

Absorption enhanced thin-film solar cells using fractal nano-structures

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Abstract

In this article, a new structure for development of thin film solar cells is proposed in which elements with fractal shapes are integrated inside the cell to enhance its performance in a wide range of wavelengths. Two different structures are studied. In the first structure, a metallic fractal nano-carpet is integrated inside the silicon layer in order to trap and absorb sunlight by exciting surface plasmon polaritons and local surface plasmons at different wavelengths. Numerical analysis shows that this technique increases the short circuit current provided by the cell by a factor of 2.40 for both TM and TE polarisations of the incident light. The second structure has an active layer shaped as a fractal structure, and absorbs sunlight through Mie and Fabry-Perot resonances occurring at different wavelengths. The short circuit current enhancement for this structure is 2.97 for both TM and TE polarisations of the incident light, representing a significant improvement when compared with the previous works.

1 | INTRODUCTION

Solar cells are devices which convert sunlight to electrical power, and have found great importance in the world of renewable energy. The majority of the solar cells existing in the market are crystalline silicon (c-Si) solar cells [1–3]. Although silicon is the most viable and abundant element on the Earth, the complicated processing required for crystallization makes the crystalline silicon expensive in such a way that around 40% of the cost of silicon solar cells is the cost of crystalline silicon used in them. To reduce the amount of c-Si in solar cells, researchers have worked on developing thin-film solar cells in which the thickness of the active layer is significantly decreased. However, decreasing the thickness of the active layer limits the optical path length of sunlight, leading to low absorption and efficiency of the cell [4–6]. Therefore, now a days, the trend of research in the area of solar cells is to find solutions to increase absorption and efficiency of thin-film solar cells.

One of the best solutions to increase the absorption in thin-film solar cells is to use plasmonic nano-structures in the cell in order to focus and trap the sunlight in the active layer [5–11]. Metallic nano-particles [8, 9], core-shell structures [10, 11], grating structures [12, 13], dielectric resonators

[14, 15], and optical metasurfaces [16–21] have been used in thin-film solar cells to enhance light absorption in these cells. In the grating structures, the light is coupled to the surface plasmon polaritons (SPPs) propagating along the metal-dielectric interface and then absorbed by the active layer [12, 13]. When using nanoparticles, the light excites local surface plasmons (LSP) around nanoparticles leading to local field enhancement and absorption improvement [8–11]. Metasurfaces, 2D version of metamaterials [22–25], have been also used as absorbers [16, 17], lenses [18, 19] and beam formers [20, 21] to trap sunlight inside the active layer of solar cells.

Although the aforementioned methods [8–21] enhance absorption in solar cells, some drawbacks such as dependency to polarization [13, 20] and narrow bandwidth [8, 11–13] limit their performance. To overcome some of these limitations, a new method is proposed here in which fractal structures are integrated inside solar cells, in order to improve their performance in a wide range of wavelengths. A fractal structure is a geometrical shape which consists of parts that resemble the shape of the whole structure [26–28]. In other words, a fractal structure is composed of parts that are similar in shape but different in size. The multi-scale property of a fractal geometry makes it to have similar responses at different wavelengths [26–28]. This property has been already used in the design of

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wideband absorbers [29], multiband antennas [30, 31], broadband waveguides [32] and sub-wavelength imaging systems [33]. This property is used in the design of absorption-enhanced thin-film solar cells.

To enhance absorption of thin-film solar cells, here, two new types of solar cells are designed, and numerically analysed. In the first solar cell, a metallic fractal structure, in which resonators with different sizes are used to excite SPP and LSP modes at different wavelengths, is integrated inside the active layer of a thin-film solar cell. The second structure studied in this article, has an active layer shaped as a Sierpinski fractal nano-carpet in which the sunlight is absorbed inside the resonators at different wavelengths due to the Mie resonance occurring in resonators with various sizes. In other words, instead of using an active layer in the solar cell, the active resonators have been used, which saves a considerable amount of crystalline silicon used in construction of the cell. Furthermore, using dielectric fractal structures instead of metallic ones decreases the plasmonic loss resulting in higher efficiency of the cell.

