Ultrabroadband Rectangular Double Split Ring Based Perfect Solar Absorber

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Abstract — Metasurfaces could be very beneficial when elaborating solar cells to succeed in balancing between cost and efficiency. Thus, thin absorbers achieving high performance are attainable with the possibility to use any material. In this work, a perfect absorber based on a tungsten (W) metal-insulator-metal (MIM) metasurface is proposed. The MIM array consists of a rectangular double split ring resonator (RD-SRR) pattern with a specific set of parametric values that maximize the structure's absorption. The study results in an ultrabroadband absorption over a minimum value of 97.02% and reaching a high peak of 99.9%. Its integrated absorption over the entire spectral solar at AM1.5 is 99.6%. This absorber fulfills efficiently solar devices’ requirements including the ability to work under high temperature conditions afforded by the use of tungsten.

Keywords — Metasurface, Perfect absorber, Solar light, Ultrabroadband absorption.

I. INTRODUCTION

The development of applications in the field of light harvesting and the need for alternatives to silicon in photovoltaic devices has led to strong demand for materials with new optical functions [1]. This requires light control at the wavelength scale. The tremendous advances in nanoscience over the past two decades have given rise to many concepts of nanophotonics, of which we especially remember perfect absorbers (PAs) based on metasurfaces [2], [3]. Other designs are multi-layered or complex which makes them costly and inadequate for solar-cell manufacturing [4]–[6].

Metasurfaces are ultrathin nanostructures that enable various physical phenomena which were inaccessible using conventional materials. For solar devices, it’s about the compensation of the mismatch between light absorption and carrier diffusion length for better cell efficiency.

Metasurface PAs rely on subwavelength pattern arrangement possessing resonant behaviour. Thanks to the nanoelectronics industry, this structure realization has been made possible paving the way for higher-efficiency solar systems on small dimensions. The most interesting feature of these absorbers is the ability to tailor the response by simply adjusting the geometry [7].

Most of metasurface PAs consist of Metal-Insulator-Metal (MIM) structures. They are made of patterned and continuous metallic layers respectively at the front and the back, which are separated by a dielectric spacer. The continuous layer plays the role of a ground plane that blocks all EM waves from being transmitted. Many geometries could be used in the patterned layer. A common way of using multiple sized patches on the same unit facilitates the achievement of a broadband response thanks to multiple resonances occurring at different frequencies; like the broadband absorber proposed by Ming and Tan [8] which is based on four different size resonant square metal patches with an absorption spectrum higher than 76% along with the visible range. Or the broadband absorber based on 16 distinct nanoresonators achieving an absorption over 90% introduced by Azad et al. [9].

Many shapes have been used in literature. There are symmetrical designs like disks[10], [11], crosses [12], [13], crossed trapezoids [14], and nanorings [15] or asymmetrical ones like ellipsoidal pairs [16],
pentagon patches [17], multi-grooves [18], [24], and split ring (SRR) or electric-field-coupled-LC (ELC) resonators [19], [20].

The SRR design was first proposed as an absorber in the microwave regime by Schurig, Mock, and Smith [21] and as an absorber in the same regime by Bilotti, Nucci, and Vegni [22]. In the terahertz domain, Tao et al. [23] proposed a double band absorber. It was also used in the visible frequencies by Tang, Xiao, and Xu [20] in a three-layer absorber with a broadband absorption above 90%. Besides, Cheng, and Du [24] presented a circular-SRR based nanostructure with a broadband perfect absorption above 98% from 514 THz to 638 THz.

Replacing noble materials with refractory ones like tungsten is a good strategy to broaden the absorption response and enhance the structure absorption performance. Tungsten is a good candidate for light harvesting since it features a high intrinsic loss. It’s also adequate to be used in thin film solar cells in order to enhance their temperature stability thanks to its high melting point [25]. Various solar perfect absorber designs material consisted of tungsten. Rana et al. [26] reported a tungsten cross-shape based absorber with high absorption across the visible range. Cheng et al. [27] proposed an ultrabroadband perfect solar absorber based on tungsten ring arrays. They found an absorption higher than 90% over the visible range with an average absorption efficiency of 96.2%.

II. STRUCTURE DESIGN AND SIMULATION

In this paper, we propose an ultrabroadband metasurface perfect solar absorber which structure is consisting of a tungsten periodic rectangular double split ring resonator (RD-SRR) array and a continuous W layer. The two layers are separated with a lossless dielectric one made of polyimide behaving as a spacer (Fig. 1).

![Fig. 1. Schematic illustration of the proposed absorber design. (a) Single 2D unit cell top view with geometric parameters. (b) Single 3D unit cell view. (c) 3D 2x3 array based structure.](image)

The RD-SRR pattern embodies two rectangular split rings that are attached together from the front forming a capacitor like region. They are subwavelength elements that act as resonators. The back layer not only behaves as a physical support but is thick enough to guarantee that the structure’s entire light transmittance is almost zero so that the absorption approaches the unit.

