsilon_r = 2.2$ and thickness of $2l_1$. A central metalized via hole with diameter of $D$ is used to produce two resonant modes in the PPW. It should be pointed out that the embedded aperture antennas in each unit cell are realized by notches with the length and width of $l_4$ and $w_4$, respectively.
length of the absorption path are defined as \( Z \), which can be calculated by their dimensions using the capacitances and inductances of the notch and the metallic strip, respectively. Moreover, it should be pointed out that although there is no ground, the short line still exists in the circuit due to the cut frequency of the waveguide pattern. Then, the transfer matrix of this subnetwork is expressed as

\[
\begin{pmatrix}
A_I & B_I \\
C_I & D_I
\end{pmatrix} = \begin{pmatrix}
1 & 0 \\
Y_{FSS} & 1
\end{pmatrix} \begin{pmatrix}
\cos \theta_1 & jZ_1 \sin \theta_1 \\
j \sin \theta_1 / Z_1 & \cos \theta_1
\end{pmatrix} \times \begin{pmatrix}
1 & 0 \\
\infty & 1
\end{pmatrix}
\]

(1)

where \( Y_{FSS} \) is defined as

\[
Y_{FSS} = \sum_{i=1}^{2} \frac{1}{j (\omega L_i - 1 / \omega C_i)} + \frac{1}{R}
\]

(2)

On the other hand, the transmission path consists of a parallel-plate waveguide and a center metalized via hole, whose equivalent circuit model is shown in Fig. 3. The transmission line \((Z_2, \theta_2)\) represents the PPW path, and \(C_p\) donates the discontinuity between the PPW and the air space, which was estimated in [36]. In addition, the center metalized via hole introduces an inductance \(L\) to generate another resonance, whose value can be calculated as [37]

\[
L = \frac{\mu_0}{2\pi} \left[ H \ln \left( \frac{H + \sqrt{(D/2)^2 + H^2}}{D/2} \right) + \frac{3}{2} \left( \frac{D}{2} - \sqrt{\left( \frac{D}{2} \right)^2 + H^2} \right) \right]
\]

(3)

Then, the transfer matrix of the transmission subnetwork is expressed as

\[
\begin{pmatrix}
A_{II} & B_{II} \\
C_{II} & D_{II}
\end{pmatrix} = \begin{pmatrix}
1 & 0 \\
j \omega C_p & 1
\end{pmatrix} \begin{pmatrix}
\cos \theta_2 & jZ_2 \sin \theta_2 \\
j \sin \theta_2 / Z_2 & \cos \theta_2
\end{pmatrix} \times \begin{pmatrix}
1 & 0 \\
j \omega C_p & 1
\end{pmatrix}
\]

\times \begin{pmatrix}
\cos \theta_2 & jZ_2 \sin \theta_2 \\
j \sin \theta_2 / Z_2 & \cos \theta_2
\end{pmatrix} \times \begin{pmatrix}
1 & 0 \\
j \omega C_p & 1
\end{pmatrix}
\]

(4)

Thus, we can calculate the impedance matrices \(Z_I\) and \(Z_{II}\) of the absorption and transmission paths through the simple conversion between \(ABCD\) matrices and impedance matrices [35], and the scattering parameters can be obtained from the total impedance matrix \(Z\), which equals to \(Z_I + Z_{II}\).
The simulated and calculated transmission and reflection coefficients of the proposed 3-D AFST under normal incidence are displayed in Fig. 4, which are obtained by the ANSYS HFSS using periodic boundaries and Advanced Design System (ADS). It is shown that their results are in good agreement. The proposed AFST exhibits a relatively wide bandpass response from 4.71 to 5.78 GHz with a fractional bandwidth of 20.5%, and a wide absorption performance from 5.94 to 7.94 GHz with a fractional bandwidth of 20.5%, and a wide absorption band from 4.71 to 5.78 GHz with a fractional bandwidth of 28.8%. In addition, two transmission poles at $f_p'$ of 5.03 GHz and $f_p''$ of 5.58 GHz are generated in the passband to realize a flat filter property, and two reflection zeros at $f_{a1}$ of 6.68 GHz and $f_{a2}$ of 7.8 GHz are engendered in the upper absorption band resulting in a wide absorption band. Furthermore, it should be mentioned that the proposed structure has no backed discontinuous ground plate, and still exhibits a good absorption performance.

