Air Based Flexible Ultra-Thin Transparent ITO Based Broadband and Polarization Insensitivity Metamaterial Absorber

Gokhan Ozturk, Fatih Tutar, Mehmet Ertugrul, Abdulsemih Kockeser, and Yakup Ozturk

***Abstract*—In this study, a metamaterial-based transparent and flexible microwave absorber design was carried out. Transparent PET (polyethylene terephthalate) was used as the dielectric substrate and ITO (indium tin oxide) was used as the conductor for the air and metamaterial structure. The intended absorber provides %90 absorption in the range of 9.6 GHz to 34.8 GHz with a normal incidence angle of approximately 25.2 GHz. Oblique angle performance shows % 80 absorption up to 45 degrees. In addition, the designed absorber works as a polarization insensitive absorber as it provides the same absorption performance in both TE and TM polarization under the normal incidance of the electromagnetic wave. The transparent dielectric is only 2.85 mm thickness, making it thinner than comparable ultra-wideband transparent materials. The study was carried out as a simulation in the CST microwave simulator. The results obtained were compared with other reference studies.**

***Index Terms*—Transparent, ultra-thin, metamaterial absorber, flexible, wide-band**

I. Introduction

IN recent years, metamaterials have increased their importance in microwave device design with their superior properties as a negative refractive index (n), high resonance and periodically manufacturing. Metamaterials are called left-handed materials because they propagate waves in the opposite direction of conventional materials. The first theoretical work on left-handed materials was carried out by Veselego. Veselego proved that mathematically the refractive index occurs simultaneously with the negative constitutive parameters [1]. Experimentally, Pendry fabricated the negative permittivity material with an electric field applied to infinitely thin wires, similar to the behavior of gases at plasma frequency. He also fabricated negative permeability with SRR (Spling Ring Resenator) [2], [3]. Later, these two structures were combined in one material and left-handed material was produced [4]. Besause of the unique feature of metamaterials, they use a lot of area such as optical lens [5], sensor [8], antenna [6], solar systems [7], invisibility cloak [9], polarization converters [11] and absorbers [10].

There are numerous absorber applications to use in civil and military radars. In these applications, it is aimed to reduce the radar cross sectional (RSC) in order to prevent the detection of the target. The first metamaterial absorber designed by Landy inspired the use of metamaterials as absorber[10]. Afterwards, metamaterial based absorbers have been diversified by considering features such as multi [12] or single layer [13], polarization insensivity [14], oblique angle performance [15] and thickness according to wavelength [16] in the literature. The absorbers designed using various geometries were made not only for the GHz frequency region [17] but also for the THz region [18]. In some metamaterial-based broadband absorber applications, SRR structure combined with lumped elements [19] and thin films [20] to overcome their bandwidth limitation. Metamaterial absorbers can also be classified in terms of the bandwidth they cover such as one [17], double [21], triple [22] or penta band [23]. In addition, in order to provide this wide band gap, wideband absorber designs have been carried out using transparent materials, since the selection of completely transparent materials will provide more advantageous situations like invisibility [24]. Various microwave absorbers have been designed using materials such as glass, PDMS, PVC and PET as optically transparent materials. Peng designed an absorber with %90 absorption in the 6.4-30 GHz band using water, PDMS and ITO transparent materials. He did not report the oblique angle performance of his absorber in his study [25]. Gao designed an absorber operating in the 14.4-30.4 GHz band using air, water and ITO transparent materials. The oblique angle performance was the same up to 30 degrees for both TE and TM polarizations, and the thickness of the absorber was only 0.184 λ [24]. In addition, although there is high oblique incidance performance for wider bandwidth in other transparent absorber studies, the thickness of the absorber was a disadvantage for thin applications [26], [27], [28]. In addition, the flexibility of the absorbers was reported as a valnerable feature in studies. In this study, we proposed completely transparent ITO-based metamaterial

