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Comment on Lu et al. Ultrathin Terahertz Dual-Band Perfect Metamaterial Absorber Using Asymmetric Double-Split Rings Resonator. *Symmetry* 2018, *10*, 293

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Abstract: In this study, the design of a dual-band terahertz absorber, previously published by Lu et al. (*Symmetry* 2018, *10*, 293), was re-simulated. Our findings showed significantly different absorption results from those published in the article. A detailed analysis was conducted to explain this discrepancy, which was attributed to the reflection of an unaccounted orthogonal component of the waves from the design, rather than absorption. The metasurface design has two resonances at 4.48 THz and 4.76 THz, respectively. It was reported that at these frequencies, the structure achieved absorption of 98.6% and 98.5%, respectively. However, in our results, it was found that at the second resonance (4.76 THz), the structure acted as a strong cross-polarization converter, reflecting a significant amount of incident energy in the cross-polarization component of the reflected wave. When this component is considered in the reflection coefficient calculations, the absorption reduces to 41% (from 98.5%), which is not an acceptable level for an absorber. In addition, the structure was simulated for both lossy and lossless (FR4) substrate cases to understand the effect of substrate losses. The results showed that the absorption response significantly deteriorates at the first resonance (4.48 THz) in the case of a lossy FR4 substrate.

Keywords: polarization conversion; metasurface; terahertz; cross-polarization; absorber design

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1. Introduction and Background

Electromagnetic wave (EM) absorbers have a range of applications in radio, microwave, infrared, and optical frequencies. They are used for stealth purposes, such as hiding an aircraft from radar waves in the RF range, and for microwave shielding of sensitive electronics in the microwave range as well as for energy harvesting in the microwave, infrared, and optical regimes. In the past, absorbers were made from special materials with inherent absorptive properties for the desired wavelength, but these materials were costly, bulky, and narrowband. Recently, there has been significant interest in a metasurface-based absorber design, with many designs reported in the literature for different frequency ranges [1–4].

In the last few decades, metamaterial-based absorbers have gained attention due to their low cost and ease of fabrication. However, the absorber designs reported in the literature are narrowband and often involve complex, multi-layer structures. It remains a challenge to achieve wide-band absorption using single-layer periodic structures. While there are several single-layer designs reported in the literature that researchers claim to be absorbers [5–10], they are cross-polarizers [11–15] in reality. These articles only consider the co-polarization component of the reflected wave in their analysis and mistakenly conclude that their structures are perfect wide-band absorbers. To accurately determine absorptivity, both the cross-polarization and co-polarization components must be included

in the absorption analysis [16,17]. The absorptivity of a linearly polarized wave incident on a metasurface can be calculated as follows:

$$A(w) = 1 - |R| - |T| \quad (1)$$

where $|R|$ and $|T|$ represent the reflectance and transmittance, respectively. To prevent any transmission from the metasurface, the design is grounded with copper at the back of the dielectric, effectively setting the transmission coefficient to zero. The reflectance can be expressed as $|R| = |R_{yy}|^2 + |R_{xy}|^2$, where the terms R_{xy} and R_{yy} are the cross- and co-polarization reflection coefficients, respectively, corresponding to *y*-polarized incidence.

2. Design Details

In this comment article, we examined a single-layer metasurface-based terahertz "absorber" described by Lu et al. [1]. The reported design employs an FR-4 dielectric substrate with a lossless conductivity of σ = 0 and a relative permittivity of ε_r = 4.3. As shown in Figure 1, the upper side of the dielectric substrate comprises an asymmetric split-ring resonator with two gaps oriented in opposite directions, while the back side is grounded using a metal sheet. The metal utilized on both sides of the substrate is copper with a thickness of t = 0.036 μm and an electrical conductivity of 4.58×10^7 S/m.

