Polarisation-insensitive and wide-angle multi-layer metamaterial absorber with variable bandwidths

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Three different metamaterial absorbers based on ultra-thin multi-layer structures, with different bandwidth characteristics, are presented. The proposed structure is composed of three vertically stacked metal-dielectric layers backed by a metal ground. All the metallic patches are of crossed dipole shape and have different geometrical dimensions, which can be manipulated to design triple-band, 3 dB and 10 dB absorbers separately. The designed structures are polarisation-insensitive as well as wide-angle absorptive for both TE and TM polarisations. The 10 dB broadband structure, exhibiting an absorption bandwidth of 7.5% at 10 GHz, has been fabricated and the absorption performance has been verified with the simulated response. The proposed absorber has the advantages of ultra-thin thickness ($\lambda_0/50$ corresponding to the centre frequency), compact size, simpler design, tunable absorption bandwidth and experimental validation, which makes it a promising candidate for many potential applications.

Introduction: Electromagnetic (EM) wave absorbers are of critical importance due to their wide range of applications relating to such as radar cross-section reduction, stealth technology, the anechoic chamber, EM compatibility, EM interference and so forth. However, conventional microwave absorbers are mostly limited to a minimal thickness of one-quarter wavelength and have large surface mass densities, which restrict them from many practical applications [1]. With the recent advancement in the metamaterial approach, absorber structures can be made not only ultra-thin, but also near-unity absorption can be achieved over different frequency bands from the microwave to the terahertz range [2]. These metamaterial absorber structures usually consist of a periodic arrangement of metallic elements imprinted on very thin grounded dielectric substrates. These structures have the attractive properties of controlling the effective medium parameters so that the input impedance gets matched with the free space impedance, which results in minimal reflection from the structure. To date, several designs on metamaterial absorbers have been investigated exhibiting different characteristics, namely, single-band, multi-band, bandwidth-enhanced, polarisation-insensitivity, wide-angle absorption and so forth [3].

In this Letter, an ultra-thin polarisation-insensitive and wide-angle metamaterial structure is presented that has variable absorption bandwidths. The proposed structure consists of three different cross-dipole-shaped metallic patches, each of which is printed on a very thin dielectric substrate and the overall structure is backed by a metal ground. By controlling the geometrical dimensions of these metallic patches, the proposed structure exhibits three different types of absorbers: a triple-band absorber, an absorber providing a 3 dB bandwidth of 20% and a broadband absorber having a 7.5% 10 dB absorption bandwidth. The designed absorbers satisfy polarisation-insensitive behaviours as well as provide high absorptions (above 80%) up to a 45° incident angle for both TE and TM polarisations. The magnetic field distributions at the absorption peaks are also investigated to gain insight into the absorption mechanism. Finally, the 10 dB broadband absorber has been fabricated and experimentally verified, thus providing a promising approach for tunable metamaterial absorbers using a multi-layer design.

Design and simulated results: The proposed metamaterial absorber consists of three stacked dielectric layers, with different cross-shaped metallic patches imprinted at the top of each of them as shown in Fig. 1. The whole structure is backed by a continuous metal plane to ensure zero transmission. FR4 has been used as the dielectric substrate, having the thickness of 0.2 mm and a complex dielectric constant of $\varepsilon_r = 4.4 \times (1 - j0.02)$. The metallic patches along with the ground plane are made of copper ($\sigma = 5.8 \times 10^7$ S/m), each having a thickness of 0.018 mm.

When an EM wave is normally incident on the proposed structure, the absorptivity can be calculated as $A = 1 - |S_{11}|^2 - |S_{21}|^2$, where the reflection and transmission coefficients can be expressed as $R = |S_{11}|^2$ and $T = |S_{21}|^2$, respectively. Since the structure has been backed by the metal plate, transmission is blocked, and the absorptivity can be given as $A = 1 - |S_{11}|^2$. Now, by varying the geometrical dimensions of the metallic patches, the resonance frequencies corresponding to each of the metal-dielectric layers can be controlled and three different types of absorbers can be obtained.

Fig. 2 shows the simulated reflection coefficient spectra for the three different types of absorbers. The dimensions of all three absorber structures are listed in Table 1. A triple-band absorber has resulted exhibiting three distinct reflection dips at 7.59, 9.16 and 11.09 GHz with reflection minima of −18.8, −18.56 and −18.08 dB, respectively. When the dimensions of the metallic patches are changed, these three peaks are brought closer to generate a broadband absorber having a 3 dB (full width at half maxima (FWHM)) absorption bandwidth of 1.92 GHz (19.47% at 9.86 GHz). With more precise tuning, the broadband absorber corresponding to a 10 dB absorption bandwidth of 0.75 GHz (7.5% at 10 GHz) can also realised as shown in Fig. 2.