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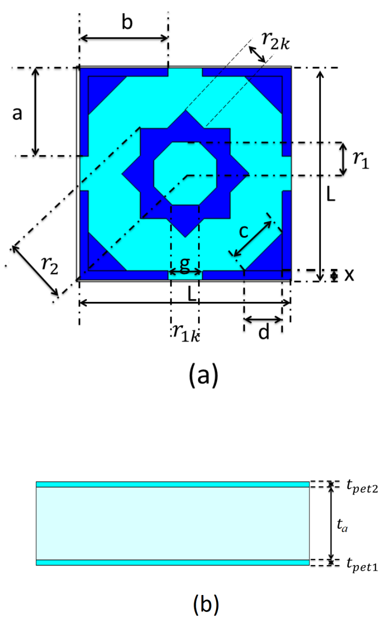

Fig. 1. (a) Front profile and (b) side profile of proposed metamaterial based transparent absorbent design

absorber design which operate between the 9.6-34.8 with 25.2 GHz bandwidth approximately and cover the X-, Ku-, K- and Ka- bands with 90% absorption performance. The design consists of air, PET and ITO, which are flexible and transparent. Absorber acts as polarization insensivity, because the proposed design shows the same absorption performance in both TE and TM polarization. The thickness of the intended absorber is only $2.85mm(0.21\lambda)$ and it show ultra-thin feature compared to other transparent metamaterial absorbers in the literature. In Section II, the design of the absorber and the theoretical background are given to understand the absorption mechanism. Absorption, impedance and constitutive parameters were obtained by using the simulation results in Section III. Finaly, the oblique incidance performance, relative bandwidth (RB), flexiblity, thickness of absorber were compared with other reference studies in Section IV.

II. Theory and Design

The proposed transparent metamaterial absorber is as shown in Fig. 1 (a-b). As seen in Fig. 1 (a-b), the bottom and top parts of the three-layer structure covered with ITO material, which is a transparent and conductive thin film. The battom level consists entirely of ITO with a thickness of $100nm$ and $10\Omega/m^2$ resistance. As seen in Fig. 1 (a), the top part consist of metamaterial coated by ITO with $100nm$ thickness and $35\Omega/m2$ resistance (the parts shown with dark blue). Dimensions of the ITO structure shown in Fig. 1 (a); $L = 12.2$ mm, $r_1 = 1.83$ mm, $r_2 = 3.2$ mm, $a = 5.10$ mm, $b = 5.10$ mm, $x = 0.50$ mm, $c = 3.14$ mm, $d = 4.6$ mm, $g = 2$ mm, $r_{1k} = 1.52mm$ and $r_{2k} = 1.52mm$, respectively.

An part of the lowest ITO coated level and a lower level of the uppermost ITO coated metamaterial structure consists of PET as Fig. 1 (b). The dielectric constant of PET is $\varepsilon_r = 3.2$ and the loss tangent is $\sigma = 0.003$. The middle part consists of an air medium with a dielectric $\varepsilon_r = 1$ and a thickness of $d = 2.5$ mm. The thickness of the upper level and the lowest level PET has a thickness of $t_{pet1} = t_{pet2} = 0.175mm$ and air thickness is $t_a = 2.5mm$. The metamaterial structure at the top consists of ITO with a conductivity of $35\Omega/m2$ and a thickness of $100nm$. The design given in Fig. 1 consists of transparent and flexible, which are air, water and PET. Therefore, the design can provide optically transparenty and flexibility advantage. Depending on the scattering parameters, the microwave absorption performance can be obtained as follows [27]

$$Absorbtion = 1 - R(\omega) - T(\omega), \tag{1}$$

Here $R(\omega) = |S_{11}|^2$ and $T(\omega) = |S_{21}|^2$, where S_{11} and S_{21} are reflection and transmission scattering parameters, respectively. Impedance matching is an important criterion to achieve good performance of the absorber. Using the scattering parameters, the normalized wave impedance of the absorber can be obtained as follows [30]

$$\bar{z} = \sqrt{\frac{\mu_{eff}}{\epsilon_{eff}}} = \sqrt{\frac{(1+S_{11}^2) - S_{21}^2}{(1-S_{11}^2) - S_{21}^2}}, \tag{2}$$

