International Journal Of Engineering Research And Development
e- ISSN: 2278-067X, p-ISSN: 2278-800X, www.ijerd.com
Volume 20, Issue 8 (August, 2024), PP. 87-92

Investigating Permittivity Sensing using a Dual-Band Ring Resonator Metamaterial Absorber

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ABSTRACT
This paper investigates permittivity sensing using a dual-band metasurface absorber. Dual-band perfect absorption is realized using a pair of concentric ring resonators, with their geometries exploited to provide electromagnetic absorption at 2.4 GHz and 5 GHz. Each unit cell is a three-layered structure, consisting of a pair of ring resonators as the top layer, an intermediate dielectric layer, and a metallized ground plane. Full-wave numerical simulations of the proposed absorber demonstrate both polarization- and mode-insensitivity, in addition to wide incident-angle operability. Furthermore, sensitivity levels up to 2.4% in the absorption characteristic, with per-unit changes in the permittivity of a loaded test sample, suggest a potential for employing the proposed structure in material sensing applications.

Date of Submission: 04-08-2024 Date of Acceptance: 15-08-2024

I. INTRODUCTION

Following the demonstration of perfect absorption by Landy et. al.[1], interest in the development of metamaterial absorbers has grown significantly over the past decade and a half, with applications ranging from energy harvesting, to stealth, imaging, and sensing, among others [2], [3]. Metamaterial absorbers are characterized by sub-wavelength periodic unit cells, which typically absorb incident electromagnetic energy at specific frequencies, and prevent reflection and transmission at those frequencies. Microwave-based sensors and detectors often function by mapping changes in a material under consideration to the variation of an electromagnetic property of the sensor. With metamaterial absorbers, variations in material properties, such as permittivity, can be mapped to changes in absorption [4], [5].

Various techniques have been developed to enable the development of metamaterial absorbers with different functional characteristics in both microwave and terahertz regimes. Multiband absorption is a popular functional requirement to increase the versatility of an absorber design. For instance, triple-band [6] and quad-band [7] absorption has been realized within sub-20 GHz spectra, and five-band absorption has been demonstrated at terahertz frequencies [8], [9]. Microwave dual-band realizations, however, still evoke significant considerations, often to match prevailing spectral assignments.

Split-ring resonators are employed in [10], with a central cut-out area on the ground plane, to achieve polarization- insensitive absorption at the WiFi frequencies of 2.4 GHz and 5 GHz. As an alternative to the use of metallized ground planes, frequency selective surfaces have been layered to provide electromagnetic wave absorption at 2.4 GHz and 5.5 GHz [11]. An ultra-thin perfect metamaterial absorber, based on an exploded-quadrant-shaped resonator, has also been numerically shown to provide dual-band absorption at 9.12 GHz and 11.34 GHz [12]. While [11] reveals a comparatively simpler design, with performance dictated by an appropriate choice of just three geometric parameters, the absorption performance at the upper frequency is slightly degraded compared to the lower frequency. On the other hand, the design in [10] provides uniform absorption performance at the two stated frequencies, but requires a careful determination of up to five geometries to provide the required dual-band performance. Furthermore, the layered approach in [11] may not be an optimal solution in space- constrained environments. The challenge, therefore, is to provide uniform absorption performance over multiple bands, while maintaining structural simplicity.

This paper seeks to leverage on the relative simplicity and symmetry of ring resonators to achieve dual-band absorption. Diplolar, hexapolar, and surface plasmon resonances of a concentric pair of ring resonators have previously been superimposed to provide absorption peaks at five THz frequencies [8]. In contrast, however, this paper employs the individual quasistatic LC resonance of each ring resonator to provide absorption peaks at 2.4 GHz and 5 GHz, respectively. The frequencies and absorption performance of the proposed structure is determined solely by an optimal selection of the radii and widths of the concentric ring resonators.

II. STRUCTURE DESIGN AND SIMULATION

The frequency-dependent effective input impedance of a metamaterial unit cell is determined using its scattering parameters:

$$z_{in}(\omega) = \pm\sqrt{\frac{(1+S_{11}(\omega))^2 - S_{21}{}^2(\omega)}{(1-S_{11}(\omega))^2 - S_{21}{}^2(\omega)}} \quad (1)$$

Likewise, given the intrinsic free-space impedance z_0, the reflectance is defined by

$$\Gamma(\omega) = |s_{11}|^2 = \left|\frac{z_{in}(\omega)-z_0}{z_{in}(\omega)+z_0}\right|^2 \quad (2)$$

The absorptance of the structure is provided by

$$A(\omega) = 1 - \Gamma(\omega) - T(\omega) \quad (3)$$

where $T(\omega) = |s_{21}|^2$ represents the transmittance. Perfect absorbtance, $(\omega) = 1$, requires that the square of the reflection coefficient, $|s_{11}|^2 = 0$. This condition arises when the input impedance of the structure is the same as the characteristic impedance of free-space, i.e. $z_{in}(\omega) = z_0 = 377\Omega$. Concurrently, perfect absorbtance requires that there is no transmittance, i. e. $|s_{21}|^2 = 0$, which can be achieved by placing a ground plane beneath the dielectric substrate.