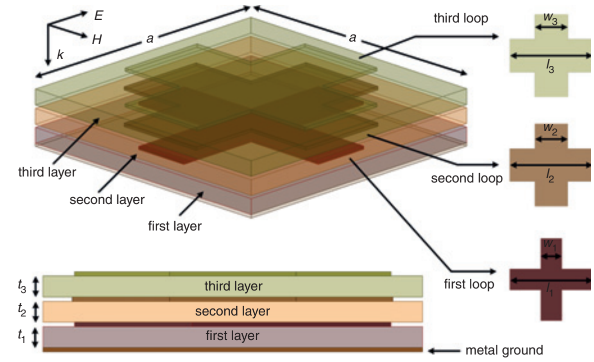

Fig. 1 *Schematic diagram of unit cell of proposed absorber*

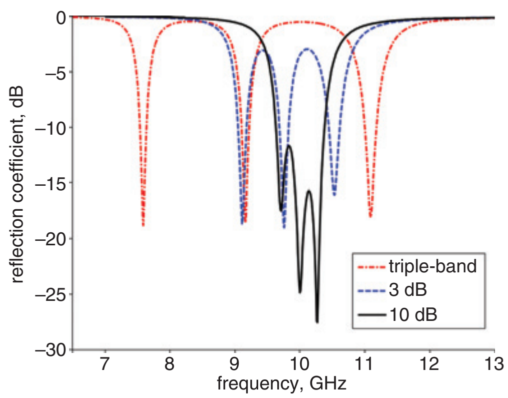

Fig. 2 *Simulated reflection coefficients of three types of absorbers*

Table 1: Dimensions of three different types of absorbers

Absorber	a	l_1	w_1	l_2	w_2	l_3	w_3	t_1, t_2, t_3
Triple-band	9	8.9	2.6	8.2	3	6.7	3	0.2
3 dB	9	7.9	2.6	7.7	3	7.2	3	0.2
10 dB	9	7.5	1.9	7.6	3	7.5	3	0.2

To explain the physical insight behind the absorption of the proposed absorbers, the magnitudes of magnetic field distributions at three absorption peaks of the 10 dB broadband absorber are shown in Fig. 3. The resonance at 9.71 GHz is primarily associated with the excitation of the bottom resonator, whereas the resonances at 10 and 10.27 GHz are mainly the consequences of the excitation of the top and middle layers, respectively. Increasing the patch distance from the metal ground, the capacitance value increases, and therefore the absorption frequency corresponding to the metallic patch increases. Thus, the bottommost layer (first layer) provides the smallest resonance frequency (9.71 GHz) and the remaining layers generate the other frequencies.

The proposed multi-layer absorber structures are polarisation-insensitive due to the four-fold symmetry. The 10 dB absorber has also been studied for oblique incidence under both TE and TM polarisations as shown in Figs. 4*a* and *b*, respectively, where it is observed that the structure maintains broadband absorption (above 85% for TE and 80% for

TM) up to the 45° incident angle. It is expected that the other types of proposed absorbers also maintain wide-angle absorption properties.

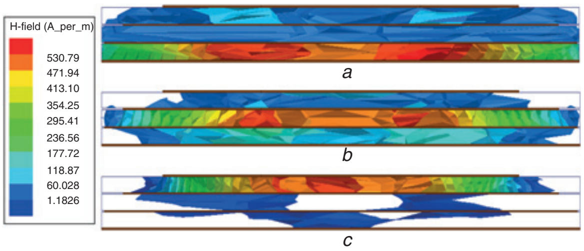

Fig. 3 *Side view at centre of unit cell showing magnetic field distributions of designed 10 dB absorber structure at absorption frequencies of 9.71, 10 and 10.27 GHz*

a 9.71 GHz
b 10 GHz
c 10.27 GHz

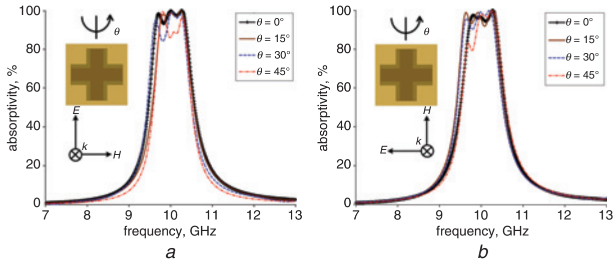

Fig. 4 *Simulated absorptivities of proposed multilayer 10 dB broadband absorber at different incident angles*