Here $\bar{z}$, ε_{eff} and μ_{eff} are normalized wave impedance, electrical permittivity and magnetic permeability, respectively. The electric and magnetic dielectric constants of the absorber directly affect the normalized impedance as seen in equation 2. The permittivity and permeability of the metamaterial absorber can give information about how the absorber works and performance of absorber. Depending on the scattering parameters, the permittivity and permeability of the absorber can be obtained as follows [30]

$$\epsilon_{eff} = 1 + \frac{2jS_{11} - 1}{k_o d S_{11} + 1}, \tag{3}$$

$$\mu_{eff} = 1 + \frac{2jS_{11} + 1}{k_o d S_{11} - 1}, \tag{4}$$

Where, k_o is the wave number of the free-space and d is the thickness of the absorber. Since the bottom of the proposed absorber is covered with high conductivity ITO material, ε_r and μ_r can be roughly obtained by assuming that the S_{21} parameter goes to about 0 in equations 3 and 4. For another analysis of the metamaterial absorber physical infrastructure and working mechanism, the equivalent circuit based on transmission line theory is given in Fig.1. Impedance Z_a refers to the part below the metamaterial in Fig. 2 and is expressed as

$$Z_a = j\frac{Z_0}{\sqrt{\epsilon_r}} \tan \frac{2\pi f \sqrt{\epsilon_r} d}{c}, \tag{5}$$

where j is the imaginary part, d is the thickness of the substrate and ϵ_r is the relative permittivity, f the frequency of the incident wave, c is the velocity of light. Z_b, which is the impedance of the metasurface, can be written as [29]

$$Z_b = R + j(2\pi f L - \frac{1}{2\pi C}), \tag{6}$$

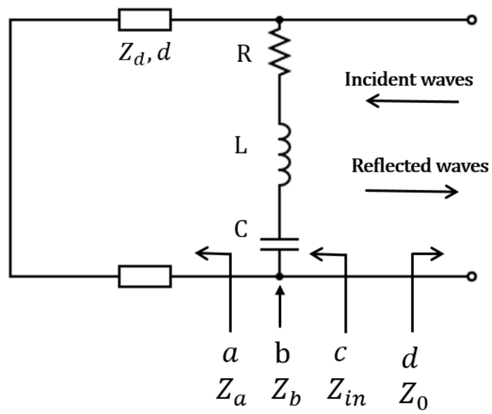

Fig. 2. RLC Equivalent circuit of proposed metamaterial based transparent absorber

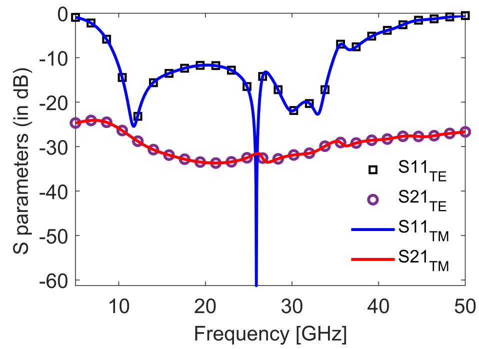

Fig. 3. S-parameters of the proposed metamaterial-based transparent absorber design in dB for TE and TM mode under normal incidance.

The total input impedance of port c, which includes impedances of Z_a and Z_b, is given with Z_{in} as follow

$$Z_{in} = \frac{Z_a Z_b}{Z_a + Z_b}, \tag{7}$$

Port d represents the characteristic impedance of free space and is denoted by Z_o and its value is 377Ω .