Consequently, the metamaterial absorber unit cell is designed as a pair of 0.035 mm-thick concentric copper ring resonators, whose planar dimensions, as listed in Table 1, are optimized to match its input impedance to the free-space impedance, specifically at 2.4 GHz and 5 GHz. The unit cell pattern, as shown in Fig. 1, is placed on an FR4 dielectric substrate ($\varepsilon_r = 4.3$), backed by a ground plane of 0.035 mm thickness. Simulation and numerical analysis of this structure is performed using CST Studio Suite®, using unit cell boundary conditions and Flouquet port excitations, also shown in Figure 1

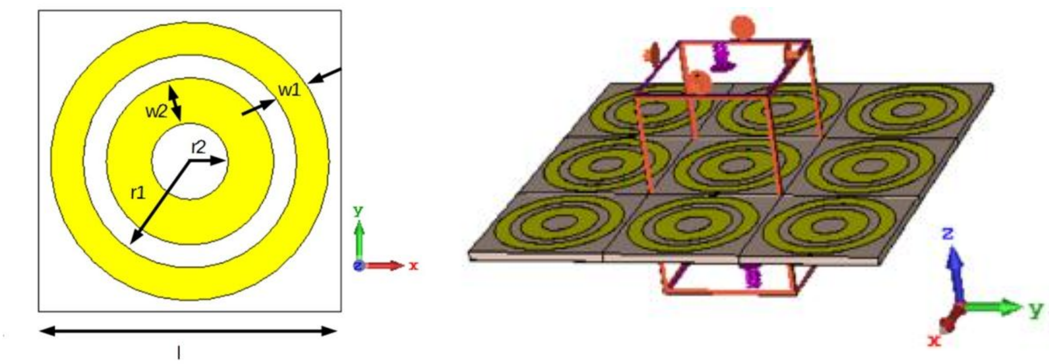


Figure 1. Unit cell structure and simulation set-up

Table 1 Dimensions

Parameter	Value (mm)
l	26
r1	9.2
w1	2.8
r2	3.3
w2	3.9

III. NUMERICAL RESULTS

The dual-band absorptance characteristic of the concentric ring resonator structure is revealed when it is impinged upon by a 0o-polarized normal incident excitation. As shown in Fig. 2a, perfect absorptance and zero reflectance both occur at the required frequencies of 2.4 GHz and 5 GHz, while the transmittance remains zero for all frequencies within the observation window. Figs 2b and 2c both reveal that the 2.4 GHz performance is dictated by the outer ring resonator, while the inner ring resonator accounts for the 5 GHz characteristic.
Figure 3. reveals that the symmetry of the unit cell structure imposes insensitivity to the polarization of the excitation. Similar results are obtained for TE and TM mode excitations.