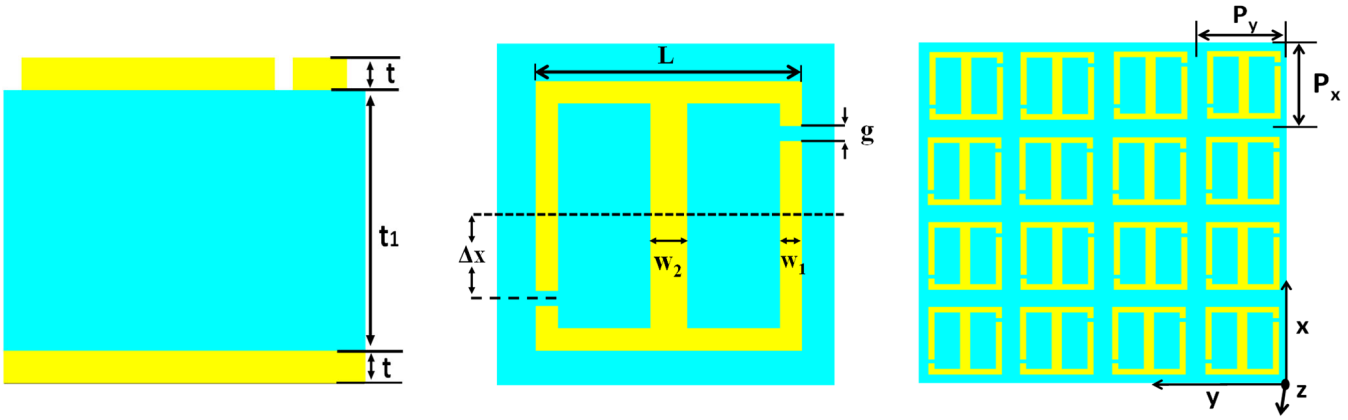

Figure 1. (**a**) Side view of unit-cell design with t = 0.036 μm and t_1 = 7 μm; (**b**) the top view of the unit cell with optimized geometric parameters L = 36 μm, w_1 = 2 μm, w_2 = 4 μm, g = 2 μm, and Δx = 11 μm; (**c**) periodic structure of unit-cell with $P_y = P_x$ = 40 μm.

The proposed absorber's unit-cell was numerically analyzed using the commercially available software, CST Microwave Studio™ (2019). The design's bounding box in CST was subjected to periodic boundary conditions in the x- and y-directions, while a Floquet waveguide port was utilized as the excitation source in the z-direction. It was verified that the only propagating modes present were the linearly polarized TE_{00} and TM_{00} modes, representing *x*- and *y*-polarized waves. Figure 2a,b highlight the crucial role of cross-reflection components of both incident *x*- and *y*- polarized waves, respectively. It is apparent from Figure 2a that at the second resonance (4.76 THz), the magnitude of the cross-polarization reflection component (R_{xy}) is higher than the co-polarization component (R_{yy}), and therefore, it cannot be neglected. The key point is to include the cross-component of the reflection coefficient R_{xy} in a reflectance computation, which the authors of [1] neglected when simulating their design.

