A Frequency Selective Rasorber by Engineering Transverse Standing Waves of Surface Current

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ABSTRACT The low RCS level out of operating band is urgent for radome while keeping its communication window. To solve this problem, we propose a frequency selective rasorber (FSR) that exhibits a pass-band between two absorption bands in this paper. The surface currents on a finite metallic wire media is analyzed firstly to elaborate transverse standing waves mechanism. High-efficiency and broadband absorption can be achieved by loading lumped resistors at high amplitude of standing waves. By delicately engineering the transverse standing waves versus frequency, a transparent window can be opened within an absorption wideband and it can be modulated by adjusting structural parameters. The transparent window centered around 10.0 GHz in the absorption band from 5.8 GHz to 18.0 GHz. Prototypes were fabricated and measured. Both the simulated and measured results show that for both x- and y-polarized waves, insertion loss of the transparent window at 9.85 GHz is below 0.2 dB while the absorption is above 90% in the two sidebands of 5.8-7.8 GHz and 11.8-18.0 GHz. Furthermore, the rasorber can also work well under oblique incidence angles up to 45 degrees. This work may find wide applications in electromagnetic compatibility, stealthy radomes, etc.

INDEX TERMS Metamaterial, electromagnetic absorption, transparent window, transverse standing wave.

I. INTRODUCTION

The field of metamaterial, both in theory and in design, has got a huge progress in the past several decades. With the deepening of research, the metamaterial theory has been specifically applied to practical design aspects like radar cross section (RCS) reduction [1]–[9], electromagnetic wave transmission enhancement [12]. Particularly, for applications in RCS reduction, typical existing mechanisms of metamaterials include scattering cancellation [1], absorption [2]–[9], [23] and polarization conversion [11]. Of them, the reflected wave of scattering cancellation and polarization conversion may still be detected by bi- or multi-static radar systems. Therefore, the absorption scheme is more preferable for RCS reduction in practical applications.

In recent years, many wideband absorption designs have been reported [2]–[4]. On this basis, researchers further proposed absorptive/transmissive frequency selective surface (ATFSS). Motevasselian presents a typical circuit-analog absorber (CAA) that can use frequency selective surface to be ground plane [21]. A transparent window out of an absorption band can be generated. Munk proposed a conceptual design called “rasorber” which can be a radome [10]. Li et al. [8] proposed a tunable metasurface which can switch between perfect transparency and perfect absorption, which is implemented by integrating two PIN diodes on the top and bottom surfaces and by adjusting the parameters of diodes. Due to destruction of symmetry, the design can be a good rasorber as the parameters of diodes is 0.50 V/2060 Ω. However, this design cannot achieve high absorption out of transparent window. Zhang et al. [19] proposed a wideband absorption design on the basis of multimode resistor-embedded metallic strips. The work has four resonant points at 3.26 GHz, 6.69 GHz, 10.09 GHz and 11.74 GHz, so it can form a wide absorption bandwidth from 2.68 GHz to 12.19 GHz. The bend technique is used in the design to equivalently increase the electrical size of the unit structure, so as to work in low-frequency
band. Chen et al. [6], [24] find that electrical resonator can short-circuit the resistance sheet, which makes it possible to open a transparent window in an absorption band. In a previous work, Sun et al. [5] propose to achieve wideband absorption based on longitudinal standing wave modulation. Resonant structures are stacked in the longitudinal direction according to the wavelength at a specific resonant frequency point. This design is similar to Jauman Screen [25]. Nevertheless, it cannot perform well in low frequency band since much large thickness is indispensable and will has an adverse impact to the transparent window. In the practical application situation (i.e., radar radome), it is urgent to meet the requirement of low RCS out of operating band while has no effect to its communication window. But for the longitudinal standing wave, the superposition of multi frequency points provides a determination for the bandwidth extension, so as the thickness of absorber device. Compared to the longitudinal standing wave, the transverse one has a greater free degree to make a wideband absorption within a limited thickness.