$T(\omega)$ mentioned in equation 1 is the transmission scattering coefficient and it can be taken as approximately zero since the back of the design below shows metal feature and $R(\omega)$ expressed as follow

$$R(\omega) = |\frac{Z_{in} - Z_0}{Z_{in} + Z_0}|^2, \tag{8}$$

The matching of free space and total impedance Z_{in} has to be equal Z_0. Equations 9 and 10 are obtained by using equations 5-8.

$$\frac{R}{R + (2\pi f L - \frac{1}{2\pi C})} = \frac{1}{Z_0}, \tag{9}$$

$$\frac{(2\pi f L - \frac{1}{2\pi C})}{R^2 + (2\pi f L - \frac{1}{2\pi C})^2} = \frac{\sqrt{\epsilon_r}}{Z_0} \cot\left(\frac{2\pi f \sqrt{\epsilon_r} d}{c}\right), \tag{10}$$

The mathematical expression of R, which is in the equivalent circuit by means of equations 9 and 10, is expressed as follow

$$R = \frac{Z_0 \tan^2(\frac{2\pi f \sqrt{\epsilon_r} d}{c})}{\epsilon_r + \tan^2(\frac{2\pi f \sqrt{\epsilon_r} d}{c})}, \tag{11}$$

Besides, relationship between equivalent parameters in the Fig. 2 as follow

$$(2\pi f L - \frac{1}{2\pi f C}) = -\frac{\sqrt{\epsilon_r} Z_0 \tan(\frac{2\pi f \sqrt{\epsilon_r} d}{c})}{\epsilon_r + \tan^2(\frac{2\pi f \sqrt{\epsilon_r} d}{c})}, \tag{12}$$

Where, L and C are equivalent inductance and equivalent capacitance, respectively.

III. Simulation Results

In order to determine S-parameters in the CST simulator, frequency domain is selected in software and unitcell boundary conditions are applied in flouquet mode for boundary condition. The hexahedral mesh type was chosen for precision analysis. 20x20 mesh cells were set to the unitcell metasurface. Accuracy set to $1e^{-12}$ and solver order high accuracy in frequency domain solver. After applying the boundary conditions in CST, the S-parameters results were obtained for TE and TM mode as given in Fig. 3. As seen in Fig. 3, reflected waves in the range of 9.6 GHz to 34.8 GHz for both modes are below $-10dB$. The $x - y$ plane symmetrical geometry of the proposed design ensures that the same S-parameters are obtained for both TE and TM modes as polarization insensitivity. Also, at the back of the design, there is metal termination by choosing a very small resistive ITO surface $(10\Omega/m^2)$. This surface acts just like metal termination with good conductor. Thus, the transmission scattering parameter (S_{21}) approached almost zero, providing transmission at approximately $-20dB$. In Fig. 3, design shows strong resonance and absorbation at 11.73 GHz, 25.84 GHz, 29.71 GHz and 32.85 GHz. The S11 parameter drops sharply at 30.56 GHz, where the reflection is minimum. Fig. 4 show absorbtion results under normal incidence for both TE and TM polarizations. The absorption results are the same in both polarization due to the symmetrical design. As seen in Fig. 4, more than % 90 absorption was achieved from 9.6 to 34.8 GHz. Maximum absorption with % 99.99 were achieved at the 29.71 GHz frequency, because there is a minimum reflection in this frequency. By using the S-parameters to equation 1, oblique incidence absorption performance for TE and TM polarization are presented with % 80 absorption in Fig. 5 (a-b). As it can be seen in Fig. 5 (a-b), if incidence angle increase, absorption performance decreases, gradually. Absorption performance of the design under oblique incidence is up to 45^o. Especially, angle sensitivity of absorber for TM mode is more than TE mode between $30^o - 45^o$. For strong impedance matching, the normalized impedance of the proposed absorber is expected to approach the normalized impedance of air. The real and imaginary part of the normalized impedance obtained using equation 2, the real and imaginary parts of the electric and magnetic permeability using equation 3-4 are given in Fig. 6 (a-b-c). As can be seen from the impedance of the absorber in Fig. 6 (a), between 9.6-34.8 GHz, the z_{real} expression oscillates around 1 value, while the z_{imag} expression oscillates around 0. Fig. 7 shows the surface current distributions for four resonance

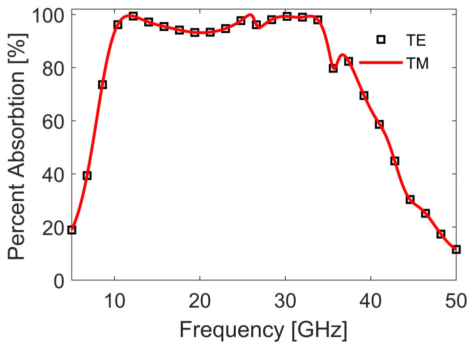

Fig. 4. Percent absorption performance of the proposed metamaterial-based transparent absorbent design for TE and TM mode under normal incidence.