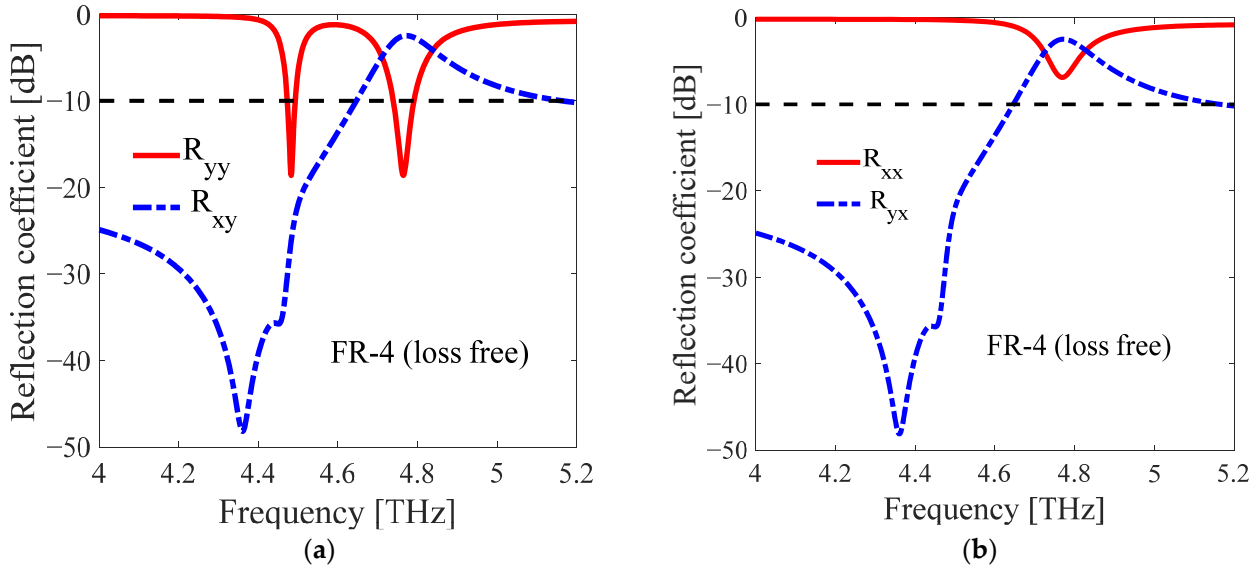

Figure 2. Simulation results of magnitudes (in dB) of cross- and co-polarized reflection coefficients for incident: (**a**) *y*-polarized wave and (**b**) *x*-polarized wave.

3. Results and Discussion

To understand the mechanism of polarization conversion in a linearly polarized wave, a set of orthogonal axes is selected, and the reflection behavior of the design is analyzed along these axes. The aim of this analysis is to determine the impact of the reflection coefficients along these axes on the polarization of the reflected wave. The simulation of the proposed unit-cell is performed by resolving the incident electric field into v- and u-components at $\pm 45^{\circ}$ relative to the principal coordinate axes, as shown in Figure 3a. The simulation uses v- and u-polarized field excitations as input. If the co-polarization reflection coefficients ($\boldsymbol{R_{uu}}$, $\boldsymbol{R_{vv}}$) are in phase, the reflected wave's polarization is the same as that of the incident wave. However, if there is a phase difference of 180° between the two reflection coefficients, the reflected wave's polarization rotates 90° relative to the y-incidence. A 100% cross-polarization conversion occurs when the magnitudes of the two reflection coefficients are equal to unity (i.e., $|\boldsymbol{R_{uu}}| = |\boldsymbol{R_{vv}}| = 1$) with a phase difference of $\pm 180^{\circ}$ (i.e., $\angle \boldsymbol{R_{uu}} - \angle \boldsymbol{R_{vv}} = \pm \pi$). As depicted in Figure 3c, the phase difference is 0° up to 4.5 THz, indicating 0% cross conversion, but at the second resonance frequency (4.76 THz), the phase difference jumps to nearly equal to 180°, indicating a strong polarization conversion. Figure 3b plots the magnitudes of $\boldsymbol{R_{uu}}$ and $\boldsymbol{R_{vv}}$ over the entire band. At 4.76 THz, the u-component is more strongly reflected than the v-component, but since they are out of phase, a polarization conversion of 90% is achieved. The results clearly indicate that the design acts as a cross-converter at that frequency.

When the cross-polarized component of the reflected wave is included in Equation (1), a much smaller value of absorptivity is achieved, as depicted in Figure 4a. At the resonance frequency (4.76 THz), the actual absorption is close to 41% instead of 98.5%, which contradicts the authors' claim of 98.5%.

Finally, the polarization conversion efficiency of a design is characterized by a well-known metric called polarization conversion ratio (PCR). The PCR relation is given in Equation (2).

$$PCR = \frac{|\boldsymbol{R_{xy}}|^2}{\left(|\boldsymbol{R_{yy}}|^2 + |\boldsymbol{R_{xy}}|^2\right)} \tag{2}$$