In this paper, instead of focusing on longitudinal standing waves as in the design of conventional absorbers, we put our attention to engineering transverse standing waves of surface currents formed on metallic structures and propose a frequency selective rasorber (FSR) with customized transparent window. By loading lumped resistors at high amplitude of transverse standing waves, high efficiency and broadband absorption can be achieved. A customized transparent window can be opened in an absorption wideband as setting short-out at bellies. To verify the design, the prototype of rasorber which opens a transparent window in an absorption wideband from 5.8 GHz to 18.0 GHz is fabricated and measured. This work provides a novel method to design FSR and may find wide applications in anti-interference communications, electromagnetic compatibility, stealthy technologies and others.

II. DESIGN THEORY ANALYSIS

The implementation of negative index media based on the wire media [13], originally pioneered by Pendry et al., shows that the periodic thin wires structure possesses typical Drude behavior:

\[
\varepsilon(\omega) = 1 - \omega_p^2/\omega(\omega + i\gamma), \quad \omega_p^2 = ne^2/\varepsilon_0 m
\]

where \(\varepsilon(r)\) is the effective permittivity of infinite metallic wire and \(\varepsilon_0\) is permittivity of vacuum. \(n\) is the electron density, \(m\) and \(\varepsilon\) represent the electronic mass and electron elementary charge, \(\gamma\) is damping coefficient, \(\omega_p\) is plasma frequency. But it requires continuous electrical connections for wires between unit cell. After that, some researchers find that finite wires can act like bulk [14] and, the electrical resonator [15], satisfy the Lorentz model:

\[
\varepsilon(\omega) = 1 + \omega_0^2/(\omega_0^2 - \omega^2 - i\gamma\omega)
\]

where \(\Omega\) is incident wave frequency. \(\Omega_0\) is resonant frequency of electrical resonator. It can be inferred that, \(\varepsilon\) is approximately equal to 1 as frequency is less than \(\Omega_0\). Thus, it can form a transmission band. And as frequency is larger than \(\Omega_0\), stopband appears when \(\varepsilon\) is less than 0. Thus, the finite wires structure, the typical electrical resonator, is always applied in frequency selective surface design [13], [16]–[18].

In our research, the finite metal liner media can constraint the EM wave to form transverse standing wave. As we can observe from Fig.1, the strength of current in the middle of wire is much higher than two sides. That is because, the free electrons in wires are driven by alternating electric field towards the opposite directions, forming two currents in the same direction. The currents with a phase difference of \(\pi\) is superimposed to form a first-order standing wave. And, it can be inferred from Maxwell’s equations that the wave-velocity and wavelength of EM wave in dielectric structure:

\[
v_d = 1/\sqrt{\varepsilon(\omega)\mu(\omega)} \quad \lambda_d = v_d/\omega
\]

\(\varepsilon\) and \(\mu\) are the equivalent permittivity and permeability of structure respectively, and they are dispersive. That means the EM waves travel through the structure with a shorter wavelength and slower speeds in structure. The electrical size of incident wave coupled on the structure surface is the same as the surface current. Thus, we can analyze the surface current of structure to understand the laws of EM wave after it is incident on the structure. However, in the study of the surface current of finite wires, we realize that, as electromagnetic (EM) wave is incident on the surface of structure, the current is mainly concentrated on the wire because of the skin effect of dielectric [22] and the conductivity of metal.

In fact, many researches [7], [9], [19], [24] have found that the absorber can be obtained by loading lumped resistors onto the finite wires and placing metal plate at a distance far from the structure surface. (The FSS can replace metal plate so as to obtain a pass band outside the absorption band in
FIGURE 2. (a) The surface currents on two kinds finite wires which have different resistor lumped methods ($L = 8\text{mm}$, $l = 4\text{mm}$, $D = 5\text{mm}$, Resistance = 150Ω). (b) The surface currents on two kinds square rings which have different resistor lumped methods. (c)-(d) The reflection performance of single polarization finite wire medias and polarization insensitivity square rings (metal plate as ground plane).

FIGURE 3. (a) The unit cell of structure which includes resistive sheet, PMI foam interlayer and FSS ground plate. (b) The S-parameters and equivalent circuit of FSS (the thickness of substrate is 0.5mm). (c) The S-parameters of unit cell (blue for absorption(A), black for transmission(T), gradient ramp for transition bands(G)).
most cases.) The majority of these works mainly load lumped resistors in the middle of finite wires, where is the belly of the first-order standing wave. Whereas we find that the same absorption performance, even better one, can be still obtained by changing the number and position of resistors, leaving the complete space to further design.