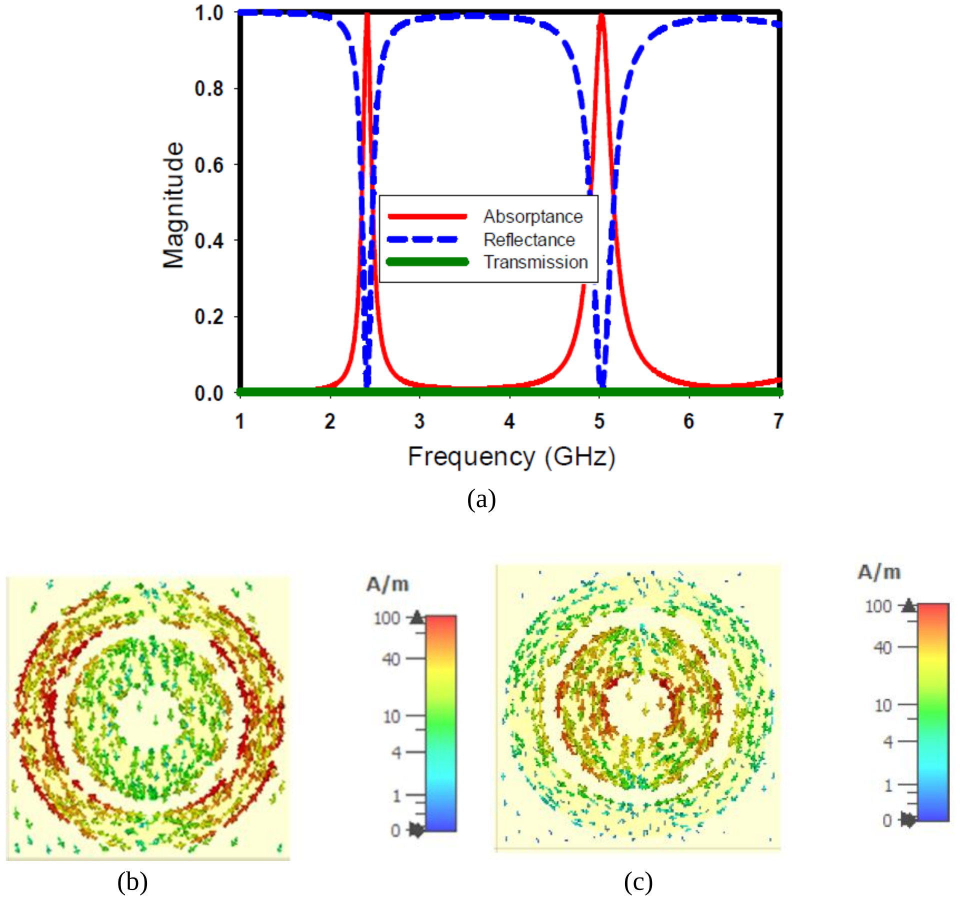


Figure 2. Dual-band characterization of ring-resonator absorber: (a) coefficients; (b) surface current distribution at 2.4 GHz; (c) surface current distribution at 5 GHz.

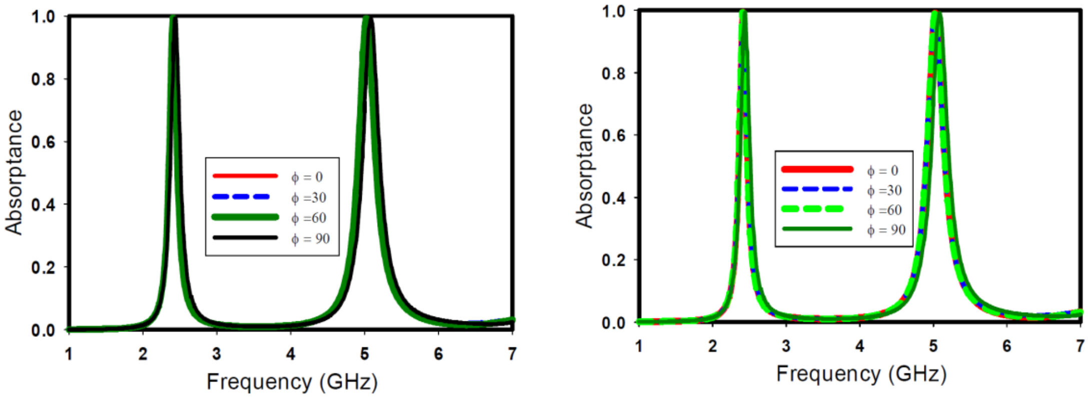
While the structure exhibits a level of incident-angle insensitivity, it is not completely impervious to the impact of variations in the excitation incident angle, as revealed in Figure 4. While the lower absorptance peak is consistent in frequency as the incident angle is increased, there are slight variations in the frequency at which the upper absorptance peak occurs. Beyond 60o, the absorptance of the unit cell degrades at both 2.4 GHz and 5 GHz, with a more significant impact occurring at the upper frequency peak. These variations at the upper frequency peak are more pronounced with TM mode excitation, and can be attributed to the relatively greater width of the inner ring resonator.

To demonstrate the potential of the proposed structure to sense permittivity variations, a 1 mm-thick sample material is loaded in direct contact with the concentric ring resonators. Fig. 5 reveals that increasing the relative permittivity of the sample directly translates to decreasing the frequencies at which the two absorption peaks occur. In addition, it is noticed that peak absorptance at the upper frequency declines with increased permittivity of the sample.