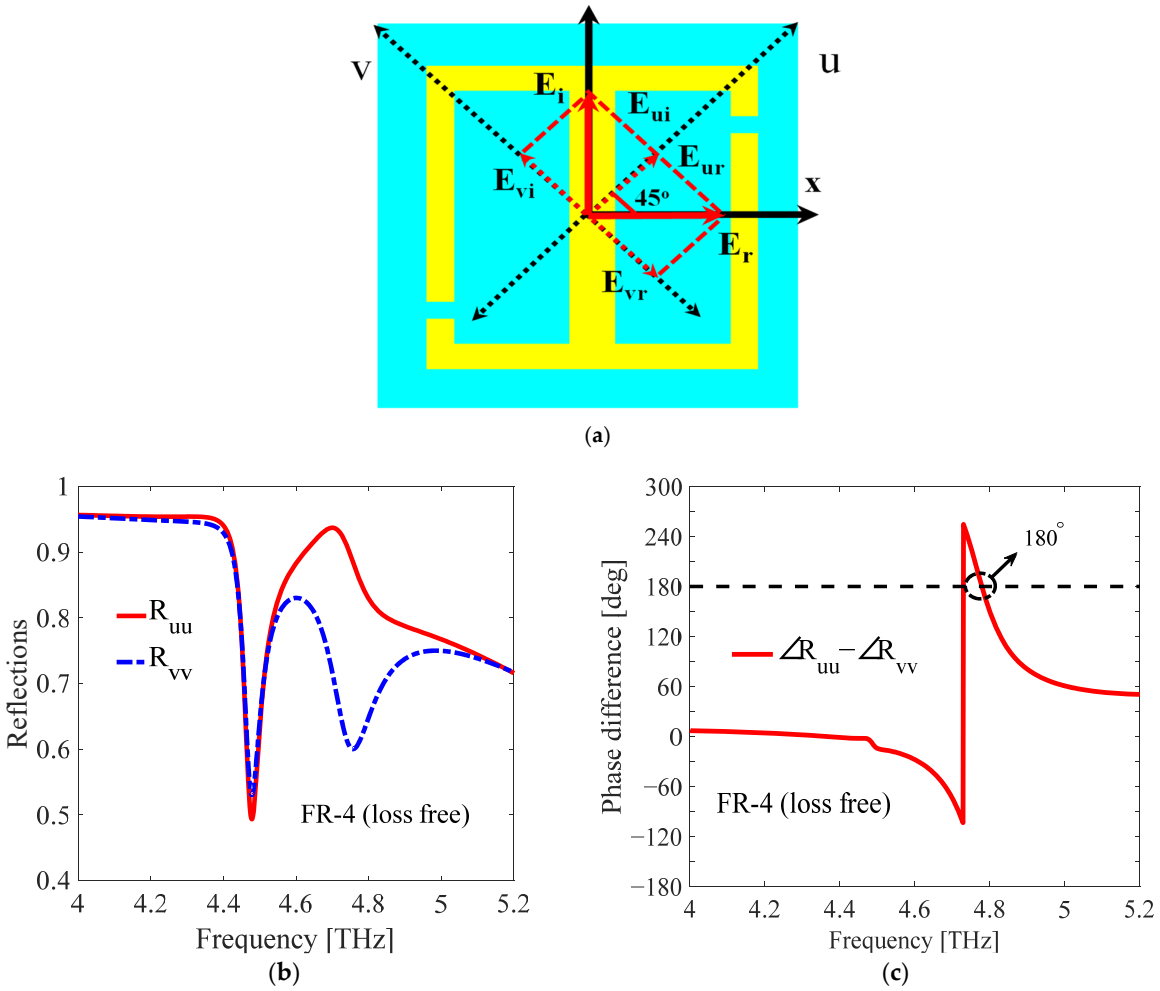

Figure 3. (**a**) Top view of the unit cell showing the decomposition of *y*- and *x*-axes, (**b**) the magnitude of the reflection coefficients for incident *v*- and *u*-polarized waves (R_{vv} and R_{uu}), and (**c**) phase difference between incident *u*- and *v*-polarized wave.