The amount of absorbed light by the device is represented by the absorption coefficient as follow:

\[ A = 1 - |S_{11}|^2 - |S_{21}|^2 \]

where \( S_{11} \) and \( S_{21} \) are the S matrix parameters accounting for reflection and transmission. Maximising \( A \) comes down to reducing both the reflection \( |S_{11}|^2 \) and the transmission \( |S_{21}|^2 \). For this structure, thanks to the ground plane \( S_{21} \) is close to zero. Equation (1) results in \( A = 1 - |S_{11}|^2 \). Then, \( |S_{11}|^2 \) is scaled down by choosing the right geometry parameters leading to an impedance matching between the air and the first layer.

Using the frequency domain solver in a finite element method (FEM) simulations software [28] to numerically solve the Maxwell’s equations, we studied the structure’s efficiency by varying the different geometry parameters.
To simulate this array while saving memory space, periodic boundary conditions were defined. Perfect magnetic conductor in the x axis and perfect electric conductor in the y axis. For the same reasons in addition to the pattern’s symmetry, only a quarter of it is reproduced in the geometry. Electromagnetic (EM) energy enters from the design’s top along the z axis at normal incidence.

Tungsten optical constants are taken from Palik [29]. For polyimide, the loss tangent equals 0.07 and the relative dielectric constant is 3.1 [30].

In order to quantify the light captured by the absorber, a reference that can represent the amount of energy incident on the earth’s surface should be envisaged. Considering the standard air-mass (AM1.5) incident solar irradiance [31], the absorbed energy irradiance spectrum at wavelengths between \( \lambda_{\text{min}} = 300 \text{ nm} \) and \( \lambda_{\text{max}} = 1000 \text{ nm} \) is given by:

\[
I_{\text{abs}} = \int_{\lambda_{\text{min}}}^{\lambda_{\text{max}}} I_{\text{AM1.5}}(\lambda) A(\lambda) d\lambda
\]  

where \( \lambda \) is the wavelength, \( I_{\text{AM1.5}}(\lambda) \) is the spectral intensity of solar irradiation at global tilt AM1.5 and \( A(\lambda) \) the structure’s spectral absorption.

The structure’s absorption performance is evaluated by means of a figure of merit (FOM) consisting of an integrated absorption expression. It represents the ratio between the absorbed energy, which is given by (2) in the same range of wavelengths, and the total incident energy at AM1.5, defined as follows:

\[
FOM = \frac{I_{\text{abs}}}{\int_{\lambda_{\text{min}}}^{\lambda_{\text{max}}} I_{\text{AM1.5}}(\lambda) d\lambda}
\]

The conducted study aims to find the best structure for a solar absorber, or in other words, to find the most efficient absorber in the right frequency domain (visible). The period \( b \) was fixed at 130 nm as to obtain desired results in the wavelength range of interest. The results presented in Fig. 2a, 2b, 2c, 2d, 2e, and 2f depict the corresponding FOM value for each value of the parameters \( h_2 \) (spacer layer thickness), \( s \) (side width), \( d \) (side length), \( ww \) (wire width), \( cl \) (capacitor length), \( cg \) (capacitor gap), respectively.

Based on the comparison between FOM values obtained for different geometry combinations using (3), the optimized geometrical configuration of the whole structure is: \( d = 95 \text{ nm} \), \( s = 55 \text{ nm} \), \( ww = 12 \text{ nm} \), \( cl = 18 \text{ nm} \), \( cg = 3 \text{ nm} \), \( h_1 \) (RD-SRR layer thickness) = 20 nm and \( h_2 = 50 \text{ nm} \). These parameters allow an ultrabroadband perfect absorption over the solar spectrum (300-1000 nm) with the lowest reflection coefficient and an integrated absorption FOM of 99.6%.

Fig. 2. Integrated absorption FOM for different geometrical parameters.
III. RESULTS AND DISCUSSION

The adopted geometry numerical simulation results in the absorption distribution, shown in Fig. 3, presents more than 97.03% between 300 nm and 400 nm and higher than 99.63% from 400 nm to 1000 nm. Two peaks appear at 412 nm and 533 nm. The first one has a value of 99.96% and the second one reaches the high value of 99.99%. These peaks are coupled to give an ultrabroadband perfect absorption throughout the solar spectrum.

![Fig. 3. Ultra-broadband absorption spectrum of the perfect solar absorber. The dashed line indicates the absorption minimum value.](image)

![Fig. 4. Spectrum of the absorbed energy from the solar energy under AM1.5 illumination.](image)

Fig. 4 shows the solar irradiation spectrum at AM1.5 along with the amount of energy absorbed under this illumination $I_{abs}$ calculated via (2). It can be seen that the two spectra are almost identical. We calculate the unabsorbed energy $I_{unabs}$ employing the following equation:

$$I_{unabs} = I_{AM1.5} - I_{abs}$$ (4)

The unabsorbed light portion is plotted on the same figure as the absorbed one in order to adequately examine the difference between the two curves. $I_{unabs}$ is near zero at all wavelengths proving that the design is an excellent solar absorber.

Some structure parameters act directly on the absorption response when changing their values either by modifying the distance separating resonances or by shifting them to other frequency ranges which can affect the integrated absorption and even cancel the possibility of using the structure in certain applications.

