Band-notched frequency-selective absorber with linear polarization rotation function

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Abstract
This article presents a novel band-notched frequency-selective absorber (BFSA) with linear polarization rotation function in-band and absorption out-of-band. When used as an antenna reflector, the BFSA can not only reduce RCS outside of the antenna’s working band, but also reduce co-polarized RCS within the working band and improve cross-polarized reflection. The BFSA realizes −0.41 dB linear polarization-rotating reflection at 4.5 GHz. In the upper and lower bands, the BFSA realizes a broad absorption function from 2.2 GHz to 4.1 GHz and 5.03 GHz to 6.5 GHz. The fractional bandwidth of linear co-polarization reflection is 98.8% with 10 dB reflection reduction. The experimental measurements are conducted to validate the polarization conversion of the band-notched absorbers, and good agreement between theory and measurement results is observed.

KEYWORDS
band-notched frequency-selective absorber, four-port equivalent circuit

1 | INTRODUCTION

In recent years, frequency selective absorber (FSA) has attracted the favor of the majority of researchers, and a large number of designs have been proposed. It is usually constructed by frequency selective surface (FSS) and absorbers to protect antennas and reduce the radar cross-sections (RCSs). Due to its excellent performance in ensuring communication and stealth in the antenna system, FSA has received more and more attention. In general, it can be divided into frequency-selective rasorber (FSR) and band-notched absorber.

According to the location of the transmission band, the FSRs can be divided into the following categories: transmission-absorption (T-A) FSRs,1,2 transmission window in-band and absorption out-of-band (A-T-A),3–7 and the transmission zero is at upper-frequency band besides absorption at lower frequency band FSRs (A-T).8–10 One limitation of the techniques proposed in Reference 8 is that the structures are polarization-sensitive, thus they are suitable for being placed upon antennas with single polarization only. To tackle this problem, dual-polarization structures are studied. Han et al. proposed a new A-T-A structure with high selective performance in Reference 3.

To maintain the radiation efficiency, the band-notched structures can be employed as a ground plane of the antenna and they are also divided into active and
passive designs. Reference 11 realizes both the wide reflection band and the wide absorption band. References 12,13 can switch EM waves from reflection state to absorption state. However, the structure in Reference 12 does not have the out-of-band absorption function, and the design in Reference 13 is polarization-sensitive. To switch between the three working modes, PIN diodes are utilized. Varactor, on the other hand, can be used to control the reflection band.

RCS is a critical factor in evaluating stealth performance. Metasurfaces can offer another way to reduce RCS with their polarized rotation properties which is different from absorber. In earlier studies, passive polarized rotating structures are realized including narrowband and broadband. In a general way, the reflective polarized rotating designs are realized by a metal ground and an oblique metal patch of $45^\circ$ which the surface current is used to analyze the structure, but, it is not enough. Aware of this, G. Perez-Palomino et al. designed the polarization rotation function from the equivalent circuit with coupler theory, which provides an idea for the future design of polarization rotation. The reconfigurable converter based on graphene is also proposed.

The application of the converter into FSA can reduce the monostatic RCS of linear-polarization incident waves. To meet this requirement, this article proposes a novel BFSA that can realize linear cross-polarization reflection in in-band frequencies and absorption in out-of-band frequencies. The cross-polarization is linear electromagnetic waves that are orthogonal to linear incident waves, and the co-polarization is own the same polarization as linear incident waves. As far as we know, this BFSA consisting of a lossy layer and a polarization-rotating layer is proposed for the first time. And a four-port equivalent circuit model with a lossy layer is realized.

The rest of this article consists of the following parts. In Section 2, the BFSA analysis and studies are presented. Section 3 analyzes the ECM of the lossy layer and polarization-rotating layer, where a four-port network ECM is presented to describe the proposed structure. The measurement results are presented in Section 4. Finally, conclusions are given in Section 5.

2 | ANALYSIS AND DESIGN OF THE STRUCTURE

The schematic of the BFSA is shown in Figure 1. As usual, the band-notched absorber is made up of two layers containing a lossy layer and a lossless layer as shown in Figure 1B. The central frequency $f$ is the passband frequency of the lossy layer and the reflection of the converter. In the absorption band, the incident waves can be absorbed.