It is necessary to investigate the surface current and electric field distributions at the poles or zeros for the sake of understanding the physical insight of the proposed AFST. When the incident wave goes into the notched waveguide structure, it will excite different resonant modes on the metallic strip, which can be utilized to construct wide transmission and absorption bands. For the metallic strip embedded with chip-resistor in the center, two resonant modes are excited, corresponding to the length $L_p$ equal to one wavelength and one and half wavelength, respectively. The current distributions at these two resonant modes are diverse, and the equivalent boundary condition in the center of metallic strip also varies accordingly [38].

1) When $L_p = \lambda$, the resonant frequency $f_p$ equals to $c/\left(1 + \sqrt{\varepsilon_{\text{eff}}}\right)$, where $c$ is the velocity of light and $\varepsilon_{\text{eff}}$ is effective permittivity. The current distribution on the strip line is

$$i(z) = \begin{cases} I_0 \sin(\kappa z), & 0 \leq z \leq \frac{L_p}{2} \\ -I_0 \sin(\kappa z), & -\frac{L_p}{2} \leq z \leq 0 \end{cases}$$  \hspace{1cm} (5)$$

where $I_0$ is a constant magnitude, and $\kappa$ is the wavenumber. As shown Fig. 5(a), we observe that the current node appears in the center of the metallic strip, and it means that no current flows through the chip resistor, which will generate a total reflection characteristic at this frequency. Then, the absorption path performs as a common ground, and the incident wave will pass through the transmission path, realizing a bandpass frequency response with little loss.

2) When $L_p = 3\lambda/2$, the corresponding resonant frequency is $f_{a2}$, and the current distribution on the strip line would be

$$i(z) = -I_0 \cos(\kappa z), \quad -\frac{L_p}{2} \leq z \leq \frac{L_p}{2}.$$  \hspace{1cm} (6)$$

Fig. 5(c) shows the simulated current distribution at $f_{a2}$, we observe that the current passes through the chip-resistor realizing a good absorption performance.

In addition, another resonance at $f_{a1}$ is excited in the notch on the aperture antenna embedded notched metallic plate, and the current distribution is displayed in Fig. 5(b). It is found that the current has maximum amplitude at the end of notch and it is almost zero at the inceptive position, corresponding to the quarter-wavelength resonance. The current will transmit to the be metallic strip and be consumed by the embedded chip-resistor because the strip works in a state between one wavelength and one and half wavelength resonances. Hence, a wideband upper absorption is obtained.

According to the aforementioned analysis, the incident wave at $f_p$ can only pass through from the PPW path. Due to the inserted via hole, the PPW path is divided into two identical parts, which are short-circuited resonator at $f_p'$, and open-circuited resonator at $f_p''$ [24]. The electric field distributions at two poles ($f_p'$ and $f_p''$) of the proposed AFST are exhibited in Fig. 6, which are principally concentrated.
in the PPW path. Fig. 6(a) depicts the electric field vectors at $f'_p$, we can observe that the electric field distribution has the same magnitude and direction at both sides of the via hole, realizing a short-circuited resonator consists of half of the PPW path and via hole. While at resonant frequency $f''_p$, the electric field distribution at both sides of the via hole still has the same magnitude but opposite directions, as shown in Fig. 6(b), performing as an open-circuited resonator.

### III. DESIGN GUIDELINES

According to the analysis of operating principle in Section-II, the effect on the resonant characteristic of the proposed AFST is studied for different design parameters, such as the thickness $H$ of the whole structure, the diameter $D$ of the via hole, the length $l_s$ of the slot and the length $L_p$ of the metallic strip. It is decent that each resonant mode can be controlled independently by adjusting aforementioned four parameters.