2 | SOLAR CELL WITH METALLIC SIERPINSKI NANO-CARPET

Figure 1 shows the proposed structure, consisting of a Sierpinski nano-carpet integrated inside the thin-film solar cell. The Sierpinski nano-carpet is a fractal structure composed of resonators with different sizes [26–28]. At its resonance frequency, each resonator enhances the light intensity around it, resulting in sunlight focusing on the active layer of the cell leading to absorption enhancement. Since the resonators have different sizes, their resonance frequencies differ from each other. This results in absorption enhancement at a wide range of wavelengths as required for solar cell application. As shown in Figure 1, second order Sierpinski fractal structure is used in this study. In this fractal structure, a big nano-brick (as the first type resonator) with the size of one third of periodicity of the structure (p in Figure 1) located at the centre is surrounded by eight smaller nano-bricks (as the second type resonator) with one-third size of the central big nano-brick.

The periodicity of the fractal structure is $p = 270$ nm and the height of the first and second resonators are $h_1 = 90$ nm and $h_2 = 30$ nm, respectively. The thickness of the anti-reflection layer and back-metal of the solar cell are $H_{ito} = 75$ nm, and $H_{Ag} = 75$ nm, respectively. Steps were taken to decrease the thickness of the active layer as far as possible ($H_{Si} = 100$ nm) while keeping the performance of the thin-film solar cell at an appropriate level. To accurately investigate the process of light focussing in the proposed solar cell, the role of each resonator is studied separately. Therefore, the Sierpinski fractal is broken into two periodic patterns as shown in Figure 2, and each pattern is studied individually.

To numerically study the structures shown in Figure 2, numerical full-wave analysis was performed using the CST software. In this analysis, the structure is excited by a normally incident plane wave impinging on the solar cell. Floquet

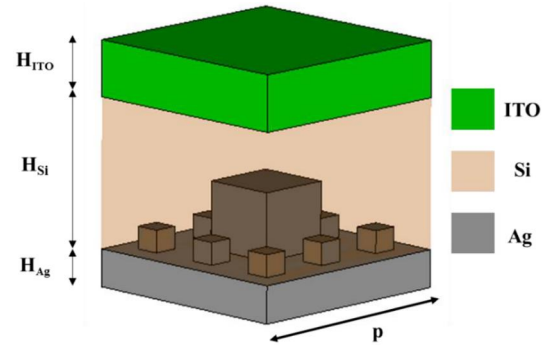


FIGURE 1 The proposed solar cell with Sierpinski nano-carpet integrated inside it

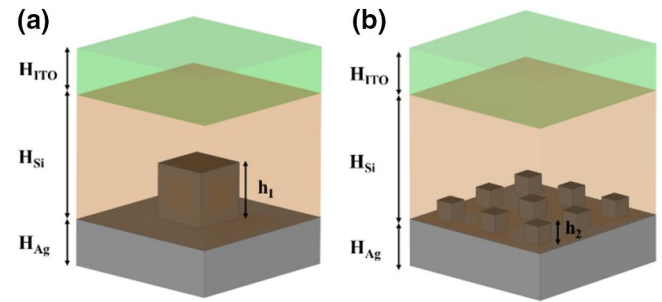


FIGURE 2 Solar cell with the (a) the first kind of resonators inside and (b) the second kind of resonators inside. The dimensions shown in this figure are as: $H_{Si} = 100$ nm, $h_1 = 90$ nm, $h_2 = 30$ nm, $H_{ITO} = 75$ nm, $H_{Ag} = 75$ nm

boundary conditions are applied to the lateral sides of the cell to mimic a periodic structure. For silver, Drude model fitted to the experimental data reported in [34], is used. The parameters used in Drude model are as follows: $\epsilon_\infty = 3.7$, the plasma frequency is $\omega_p = 1.38 \times 10^{16}$ rad/s and the collision frequency is $\gamma = 2.73 \times 10^{13}$ Hz. For the permittivity of silicon, data reported in [35] is used which considers both loss and frequency dispersion.

After numerically calculating the field intensity at different wavelengths of the incident light inside the silicon layer of the solar cell, the light absorption of the cell is calculated as [36]:

$$A(\omega) = \frac{1}{2} \omega \text{Im}(\epsilon(\omega)) \int_v |E|^2 dv \quad (1)$$

where ω is the angular frequency, E is the magnitude of electric field, $\text{Im}(\epsilon(\omega))$ is the imaginary part of the permittivity of silicon layer and the integration is taken inside the silicon layer of the cell. Since in (1), the integration is taken only in the silicon layer of the solar cell, it does not include the power dissipated in the metallic parts and therefore accurately calculates the power absorbed by the solar cell. This absorption is shown in Figures 3 and 4 for the structures shown in Figure 2a,b, respectively. These figures also show the electric field profile inside the cell at resonance wavelengths where absorption is maximum.