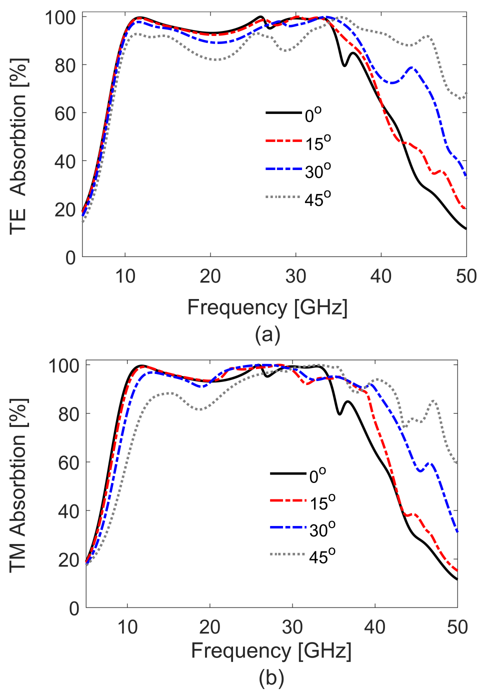

Fig. 5. (a) Percent absorption performance under oblique incidance for TE mod and (b) Percent absorption performance under oblique incidance for TM mod of the proposed metamaterial-based transparent absorber design.

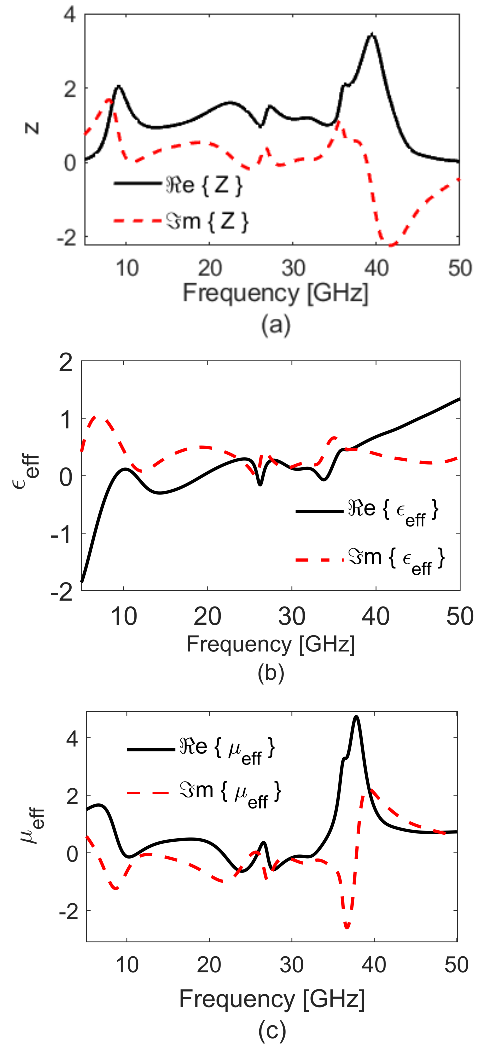

Fig. 6. (a) Real and imaginary parts of normalized wave impedance (b) real and imaginary parts of effective permittivity and (c) Real and imaginary parts of effective permeability of the proposed metamaterial-based transparent absorber design.