The PCR calculations for the design are plotted in Figure 4b. The PCR value of the designed structure is above 90% at the resonance frequency of 4.76 THz, implying that a significant amount of reflected wave energy is carried by the cross-component of the wave. Therefore, due to the high PCR at this resonance frequency, it can be concluded that the reported metasurface can be used as a highly efficient cross-polarizer rather than a perfect absorber at this frequency. Furthermore, to analyze the behavior of substrate losses on absorption and PCR, numerical simulations were performed in the frequency range of 4–5.2 GHz using the FR-4 substrate with a loss tangent of 0.02. The results are shown in Figure 5a,b corresponding to *y* and *x* incidences. When we compare these results to the results of the lossless FR-4 (Figure 2a), the resonance at 4.48 THz is greatly diminished, and only the second resonance (4.76 THz) remains, at which the design acts as a cross-polarizer. The absorption and PCR plots for different values of the loss-tangent are presented in Figure 6a,b, respectively. The absorption has been greatly reduced from 98% to about 60% at 4.48 THz, while it has increased from 40% to around 70% at 4.76 THz. The PCR at 4.76 THz has been reduced from 98% to around 70%. The effect of substrate losses is to improve absorption at the second resonance due to a diminished cross-polarization component. However, the absorption results are nowhere near ideal, and therefore, the design cannot be classified as a dual-band absorber. The authors made an error by choosing an ideal, lossless FR-4 substrate in their simulations. Substrate losses have an enormous impact on the design performance, especially at resonance frequencies, and therefore, they cannot be neglected in the simulations.

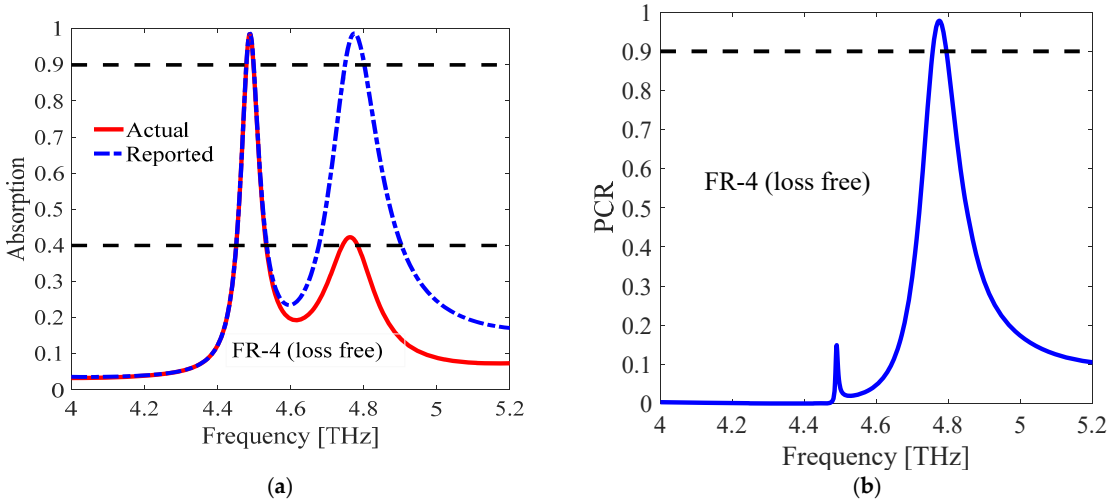

Figure 4. (**a**) Comparison between the actual and reported absorption of the reported metasurface design. (**b**) The computed PCR for the proposed design.