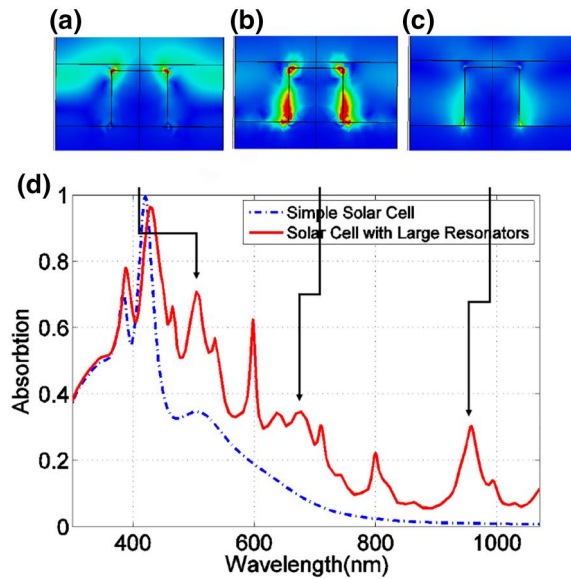


FIGURE 3 Electric profile of large resonators at the wavelength of (a) 500 nm, (b) 663 nm, (c) 970 nm. In (d) absorption of the solar cell when using only large resonators is compared with a simple solar cell without resonators

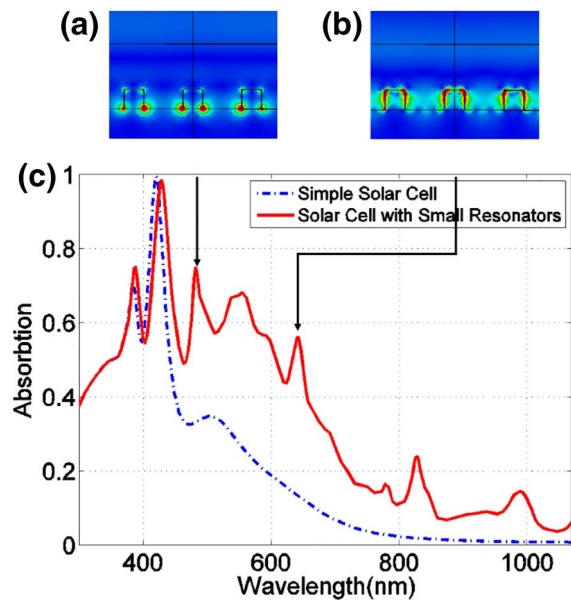


FIGURE 4 Electric field profile in the cell when only small resonators exist at the wavelengths of (a) 480 nm, and (b) 638 nm. Absorption of the solar cell using only small resonators is compared with a simple solar cell without resonators in part (c)

In Figures 3 and 4, the absorption of the proposed solar cells are compared with the absorption of a simple solar cell which does not include any resonator. The simple solar cell is compared with the proposed structures, which consist of a 100-nm thick layer of silicon on a silver layer with a thickness of 75 nm, and also includes a 75-nm thick ITO layer operating as an anti-reflection layer.

Figure 3 shows the absorption of the solar cell with the first kind of resonators. As shown in this figure, for

wavelengths larger than 450 nm, the absorption of the proposed solar cell has been enhanced. As the electric profiles shown in Figure 3 illustrate, the absorption enhancement has different reasons at different wavelengths. For example, at the wavelength of 500 nm, the electric field is confined at the corner of the large resonator, while at the wavelength of 663 and 970 nm the field is mainly confined at the interface between silicon and silver, due to excitation of the SPPs.

Similarly, Figure 4 shows the absorption of the proposed solar cell when only small resonators are inserted in the active layer of the cell. As shown in this figure, using small resonators also enhances the light absorption in most of the wavelengths when compared with a simple solar cell. The electric profiles shown in this figure clarifies the reason behind this enhancement. As shown in this figure, at the wavelength of 480 nm, electric field is focussed around the resonators due to the dipole resonance, while at the wavelength of 638 nm, SPPs excited at the interface of the metal and silicon provide field enhancement.