points which are 11.73 GHz, 25.84 GHz, 29.71 GHz and 32.85 GHz. The 11.73 GHz is the first resonance frequency and top and bottom surface currents distribution of 11.73 GHz resonance frequency are shown in Fig. 7 (a). When looking at the directions of the surface current distributions in the top and bottom parts, it is seen that they are in opposite directions, so magnetic resonance has occurred at this resonance point. The top and bottom surface currents distributions of the 25.84 GHz resonance frequency are shown in Fig. 7 (b), when looking at the directions of the surface current distributions in the top and bottom parts, it is seen that they are in the same direction, so electrical resonance has occurred at this resonance point. Likewise, the top and bottom surface currents of 29.71 and 32.85 GHz resonance frequencies are shown in Fig. 7 (c) and Fig. 7 (d), when looking at the directions of the surface current distributions in the top and bottom parts, it is seen that they are in the same direction, so electrical resonance has occurred at these two resonance points.

We analyzed the absorption performance with the loss tangent variation of the proposed absorber in the Fig. 8. As seen in the figure, the absorption performance of the proposed design decreases when the loss tangent increases too much. We also analyzed the absorption performance by varying the dielectric thickness of the proposed absorber for $t_a = 1.0$ mm, $t_a = 2.5$ mm and $t_a = 3.5$ mm. As seen in the Fig. 8, the performance of the absorber is optimum for $t_a = 2.5$ mm.

Table I give information about the performance of our and other optical transparent metamaterial absorber in the literature. The performance analysis of the study is presented based on some parameters such as the bandwidth, the relative bandwidth (RB), material thickness, flexibility in Table I. As can be seen in Table I, the proposed transparent metamaterial-based absorber is more useful for wide band applications with

TABLE I
PERFORMANCE OF THE PROPOSED ABSORBER RELATIVE TO OTHER REFERENCED STUDIES.

Ref.	Op. BW [GHz]	Flex	Angle	Thickness	RB
Ref [25]	6.4-30 GHz (23.6 GHz)	No	-	$4.5mm(0.273\lambda)$	$\%129.67$
Ref [24]	14.4-30.4 GHz (16 GHz)	No	30^o	$3.176mm(0.184\lambda)$	$\%72.07$
Ref [26]	14.4-33.7 GHz (19.3 GHz)	No	40^o	$6.4mm(0.513\lambda)$	$\%101.31$
Ref [27]	8-18 GHz (10 GHz)	Yes	45^o	$4.5mm(0.22\lambda)$	$\%76.92$
Ref [28]	5.61-29.17 GHz (23.5 GHz)	Yes	60^o	$4.5mm(0.273\lambda)$	$\%135.7$
Prop. Absorb.	9.6-34.8 GHz (25.2 GHz)	Yes	45^o	$2.85mm(0.21\lambda)$	$\%113.5$

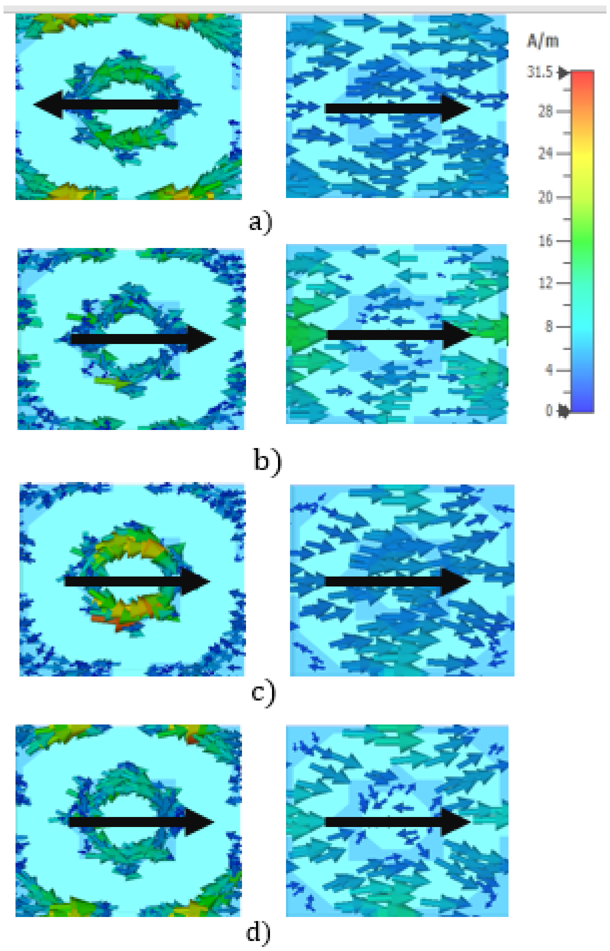

Fig. 7. Surface current distributions at the top and ground layers corresponding to a) 11.73 GHz b) 25.84 GHz c) 29.71 GHz d) 32.85 GHz