To confirm the verification of the theory, we extend the single-polarization finite wire to dual-polarization square ring (Fig. 2(b)). In the resistor mid-location condition, the currents flowing through resistors on the finite wires parallel to the electric field, are larger than any other conditions. The four resistors of the latter situation make impact when EM waves incidence but the former is only two. Hence the resistor corner-location condition has a solider absorption performance than the mid-one. More importantly, the remaining bellies in the first-order standing waves, where there is no resistor, still has a strong current density. It means a bigger stage for design, like a transparent window.

There is always a strong current density in the finite wire of square ring in the absorption band. That means as long as a strong current pass through the finite wire, the lumped resistors must have a high voltage and EM energy will be absorbed due to ohmic loss. To avoid the ohmic loss, in other word, achieve a transparent window at a specific point, we can short out the resistors to minimize the current flowing through the resistors. The simplest method is to introduce a parallel $LC$ resonance structure [24]. For the majority works [2], [6], it is hard to modulate the resonant frequency. But the resonant frequency of the parallel $LC$ resonance structure can be easy to change as its expression.

$$f_p = 1/(2\pi \sqrt{LC})$$ (4)

We can modulate the parameters to change the $L$ and $C$. The inductance-loaded stripline $L$ is influenced by the number, length, width of rectangular tooth and the width of gap $g$. The broadside-coupled capacitance $C$ is mainly influenced by the faced area of two plates and the thickness, permittivity of the substrate. At the $f_p$, the structure may cause strong resonance of EM waves and the main EM energy will be stored in it which means EM waves can pass through the structure. For the convenience of the study, we only change the faced area of $C$ to get the customized transparent window (Fig. 4).

As shown in Fig.2(d), a reflection peak at 9.85 GHz appears in the absorption band after we bring in the parallel $LC$ resonance structure. That means EM power at 9.85 GHz is not consumed by resistors. Therefore, a bandpass FSS centered at 9.85 GHz can be applied here to replace the metal plate to open a transparent window in the absorption band above.

The FSS should act like metal plate in absorption band and lens in window. Meantime, the loss of dielectric and the thickness of overall structure should be minimized. Considering all factors, a first-order bandpass FSS is most suitable in this work. It has a steady transmission performance at $f_p$. The equivalent circuit model of the FSS is also analyzed (Fig.3 (b)). The equivalent inductance $L_1$, $L_2$ and capacitance $C_1$, $C_2$ are decided by the parameters of metal chip and period of unit. The actual calculation of them are as follows [26]:

$$C = \varepsilon_0 \varepsilon_r 2a \ln(\csc(\pi g/a))/\pi$$ (5)
$$L = \mu_0 \mu_r a \ln(\csc(\pi s/2t))/2\pi$$ (6)
\( \varepsilon_0 \) and \( \mu_0 \) are permittivity and permeability of vacuum respectively. \( \varepsilon_r \) and \( \mu_r \) are relative permittivity and permeability of dielectric material. \( a \) is the period of unit. \( g \) is the gap between the center chip and the edge long wire. \( s \) is the width of long wire and \( t \) is the thickness of dielectric substrate. It is obvious that \( L_1 = L_2, C_1 = C_2 \). Therefore, the passband frequency point can be simplified: \( f_p = \frac{1}{\pi \sqrt{LC}} \). The \( f_p \) can be calculated as 9.1 GHz, which its deviation may be due to the error of the material dielectric constant.

Combined with all features, the unit cell diagram of structure and its S-parameters are shown in Fig.3 (a), (c). It works as we expected. The customized transparent window centered at 9.85 GHz is opened in the broadband absorption band from 5.8 GHz to 18.0 GHz. It can be observed from Fig.2(d) that the square-ring produce a strong resonance at 7GHz and a weak one at 16GHz. Through loading lumped-resistors at the high amplitude of the current which depends on the standing wave, the absorption at two points is due to ohmic dissipation.