To investigate the performance of the proposed solar cell with all resonators, Figures 5 and 6 show the absorption and the absorption enhancement for the solar cell with the whole Sierpinski nano-carpet inside it. Comparing Figure 5 with Figures 3 and 4, it is observed that in addition to resonance wavelengths of each resonator, when using all resonators, there are other wavelengths (see Figure 5a, b, c) at which absorption has been significantly enhanced. This can be explained through coupling between large and small resonators. As shown in Figures 5 and 6, the absorption of the proposed solar cell is much better than the simple solar at all the wavelengths larger than 450 nm. Furthermore, since the structure is completely symmetric, it provides exactly the same response for TE and TM polarisations of the incident light. The consistency of the absorption for TM and TE polarisations is one of the important advantages of the proposed solar cell when compared with previous works [12, 13, 20].

To have a more comprehensive study on the performance of the Sierpinski-fractal solar cell, here the short circuit current provided by the proposed solar cell is calculated and compared with a simple one. Having the absorption at each wavelength, the short circuit current of the cell can be calculated as [37]:

$$J_{sc} = \frac{e}{hc} \int \eta_c S(\lambda) A_{Si}(\lambda) \lambda d\lambda \quad (2)$$

where e is charge of the electron, A_{Si} is the absorption in the active layer (silicon), $S(\lambda)$ is the AM 1.5 G solar spectrum [38] and η_c is the collection efficiency, h is the Planck constant and c is the speed of light in free space [37].

Using (2), the short circuit current for a simple solar cell with 100 nm silicon layer, is calculated as 6.37 mA/cm^2 , while this value for the proposed solar cell with Sierpinski nano-carpet inside, is achieved as 15.26 mA/cm^2 . Therefore, using the proposed technique, the short circuit current can be enhanced by a factor of 2.4 for both TM and TE polarisations of the incident light, which is much higher than the enhancement reported in the previous works [13, 18–21]. The study of

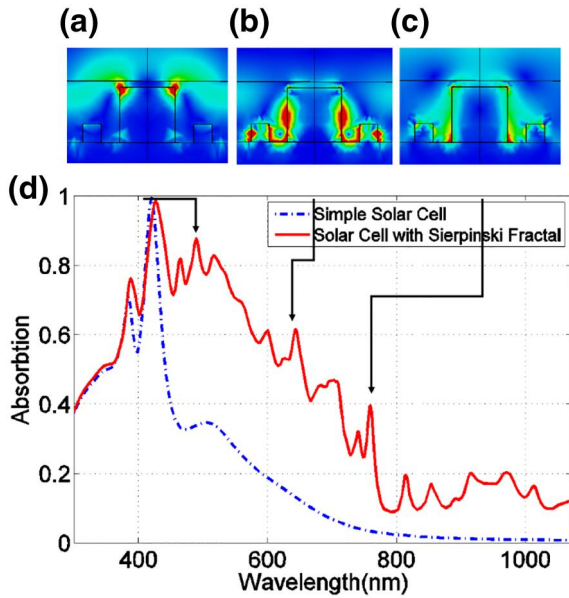


FIGURE 5 Electric field profile in the cell when both resonators exist at the wavelengths of (a) 489 nm, (b) 644 nm, (c) 760 nm. Absorption of the solar cell with the Sierpinski fractal structure inside it is compared with a simple cell without the fractal in part (d)

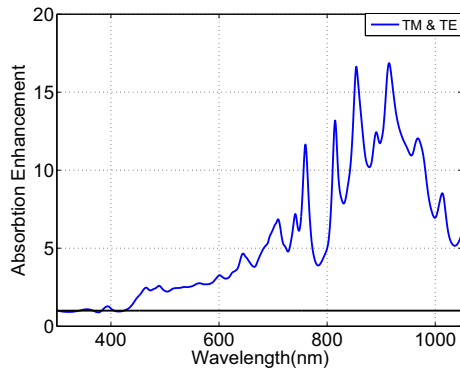


FIGURE 6 Absorption enhancement of the solar cell with Sierpinski nano-carpet in TM and TE polarisations

the effect of tilted light in the solar cell represents that current enhancement of the proposed structure is higher than 2.3 for the incident angles less than 60° (see Figure 7).