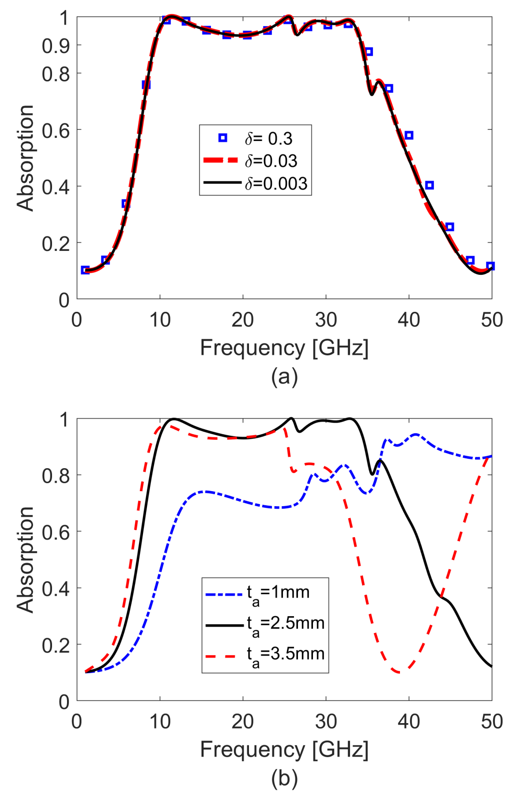

Fig. 8. The performance of the proposed absorber (a) according to the loss tangent variation (b) according to the thickness of the substrate

25.2 GHz bandwidth than references [24], [25], [26], [27], [28] and more competitive for ultra thin applications with $2.85mm(0.21\lambda)$ thickness in comparison with [24], [25], [26], [27], [28]. Besides, although referances [24], [25], [26] have a non-flexibility disadvantage, our proposed design show the flexibility performance because of selecting the flex materials. Since our design based on the air, we achieved good performance less material compared to [24], [25], [26], [27], [28]. The oblique incidence performance of absorber is up to (45^o) with wide angle relatively to other studies [24], [25], [26]. The RB performance with $(\%113.5)$ is more than references [24], [26], [27].

IV. CONCLUSION

In this study, a metamaterial-based transparent, flexible and ultra-thin absorber design is proposed. For the metamaterial structure, transparent thin film (ITO) and flexible transparent materials (air, PET). The proposed absorber design works for a very wide bandwidth (25.2 GHz) between 9.6 GHz and 34.8 GHz with $\%90$ absorption. The performance of the design is the same for both TE and TM polarized incoming waves, and the structure works as a polarization insensitive microwave absorber. In addition, the absorber shows an absorption performance of more than $\%$ 80 up to 45^o in both polarization at oblique incidence. Compared to other transparent metamaterial-based ultra wide band absorbers in the literature, it exhibits more comfortable properties in terms of bandwidth, thickness, angle and flexibility.

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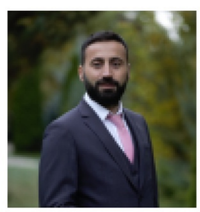
BIOGRAPHIES



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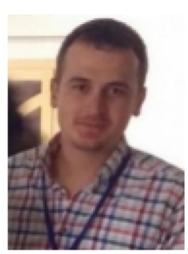

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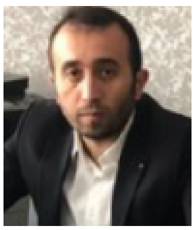

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