The poles in the passband are relatively independent of the resonant modes in the absorption band, and they are influenced by the values of $H$ and $D$, as shown in Fig. 7. When the PPW’s thickness $H$ increases, both $f'_p$ and $f''_p$ decrease, because an increasing $H$ leads to the enlargement of resonant wavelength of both resonators, as shown in Fig. 7(a). Then, the passband moves to low frequency. Fig. 7(b) shows the variation of resonant mode frequencies with respect to the diameter $D$ of via hole. We can observe that the inserted metalized via hole introduces an additional pole of $f''_p$, which moves toward higher frequency with an increasing $D$. In addition, $f''_p$ changes slightly because the open circuited resonator is independent of the via hole, and it is constant with a fixed thickness $H$. Then, a wide flat passband is achieved with a proper value of $D$.

Fig. 8 indicates the variation of the reflection zeros in the absorption band with respect to the length $l_s$ of the notch and the total length $L_p$ of the bended metallic strips, while the poles of $f'_p$ and $f''_p$ are fixed. As shown in Fig. 8(a), the absorption path is out of operation if there are no notches in the plate. Additionally, the reflection zero $f_{a1}$ will shift toward lower frequency with an impervious reflection zero $f_{a2}$ when $l_s$ increases, because $f_{a1}$ is caused by the quarter-wavelength resonance of the notches. On the other hand, increasing the value of $L_p$ will decrease the frequency of $f_{a2}$ and has little influence on $f_{a1}$, as shown in Fig. 8(b), for it only influences the resonant wavelength of metallic strip.

Then, a simple design guideline for desired frequency response can be obtained, as given in the following steps.

1) The operating band is determined by the thickness of structure, choosing a properly value of $H$ to fix the pole of $f''_p$.

2) A large diameter $D$ of the via hole can make $f'_p$ close to $f''_p$, thus the frequency response in the passband will be improved, including the flatness and insertion loss. On the other hand, increasing $D$ will reduce the bandwidth of passband. For a preferable transmission performance, $D$ should be properly adjusted.

![FIGURE 6. Simulated Electric field distributions at (a) $f'_p$ and (b) $f''_p$.](image)

![FIGURE 7. Frequency responses of the AFST with respect to (a) the thickness $H$ of PPW and (b) the diameter $D$ of metallized via hole.](image)
FIGURE 8. Frequency responses with respect to (a) the length $l_s$ of notches in the PPW and (b) the total length $L_p$ of the metallic strip.

3) The length $L_p$ of metallic strip should be chosen to make the one-wavelength resonance at $f_p$ be center frequency of the passband to ensure that the incident wave basically passes through PPW without loss.

4) The reflection pole of $f_{a1}$ should be located between $f_p$ and $f_{a2}$, and choosing a properly value of $l_s$ to realize an acceptable transmission and absorption performance.

IV. FABRICATION AND MEASUREMENT

A design example of the proposed 3-D AFST is provided here to verify the properties mentioned, and the design parameters are given in the caption of Fig. 1. The size of the unit cell is $0.12\lambda_0 \times 0.12\lambda_0 \times 0.31\lambda_0$, where $\lambda_0$ is the wavelength in free space at the center frequency of the passband. This fabricated example is built up by four kinds of parts, as illustrated in Fig. 9(a). Part I and part II are two kinds of metal-clad circuit boards with a thickness of 1 mm, which are made of Rogers RO5880 ($\varepsilon_r = 2.2, \tan \delta = 0.003$). The metalized via holes are periodically created in the center of both parts. In addition, incisions with width of 1 mm are cut in the upper and lower half of part I and part II, respectively. Both parts III and IV, being made of FR4 ($\varepsilon_r = 4.4, \tan \delta = 0.02$), are small circuit boards with 0.5 mm in thickness.