3 | USING DIELECTRIC SIERPINSKI NANO-CARPET IN THE SOLAR CELL

In the previous section, it is observed that metallic resonators enhance the electric field around them. However, a part of the field which penetrates inside the metallic parts will be transferred to heat and is wasted. To avoid this waste of energy, here, a new structure is proposed in which metallic resonators are replaced by dielectric resonators. The proposed structure is shown in Figure 8. In this structure, dielectric resonators are made of Si, and actually play the role of the active layer of the

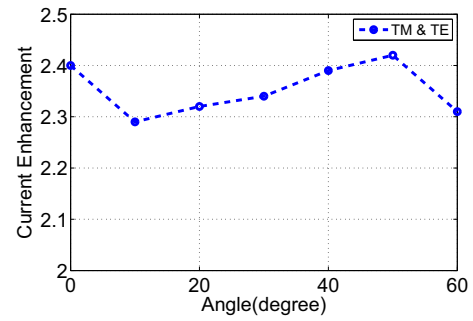


FIGURE 7 Short circuit current enhancement of the solar cell with Sierpinski nano-carpet for different angles of the incident light

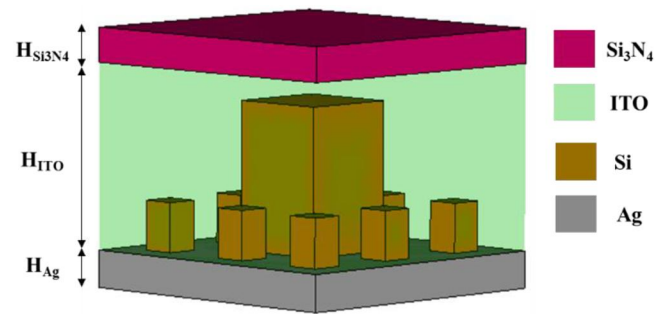


FIGURE 8 The proposed solar cell with dielectric Sierpinski nano-carpet integrated inside it

cell. In other words, electron-hole generation occurs in the resonators, which are made of crystalline silicon, and therefore focussing the field inside the resonators, will enhance the light absorption in the cell. The advantage of this method is that the amount of crystalline silicon used in the solar cell, which is the most expensive material used in the cell is significantly reduced.

As shown in Figure 8, Sierpinski fractal made of silicon resonators is used as the absorber, and is placed at the top of the silver layer with a thickness of 75 nm. The medium around the resonators is made of TiO_2 with a thickness of $H_{ito} = 375$ nm, which transports generated electron-holes to the electrode of the solar cell. The anti-reflection layer is made of Si_3N_4 with a thickness of 70 nm which has a refractive index of around two in the optical regime. The periodicity of the fractal-structure is $p = 600$ nm and the large and small resonators have a thickness of $h_1 = 300$ nm and $h_2 = 100$ nm, respectively.

The Sierpinski-fractal solar cell is numerically analysed using CST, and the results are shown in Figures 9–12. Figure 9 shows the magnitude of the electric field profile inside the cell at different wavelengths. As shown in this figure, at longer wavelengths of 560 nm, 600 nm and 834 nm (which are shown in Figure 9a–c) the electric field is focussed inside the large resonators due to Mie resonance, occurring at these wavelengths. However, at a shorter wavelength of 474 nm, as shown in Figure 9d, the field is focussed at smaller resonators due to Mie resonance occurring at this wavelength inside these resonators. On the other hand, the results shown in Figure 9e illustrate

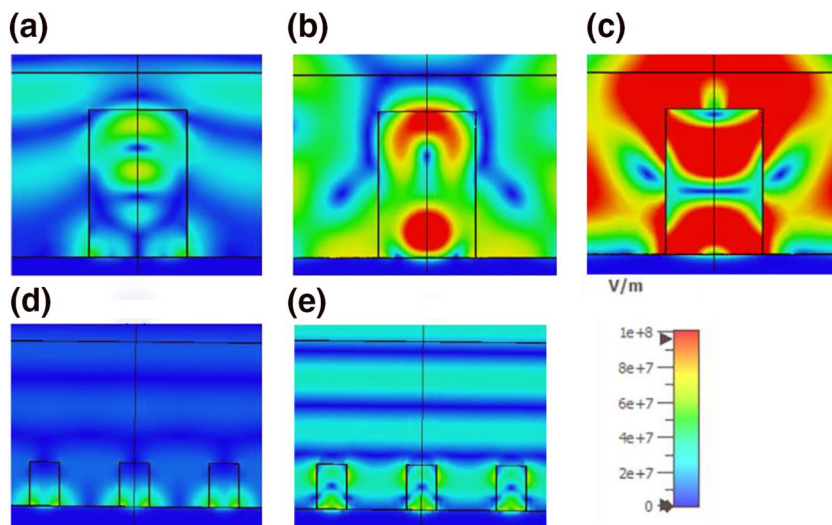


FIGURE 9 Magnitude of electric field profile in the solar cell with dielectric fractal integrated inside it at the wavelengths of, (a) 560 nm, (b) 600 nm (c) 834 nm, (d) 474 nm, and (e) 433 nm