a TE polarisation
b TM polarisation

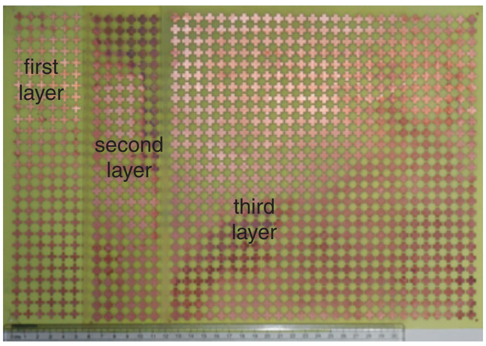

Fig. 5 *Photograph of each fabricated layer, which has been glued together to form broadband structure*

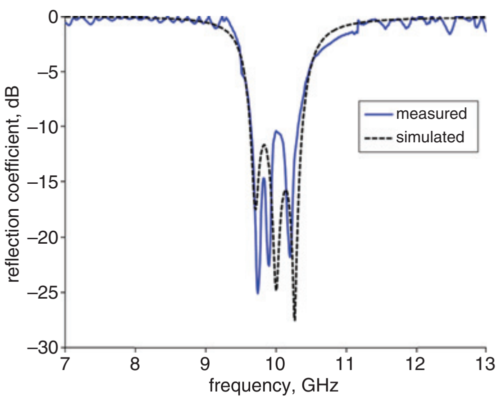

Fig. 6 *Comparison of measured and simulated reflectivities*

Experimental result: To experimentally verify the designed structures, the proposed 10 dB broadband absorber was fabricated using print circuit board technology. All three metallic layers were printed on 0.2 mm thick FR4 substrates, shown in Fig. 5, which are glued together to form the complete multi-layer structure. Two standard gain horn antennas, used as transmitting and receiving antennas were connected to a network analyser (Agilent N5230A) and the whole set up placed inside the anechoic chamber. Initially the reflection measurement was calibrated by placing a copper metal plate on the sample holder. Then the reflection coefficient from the sample was recorded and normalised with respect to the calibrated value to obtain the actual reflection from the structure. In the case of the 10 dB broadband absorber, the measured reflection dips are at 9.74, 9.9 and 10.2 GHz, covering the 10 dB absorption bandwidth of 6.82% at the centre frequency of 9.98 GHz as shown in Fig. 6. Good agreement is observed between the simulated and measured results except for some small deviations, which can be explained as being due to the fabrication tolerance and the use of adhesive for bonding layers.

Conclusion: An ultra-thin polarisation-insensitive metamaterial absorber using a multi-layer technique has been presented, which is wide-angle absorptive for both TE and TM polarisations. The proposed structure comprises three alternating stacked layers of different-sized metal plates and dielectric substrates, which can exhibit various absorption bandwidths by adjusting the geometrical dimensions of the metallic patches. The proposed absorber is much more compact and ultra-thin compared with existing 3 dB absorbers as observed from Table 2. In addition, the broadband absorber with the 10 dB absorption bandwidth has been fabricated and experimentally measured in an anechoic chamber, and there is good agreement with the simulated response. A further broadening of the absorption bandwidth is possible by increasing the number of stacked layers.

Table 2: Comparison of 3 dB absorbers based on multiple resonances

Absorber	Operating frequency	Thickness (mm)	FWHM (%)	Unit cell size (mm)
Ref. [4]	9.85 GHz	1.68 ($0.055\lambda_0$)	23.3	13 ($0.427\lambda_0$)
Ref. [5]	7.5 GHz	1.2 ($0.03\lambda_0$)	12.67	20 ($0.5\lambda_0$)
Ref. [6]	10.1 GHz	0.6 ($0.02\lambda_0$)	11	15.8 ($0.532\lambda_0$)
Ref. [7]	9.32 GHz	3.2 ($0.1\lambda_0$)	20.6	20 ($0.621\lambda_0$)
Proposed structure	9.86 GHz	0.6 ($0.019\lambda_0$)	19.47	9 ($0.295\lambda_0$)

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One or more of the Figures in this Letter are available in colour online.

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