Based on the previous works, the BFSA is designed. The BFSA is composed of the lossy layer and polarized rotator layer which are separated by an air gap with a thickness of $t_2 = 7$ mm, as shown in Figure 2. In addition, metal coppers with top and bottom layers of 0.035 mm are printed on F4BM substrates ($\varepsilon_r = 2.65$, $\tan\delta = 0.001$). Top layer resistors are positioned between
two rings with $R = 124 \Omega$, as shown in Figure 2B. The remaining dimensions are as follows: $P = 25 \text{ mm}$, $t_1 = 1 \text{ mm}$, $t_3 = 4 \text{ mm}$, $r_1 = 7 \text{ mm}$, $r_2 = 12 \text{ mm}$, $g_1 = 0.7 \text{ mm}$, $g_2 = 0.5 \text{ mm}$, $g_3 = 0.7 \text{ mm}$, $g_4 = 0.7 \text{ mm}$, $g_5 = 7.5 \text{ mm}$, $g_6 = 1 \text{ mm}$, $g_7 = 0.4 \text{ mm}$, $l_1 = 5.8 \text{ mm}$, $l_2 = 1.45 \text{ mm}$, $x = 2 \text{ mm}$, $y = 11.5 \text{ mm}$.

The simulations are shown in Figure 3. We define $R_{yy}$ and $R_{xy}$ as y-to-y and y-to-x reflected polarization conversions, respectively. The BFSA exhibits a $-0.41 \text{ dB}$ cross-polarization reflection at 4.5 GHz, and there are two absorption bands outside of the cross-reflection band from 2.2 GHz to 4.1 GHz and 5.03 GHz to 6.5 GHz.

Figure 4 shows the simulations of the reflection coefficient for the different values of the air layer. Obviously, the upper absorption band is rising and the lower absorption band is decreasing with the increasing value of $t_2$. Meanwhile, the linear cross-polarization curves $R_{xy}$ barely change. Figure 5 depicts the simulated results of the BFSA under different incident waves. The BFSA remains nearly constant until the incidence angle reaches $30^\circ$. 
The chessboard array configuration of the BFSA is shown in Figure 6A, which is consisting of a 1-bit coding metasurface of the converter. The “0” and “1” supercells are both consisting of 6 x 6 unit cells and the converters of “0” and “1” are orthorhombic. The total chessboard array contains 4 x 4 supercells with 300 x 300 mm² simulated by CST. The metal plate of PEC is chosen as a reference, and the dimension is the same as the chessboard array of the BFSA. The monostatic RCS of PEC and the chessboard array are depicted in Figure 6B. The RCS reduces containing absorption of out-of-band and scattering in-band.

The 3-D scattering patterns of the chessboard array at 3 GHz, 4.5 GHz, and 5.5 GHz are shown in Figure 7C. 3-D scattering patterns at 3 GHz and 5.5 GHz shown in Figure 7B and D are presented to illustrate RCS reduction out-of-band.

3 | EQUIVALENT CIRCUIT ANALYSIS

The equivalent circuit model (ECM) is created to further understand the mechanism of the BFSA. The analogous circuit of the converter is explained using the branching line coupler theory which is analyzed by Gerardo Perez-Palomino et al.\textsuperscript{22}

3.1 | The ECM of the converter

With the conventional decomposition of even mode and odd mode, the transmission matrix $T_c$ of the converter can be expressed by\textsuperscript{22}:

$$T_c = \begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} Y_o + Y_e & 2 \\ Y_o - Y_e & Y_o - Y_e \\ 2Y_oY_e & Y_o + Y_e \\ Y_o - Y_e & Y_o - Y_e \end{bmatrix}$$

where $Y_o$ and $Y_e$ are the parallel admittance in excitation source of even mode and odd mode. The four-port equivalent network is dual diagonal symmetry. And the Foster expansion is used to decompose the parallel admittance $Y_o$ and $Y_e$ as shown in Figure 8B. Therefore, the transmission matrix $T_c$ is the key to the frequency of polarization rotation. And the most relevant components are $L_e$ and $C_e$ in Figure 8B. In Figure 9, the surface current of the converter is shown. Four unit cells of the converter are presented to illustrate the ECM. In Figure 9A, the surface
current is mainly concentrated in the converter, thus, $L_{e1}$ comes from the metal. Coupling between the two converters in a straight line causes the $C_{e1}$. Similarly, current exits between the parallel converters causing the $C_{e2}$ and $C_{e3}$. In Figure 9B, $L_{o1}$ is also caused by metal copper. $C_{o1}$, $C_{o2}$, and $C_{o3}$ come from the parallel converter. Thus, the Foster expanding shown in Figure 8 can be obtained as follow: $L_e = L_{e1}$; $C_e = C_{e1}$; $C_m = C_{e2} + C_{e3}$; $L_o = L_{o1}$; $C_o = C_{o1}$; $C_n = C_{o2} + C_{o3}$. The final parameters of $L_e$, $L_o$, $C_e$, $C_o$, $C_m$, and $C_n$ are optimized by “ADS.”

$L_e = 3.56\text{nH}, C_e = 0.141 \text{pF}, L_o = 1\text{nH}, C_o = 0.0101 \text{pF}, C_m = 0.07 \text{pF}, C_n = 0.017 \text{pF}, R = 255 \Omega, Z_0 = 377 \Omega, Z_i = Z_0/\sqrt{\varepsilon_r} (i=1,2)$,

Furthermore, the curves in Figure 10B demonstrate intuitively that the findings of ECM constructed by ADS are very compatible with the simulated results using CST.