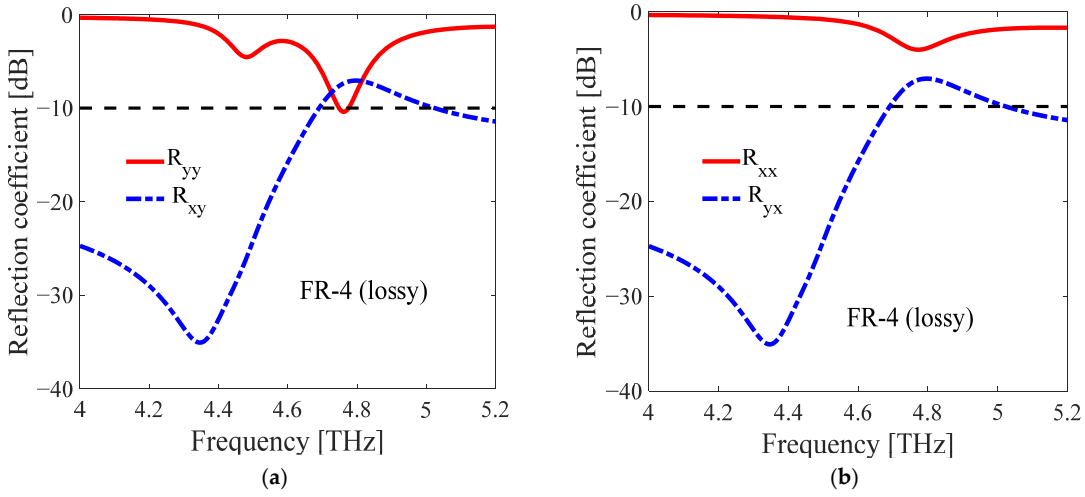

Figure 5. Simulation results of cross- and co-polarized reflection coefficients for incident: (**a**) *y*-polarized wave and (**b**) *x*-polarized wave for FR-4 (lossy) substrate.

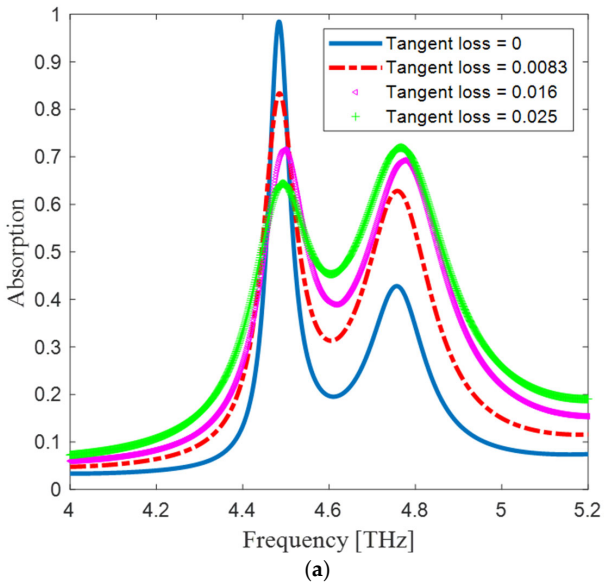

Figure 6. *Cont.*

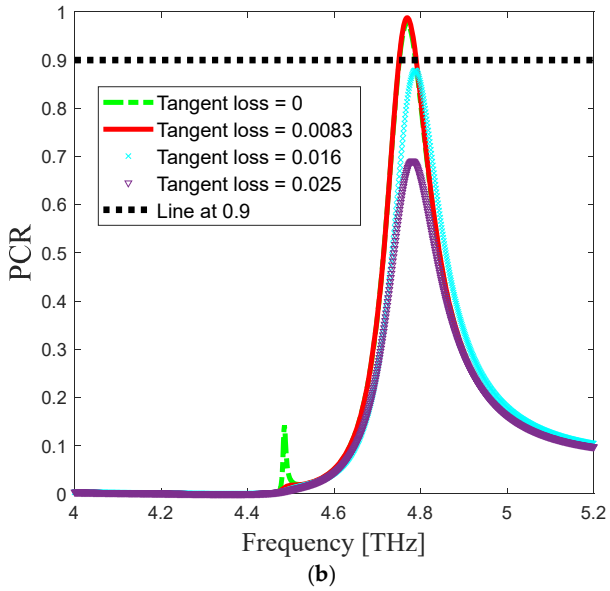

Figure 6. (**a**) Variation in absorption with increase in loss tangent of FR4 substrate. (**b**) Variation in polarization conversion ratio (PCR) with increase in loss tangent of FR4 substrate.

4. Conclusions

In conclusion, our research has found that the dual-band terahertz absorber design described by Lu et al. [1] is not effective for its intended purpose. Our re-simulation and in-depth analysis revealed that the design is not a perfect metamaterial absorber. The variance in absorption results can be attributed to the omission of an orthogonal component of the reflected wave in absorptivity computations in the original study. Additionally, we discovered that the absorption performance significantly decreases at the first resonance (4.48 THz) when using a lossy FR4 substrate. Hence, it is crucial for future studies in this field to take into account both cross-polarization reflection and substrate losses when designing metasurface-based absorbers for optimal performance.

Conflicts of Interest: The authors declare no conflict of interest.

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