To further elaborate the functional mechanism of structure, we simulate the surface currents and power flows on the resistive sheet (Fig.5). Due to the introduction of parallel \( LC \) structure, the resonant frequency gets red-shift. At low frequency band (i.e. 6.46 GHz), after EM wave is incident on the structure, it becomes the first order standing wave due to coupling of metallic structure. The current dimensions are elongated because of the inductance loaded stripline. Therefore, the currents flow through the inductance to form the closed circuit and further lost in the lumped resistor. At the short-out frequency 9.85 GHz, the parallel \( LC \) structure produce a strong resonance and current circulation, which avoids the ohmic dissipation of resistors to EM energy. At high frequency band (i.e. 14.0 GHz), the EM waves are coupled as second order standing wave from current distribution. The surface current flow through the capacitor to form the closed circuit. The resistors are welded near the bellies of currents. The surface currents at the resistors (i.e., 6.46 GHz and 9.85 GHz) are much higher than other parts which means higher voltages and higher ohmic dissipations. The power flow diagram indicates that the design works as configured performance.

### III. EXPERIMENTAL AND DISCUSSION
The unit-cell diagram of structure is shown in Fig.3 (a). It is composed of upper resistive sheet, PMI foam interlayer and FSS ground plate. After a huge data debugging, the final optimized geometric dimensions are: \( n = 6.65 \) mm, \( g = 0.3 \) mm, \( L_r = 5.4 \) mm, \( D = 5 \) mm, \( C_s = 0.3 \) mm, \( C_l = 51707 \).
TABLE 1. Performance comparison.

| Ref. | A-T| Transmission bandwire | IL (dB) | RCS-Red. Bandwidth | Thick. (λ₀) |
|------|----|----------------------|--------|-------------------|------------|
| [9]  | A-T-A | 474-642MHz | 0.19 | 0.1-0.45GHz 0.7-1.0GHz | 0.087 λ₀ |
| [19] | A   | -       | -     | 2.7-12.2GHz      | 0.245 λ₀ |
| [24] | A-T  | 9.25-9.8GHz | 1.0  | 7.7-12.4GHz      | 0.42λ₀    |
| [28] | T-R  | 4.0-9.5GHz | 0.8  | 14.4-18.0GHz 11.8-18.0GHz | 0.23λ₀ |
| [29] | A-T  | 16.5-18GHz | 0.3  | 14.2-18.0GHz 11.8-18.0GHz | 0.43λ₀ |
| [30] | T-A  | 10-11GHz | 0.2  | 5.8-7.8GHz 11.8-18.0GHz | 0.19λ₀ |

This A-T-A 9.2-10GHz 0.2 5.8-7.8GHz 11.8-18.0GHz 0.19λ₀

IL= insertion loss; RCS-Red. = RCS Reduction (lower than -10dB); Thick. = thickness.

1 A-T= the absorption band below the transmission band; T-R= the transmission band below the reflection band; A-T-A= the transmission band is between the two absorption bands

2 Transmission bandwidth is higher than -1dB

3λ₀ represents the central frequency point wave-length of operating band (from lowest point to the highest point).

The experimental results are roughly consistent with simulation. For both x- and y-polarized waves under oblique incidence up to 45 degrees, the absorption reaches 90% from 5.8 GHz to 7.8 GHz and 11.8 GHz-18.0 GHz. And the transmission above -1dB from 9.2 GHz to 10.0 GHz. The two sides transition bands of transparent window are over 5 dB/GHz. Some errors appear mainly caused by the discrepancies between the design and sample piece (frequency deviation). Fabrication errors affect the experimental results. Such as the air gap between the layers [20] and the extra solder in the resistance welds, they all make higher impendence to the structure.

IV. CONCLUSION

In this paper, we proposed a FSR with customized transparent window. By loading lumped resistors at high amplitude of standing waves, high-efficiency and broadband absorption can be achieved. After delicately engineering the transverse standing waves versus frequency, a customized transparent window can be realized in an absorption wideband and it is static adjustable. The transparent window above -1dB from 9.2 GHz to 10.0 GHz and two absorption bands above 90% are from 5.8 GHz to 7.8 GHz and 11.8 GHz to 18.0 GHz. The window can be customized through modulating the equivalent parameters of parallel LC structure. The insertion loss of design is less than 0.2 dB. For both x- and y-polarized incidences, it has a solid performance even for oblique incidence up to 45 degrees. Due to its practicability, the designed work may find a wide application field in anti-interference communications, electromagnetic compatibility, stealthy technologies and others.

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