The layouts of the assembly process are shown in Fig. 9(b), which contains two steps. Firstly, parts I and II pieces are combined through their respective incisions to form a reticulated framework for the transmission path. Secondly, parts III and IV pieces are then inlaid into the reticulated framework to construct the absorption path. Finally, an example with $28 \times 28$ unit cells is fabricated, and its size is $196 \text{ mm} \times 196 \text{ mm}$, as shown in Fig. 9(c).

The fabricated AFST is measured based on the free-space method in an anechoic chamber to obtain reflection and transmission coefficients, which is explained in detail in [39]. Fig. 10 shows a comparison of the measured and simulated results under both normal and oblique incidences. It is observed that a good agreement between them is obtained, which implies that the proposed dual-polarized AFST exhibits stable performance under the oblique incidence.

When the angle of the incident wave varies in the TE-polarization, it is noted in Fig. 10(a) that the center frequency of the passband slightly shift to high frequency and the measured insertion loss exceeds the simulated loss slightly. In addition, the transmission and absorption performances as shown in Fig. 10(b) are stable in the
TABLE 1. Comparison of others presented in the literature.

| Reference | Transmission bandwidth (%) | Absorption bandwidth (%) | Oblique | Polarization | Configuration | GND Plates |
|-----------|----------------------------|--------------------------|---------|--------------|---------------|------------|
|           |                           |                          |         |              |               |            |
| [5]       | 10                        | 100                      | /       | 30°          | Dual          | 2-D        | Yes        |
| [7]       | 8.2                       | 79.3                     | 29      | 30°          | Dual          | 2-D        | Yes        |
| [27]      | 8.4                       | /                        | 63.8    | 30°          | Single        | 3-D        | Yes        |
| [28]      | 33.5                      | 9.9                      | 69.8    | 45°          | Single        | 3-D        | Yes        |
| [30]      | 29.7                      | 58.1                     | 47.5    | 45°          | Single        | 3-D        | Yes        |
| [31]      | 42.7                      | 59                       | 34.4    | 40°          | Dual          | 3-D        | Yes        |
| This work | 20.4                      | /                        | 28.8    | 50°          | Dual          | 3-D        | No         |

FIGURE 10. Simulated and measured results of the proposed AFST under oblique incidences for (a) TE-polarization and (b) TM-polarization.

TM-polarization for the incident angle up to 50°. The measured absorption band with reflection coefficient less than −10 dB at the normal incidence is from 4.46 to 7.9 GHz, and it is a little narrower compared with the simulated results. The difference between the measured and the simulated results is mainly due to the assembly tolerance, value variations and parasitic effects of the lumped resistors, and measurement error.

A comparison of the current state of designs is shown in Table 1 to demonstrate the advantages of the proposed AFST. It is seen that our design has advantages in the bandwidth of passband and oblique incidence performance compared with the 2-D structure. For 3-D structures, the dual-polarization performance is achieved in our design. Although the AFST presented in [31] also realized a dual-polarization performance, it sacrificed the large lattice spacing. In addition, the presence of backed discontinuous ground plates adds to the difficulty of 3-D structures fabrication, and none-of-ground is another advantage of our designed AFST.

V. CONCLUSION

This paper has introduced a new design of 3-D AFST that exhibits a transmission window and an upper absorption band. The AFST is implemented using a 2-D periodic array of 3-D unit cells based on two propagation paths: one is using the aperture antenna embedded notched metallic plates and the resistor-embedded metallic strips for absorption, and the other is the PPW for the transmission window. By introducing a notch in the metallic plate, the dual-polarization issue is solved, and the bandwidth and low insertion loss of the passband are maintained. By using the resistor-embedded metallic strips which performs multimode resonances, pass and absorption bands are obtained simultaneously. Compared to existing 3-D AFSTs, the advantage of our designed structure is operating relatively wideband performance under dual-polarization incidence waves, and there is no discontinuous metallic blockage as ground plane at the bottom layer in our structure. Analysis formulas and design guidelines are provided to explain the operating principle of this AFST. Then, a design example is fabricated and measured, and measured results are in good agreement with the simulated ones, which validates the proposed design concept.

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