To assess the influence each geometry parameter has on the absorption many parameter sweeps were conducted by varying one parameter at a time while keeping the other parameters at the same values. Absorption curves, depicted in Fig. 5, were retrieved and assembled in each figure according to one parameter.
In Fig. 5a, s changes from 45 nm to 75 nm with a 5 nm step. As it increases, the two resonance peaks move away from each other and the first peak absorption value decreases. Thus, for solar applications, a good distance choice between the two peaks, allowing them to overlap, gives a broader response without sacrificing the high absorption values.

The impact of d on the output is studied in Fig. 5b. It spans from 70 nm to 100 nm by a step of 5 nm. The absorption undergoes a red-shift when increasing d and the first peak gets higher. Also, the whole absorption improves. The impact of s and d on the entire absorption proves their correlation to the dipole resonance. This assumption is investigated later in this manuscript.

Capacitor gap cg is incremented from 1 nm to 7 nm in Fig. 5c. The greater its value, the greater the absorption is, especially for the higher wavelength resonance. It also shifts to higher frequencies. So, there is a clear trade-off between suitable range and good absorption. Conversely for the capacitor length cl which goes from 14 nm to 26 nm; when it increases, the second resonance absorption weakens, and the response shifts to lower frequencies as shown in Fig. 5d. In other terms, when the capacitance increases in both cases, either by decreasing the gap or by elongating the plates, the absorption becomes narrower. The last results confirm that choosing the inadequate capacitance is unwanted for an ultrabroadband perfect absorption using RD-SRR designs since it tends to corrupt the coupling between the two resonances to make room for an undesirable narrowband response. The previous analysis proves the tunability of the nanostructure depending on the desired use.

To further understand the underlying resonance process behind the ultrabroadband and high absorption spectra, an EM field intensity distribution study was carried out at the following resonance wavelengths: \( \lambda_1 = 412 \text{ nm} \) and \( \lambda_2 = 533 \text{ nm} \). The electrical field distribution on the xy plane, at the array level (\( z = 0 \)), is displayed in Fig. 6a and Fig. 6b. On the same plane, Fig. 6c and Fig. 6d show the magnetic field diagram whereas this field is shown at the ground plane level, for the xy plane, in Fig. 6e and Fig. 6f.

For the second resonance peak \( \lambda_2 \), the incident wave electric field is mostly trapped between the capacitor plates at the gap region, as seen in Fig. 6b. In fact, RD-SRR acts like an LC oscillator circuit that produces oscillating currents on both sides of the capacitor, trapping charges at the capacitor gap region and giving rise to an electric field which is detained for the LC resonance to occur at the frequency:

\[
\omega_0 = \frac{1}{\sqrt{L_{\text{eff}}C_{\text{eff}}}} \tag{5}
\]

where structure has an effective capacitance \( C_{\text{eff}} \) and an effective inductance \( L_{\text{eff}} \) [32].
C_{eff} is evidently determined by the gap capacitance as seen previously, but its value can also be affected by the coupling between neighbouring RD-SRRs that are close enough. Fig. 6b shows that the LC resonance is actually enhanced by this phenomenon. High field is noticed at the pattern sides, parallel to the x direction, where a distance of 35 sep a rates two adjacent resonators.

While the gap capacitance is impacted by cg and cl parameters, L_{eff} is influenced by the loops (rings) sizes which are the current path of the RD-SRR [33]. So, s and d are important in adapting the response as seen in Fig. 5a and Fig. 5b.

The high field intensity concentrated along the RD-SRR wire parallel to the x direction in Fig. 6c shows dipolar resonance which is excited by the electric field. In Fig. 6e, the image dipole, that validates the presence of this resonance in λ1, is observed at the ground plane (z = -h2) center equivalently to the pattern interior (z = 0). The incident EM wave magnetic component induces anti-parallel currents at the MIM metallic layers’ surfaces. Even though the RD-SRR is an electric LC resonator, the absorption response can magnetically be excited. The same magnetic response is perceived in Fig. 6d where the field is enhanced along the wires parallel to y direction.

To sum up, the absorption peak at λ1 is due to the electric dipole resonance excitation whereas the LC resonance, resulting from circulating currents in the RD-SRR tungsten rings and the charge collection at the capacitor gap region, is the main responsible for the high absorption in λ2.

IV. CONCLUSION

We have proposed and simulated an ultrabroadband perfect absorber which is composed of a tungsten RD-SRR array as a part of a metasurface MIM design. The absorption at normal incidence is more than 96% all over the optical range between 300 nm and 1000 nm and the integrated absorption over the AM1.5 solar spectrum is 99.6%. We investigated the dimensions’ variation influence on the response and we conducted an electromagnetic distribution study. Tungsten is cost-effective compared to other metals and it is more importantly temperature resistant which is advantageous for solar applications. Its problem for now is the hard nanomanufacturing process, but it would not take long for the fabrication technology to give a solution. We assume that the use of other refractory materials could also achieve high absorption.

CONFLICT OF INTEREST

Authors declare that they do not have any conflict of interest.
REFERENCES