Sensitivity is defined as [5]:

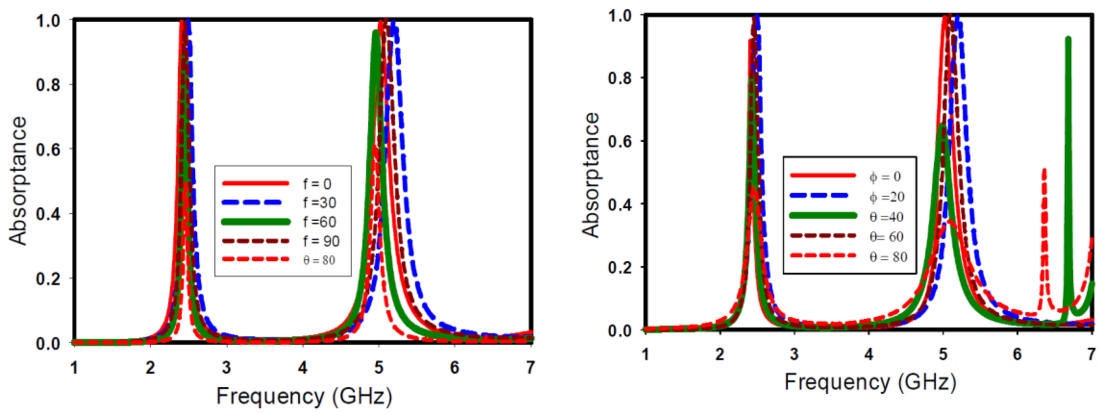
$$s = \frac{\Delta f / f_1}{\Delta \varepsilon_r} \quad (4)$$

where $\Delta f / f_1$ denotes the change in frequency of an electromagnetic characteristic normalized to its initial frequency of occurrence f_1, and $\Delta \varepsilon_r$ is the relative permittivity. Based on this formulation, the proposed unit cell structure provides sensitivities of 2.4% and 1.9%, at 2.4 GHz and 5 GHz, respectively. Redefining the sensitivity of the structure on the basis of a normalized change in absorptance with variations in relative permittivity, however, provides a sensitivity value of 2.3% for the upper frequency peak absorptivity. Although Fig. 5 is based on a normal- incident TE mode excitation, similar results are expected for TM mode excitation, due to the mode-insensitivity to normal incident excitation, revealed in Fig. 3. Fig. 6 shows that the thickness of the sample material has no influence on the absorptance characteristic of the proposed unit cell.



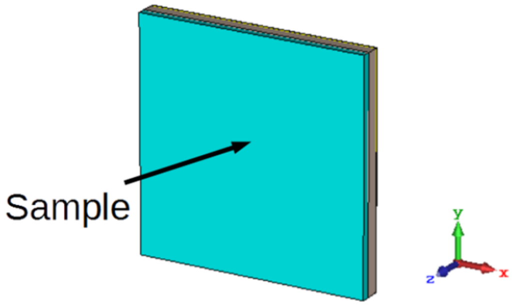
(a) (b)

Fig. 3. Absorptance with normal incident wave of different polarizations: (a) TE mode; (b) TM mode.

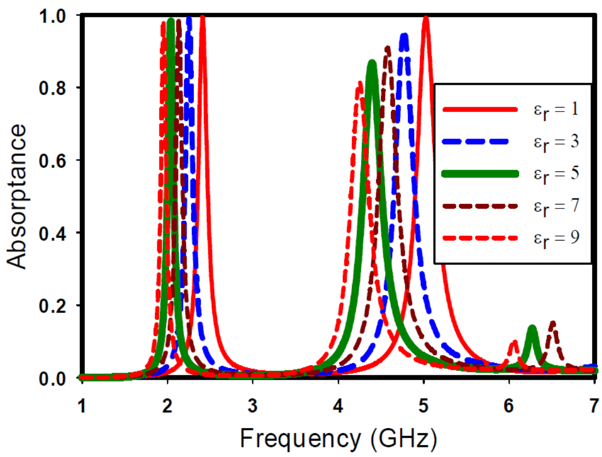


(a) (b)

Fig. 4. Absorption with horizontally polarized wave different incident angles: (a) TE mode; (b) TM mode.



(a)



(b)

Fig. 5. (a) sample material placed in direct contact with ring resonators on the unit cell (b) resulting absorption with different values of relative permittivity.

IV. CONCLUSION

This paper presents a numerical study on the application of a dual-band ring resonator metamaterial absorber for permittivity sensing. The absorber is composed of unit cells, comprised of a pair of concentric ring resonators, whose radii and widths are adjusted to individually match the free-space impedance at 2.4 GHz and 5 GHz. The resulting pattern, mounted on a ground-backed FR4 dielectric substrate, achieves perfect absorption at the two stated frequencies. In addition, the structure demonstrates mode- and polarization- insensitivity, and a wide-incident-angle characteristic at its lower peak frequency. The proposed structure senses variations in the relative permittivity of a sample material in direct contact with it, providing sensitivity levels up to 2.4%. The simplicity and symmetry of the ring resonator pattern makes it an attractive candidate for the implementation of sensors for in-situ material characterizations and measurements..

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