4 FABRICATION AND EXPERIMENTAL VERIFICATION

The proposed BFSA’s performance was validated by fabricating a prototype with $320 \text{mm} \times 320 \text{mm}$ containing $12 \times 12$ units cells, as shown in Figure 11 with the measurement environment and the prototype of the proposed structure. The air layer is replaced with foam when we validate the simulation in the experiment. In the lossy layer, $124 \Omega$ lumped resistances are soldered as shown in Figure 11B. In Figure 11C, in the original scenario, the four holes in the center of the converter are used to control the space between the lossy layer and the converter, but due to inaccurate processing, the four
holes are not used to fix with plastic screws. The vector network analyzer N9926A was used to measure the prototype.

Linear co-polarization and cross-polarization reflection were included in the measurements. Because the structure is polarization insensitive, only the horizontal-polarization incident wave is examined. A pair of horn antennas are utilized in the experiment. One is set to generate a horizontal-polarization incident wave, while the other receives dual-polarization EM waves.

Measurement results of the BFSA are presented in Figure 12. The CST simulations and measurements agree with each other. Despite this, there is a minor difference in the higher absorption band due to the unequal thickness of the foam. Thus, the upper absorption band is higher than the simulated prediction, and it is consistent with the simulations in Figure 4. The linear cross-polarization wave is reflected at 4.63 GHz and the copolarization wave is absorbed from 2.1 to 4.1 GHz, and the upper-frequency absorption band is higher than the simulation from 5.1 to 6.5 GHz, as shown in Figure 12. Moreover, the small test variation is produced by the imperfect testing environment as well as some properties of the electronic components themselves.

Table 1 compares our design to various prior works to demonstrate its superiority. The BFSA has a novel operating state, polarization-insensitive, absorption to reduce RCS, and well wide FBW when compared to other structures.
TABLE 1 Comparison with other structures

| Ref. | Operating states | Polarization | IL or Reflectivity (dB) | FBW | Lowest frequency $f_L$ (GHz) | Thickness (@ $f_L$) | Periodicity (@ $f_L$) |
|------|------------------|--------------|------------------------|-----|---------------------------|--------------------|---------------------|
| 3    | A-Co.PR-A        | Dual         | −0.12                  |     | 111.6%                    | 2.05               | 0.089$\lambda_L$    | 0.17$\lambda_L$     |
| 4    | A-T-A-T          | Dual         | −0.25/−0.1             |     | 117.7%                    | 1.67               | 0.076$\lambda_L$    | 0.147$\lambda_L$    |
| 8    | T-A              | Single       | −0.15                  |     | 94%                       | 3                  | 0.125$\lambda_L$    | 0.19$\lambda_L$     |
| 11   | A-Co.PR-A        | Dual         | −0.33                  |     | 127.5%                    | 2.12               | 0.084$\lambda_L$    | 0.137$\lambda_L$    |
| 15   | A-Co.PR-A        | Dual         | −0.45                  |     | 115.2%                    | 5.35               | 0.091$\lambda_L$    | 0.18$\lambda_L$     |
| 16   | Cro.PR-T-Cro.PR  | Dual         | −1                     |     | 91.4%                     | 5.66               | 0.184$\lambda_L$    | 0.28$\lambda_L$     |
| 21   | Cro.PR-T-A       | Dual         | −1.1                   |     | 146%                      | 3.1                | 0.13$\lambda_L$     | 0.104$\lambda_L$    |
| This work | A-Cro.PR-A      | Dual         | −0.41                  |     | 98.8%                     | 2.2                | 0.089$\lambda_L$    | 0.18$\lambda_L$     |

Abbreviations: A, absorption; AOB, absorption out-of-band; Co.PR, $R_{yy}$ (or $R_{xx}$); Cro.PR, $R_{xy}$ (or $R_{yx}$); FBW, fractional bandwidth with −10 dB reduction of the $R_{yy}$ (or $R_{xx}$); $f_L$, the lowest frequency; IL, insertion loss; T, transmission; $\lambda_L$, free space wavelength at $f_L$.

5 | CONCLUSIONS

A novel structure presenting linear polarization-rotating in-band and absorption out-of-band is proposed. The measurement results are in good agreement with simulation results. Besides, the lower and upper absorption bands to reduce RCS can be realized in the antenna system. Moreover, this special BFSA can reduce co-polarization RCS and maintain the radiation efficiency of the antenna’s cross-polarization by realizing linear cross-polarization reflection in-band. In addition, the chessboard array arrangement is used to scatter linear incident waves in four directions to reduce RCS.

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DATA AVAILABILITY STATEMENT

Research datas are not shared.

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