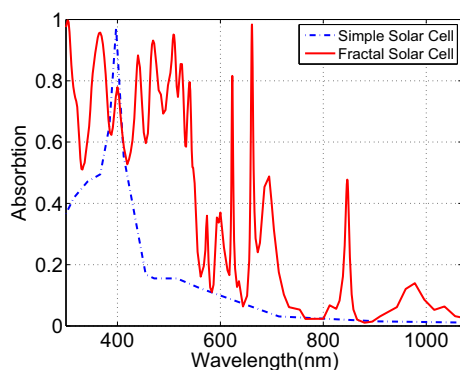


FIGURE 10 Absorption of the proposed solar cell with dielectric Sierpinski fractal structure inside is compared with a simple solar cell without the fractal

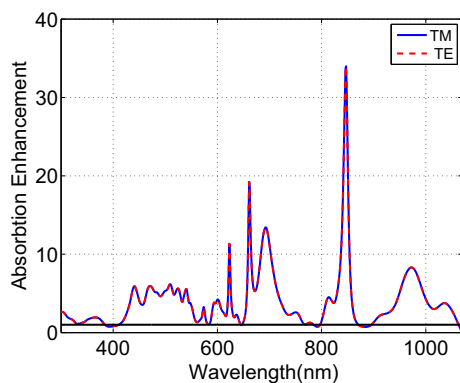


FIGURE 11 Absorption enhancement of the solar cell with the dielectric Sierpinski nano-carpet inside for TM and TE polarisations of incident light

that the light can be trapped inside the cell due to some other reasons such as Fabry-Perot resonance which occurred at the wavelength of 433 nm.

As the results of Figures 10 and 11 illustrate, using the dielectric fractal in the solar cell enhances the absorption at

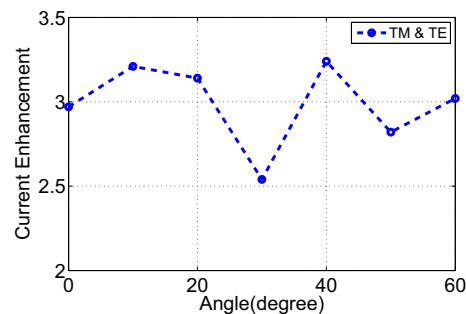


FIGURE 12 Short circuit current enhancement of the solar cell with dielectric Sierpinski nano-carpet inside for different angles of incident light

most wavelengths, especially at large wavelengths of light at which a simple thin-film solar cell has a very poor performance. Figure 11 also shows that the proposed fractal solar cell has the same behaviour for TM and TE polarisations of the incident light, which is another advantage of the proposed structure, when compared with previous works [13, 20]. The simple solar cell compared in Figures 10 and 11, is considered to have an active layer with the thickness of 43 nm to include the same volume of crystalline silicon used in the proposed solar cell. The anti-reflection and back-metal of this simple solar cell have the thickness of 70 and 75 nm, respectively, which are exactly the same as those used in the proposed solar cell. Using (2), the short circuit current for the proposed structure with the dielectric fractal inside is calculated as 11.9 mA/cm^2 , while this value for the simple solar is achieved as 4.01 mA/cm^2 . Therefore, using the proposed method results in a short circuit current which is 2.97 times higher than a simple solar cell using the same amount of crystalline silicon. The short circuit current enhancement achieved in this work is much higher than the values reported in previous works [8–21]. To study the effect of the incident angle, Figure 12 illustrates the short circuit current enhancement for different angles of incidence. As the results of this figure show for angles less than 60° , an enhancement which is higher than 2.5 is obtained.

4 | CONCLUSION

Two new structures were proposed to develop thin-film solar cells, and were numerically analysed using full wave simulations. The first structure, which included a metallic Sierpinski fractal nano-carpet, was shown to increase the absorption inside the cell by excitation of SPPs at some wavelengths and LSPs at other wavelengths. Numerical results showed that a short circuit current enhancement of 2.40 is achieved in the first structure for both TM and TE polarisations of the incident light. In the second structure studied, to save the amount of crystalline silicon used in the cell, the active layer was shaped as a fractal structure. It was shown that the second structure increases the absorption inside the cell due to Mie resonance which occurs at resonators with different sizes. The short circuit current enhancement achieved for the second structure, was 2.97 for TM and TE polarisations of the incident light.

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