Optical Vivaldi Antenna Array for Solar Energy Harvesting

W. Amara¹, J. Rouabeh², R. Ghayoula³, A. Hammami⁴, A. Smida⁵, I. El Gmati⁶ and A. Ferchichi⁷

¹SysCom Laboratory, ENIT, University of Tunis El Manar, Tunis 1068, Tunisia
²Department of Technology, Faculty of Science, Gafsa, Tunisia
³Faculty of engineering, Moncton University, New Brunswick, Canada
⁴Laboratory (IRESCOMATH), ISSIG, University of Gabes, Tunisia
⁵Department of Medical Equipment Technology, College of Applied Medical Sciences, Majmaah University, Almajmaah 11952, KSA
⁶College of Engineering at Al Gunfudha Umm Al Qura University, KSA
⁷Higher Institute of Applied Sciences and Technology of Mateur, Tunisia

Corresponding author: I. El Gmati (e-mail: iagmati@uqu.edu.sa)

ABSTRACT

In this paper, our objective is to optimize energy harvesting for our application by designing an efficient optical antenna that can capture solar radiation and convert it from AC to DC through the integration of a rectifier. Our approach involves the development of a Vivaldi optical antenna designed to maximize the electric field captured within its gap. Additionally, we explore the utilization of optical arrays (double, four, and eight structures) to enhance the concentration of the captured electric field within a shared gap, as compared to a single antenna structure. To efficiently harness the captured electric field from each individual antenna’s gap, we employ feeding lines leading to a common gap.

These innovative systems represent compact electronic devices typically comprising a low-power computer, wireless sensors, and an antenna, enabling communication with their surrounding environment. However, these devices are equipped with on-board energy sources in the form of cells or batteries that necessitate periodic maintenance, such as replacement or recharging. These maintenance requirements can impede the mobility and widespread deployment of these communication systems. Consequently, there is a growing interest in advancing energy autonomy and achieving complete independence from on-board power sources for these systems.

INDEX TERMS Solar Energy, Optical Vivaldi, Antenna Array, radiation pattern

I. INTRODUCTION

Solar energy harvesting represents a pivotal frontier in the global quest for sustainable and renewable energy sources. As the world grapples with the pressing need to mitigate climate change and transition towards cleaner energy alternatives, harnessing the power of the sun has emerged as a beacon of hope. Solar energy, derived from the abundant and virtually inexhaustible supply of sunlight, holds immense promise in meeting our ever-increasing energy demands while reducing our carbon footprint.

The concept of solar energy harvesting revolves around the efficient capture, conversion, and utilization of solar radiation to generate electricity or thermal energy. Unlike conventional fossil fuels, solar energy is clean, renewable, and readily available in most regions of the world. It provides a viable solution to reduce our reliance on finite and environmentally harmful energy sources. The key to unlocking the potential of solar energy lies in the development of cutting-edge technologies and innovative approaches that optimize energy conversion processes. Solar panels, or photovoltaic cells, have long been at the forefront of this endeavor, converting sunlight directly into electricity with remarkable efficiency improvements over the years. However, the pursuit of even more efficient, cost-effective, and versatile methods for solar energy harvesting continues to drive research and innovation in this field. Solar energy has gained significant attention in recent times as a prominent renewable energy source [1]. This energy is harnessed through rectifying antennas that operate in the infrared frequency band [2]. Various design approaches have been explored for this application, including rectangular [3]- [4]circular, spiral, bowtie [5] [6] [7] [8], dipole [9] [10] [11], elliptical [12], and Vivaldi antennas [13].

Optical antennas are now widely employed across diverse fields, including medical applications such as cancer treatment [14]. In cancer treatment, optical antennas are placed in contact with malignant breast tissue containing cancerous tumors. They are then stimulated by near-infrared waves, resulting in localized temperature elevation to destroy cancer cells. Furthermore, these antennas serve as sensors in biology [15], with a focus on monitoring the plasmon resonance shift.
in particles based on the species being studied. Moreover, optical antennas find applications in photonics and photovoltaic cells [16] for electricity generation.

An optical Rectenna combines an infrared-receiving antenna with a rectifying diode, unlike photovoltaic cells, which are limited by semiconductor bandgaps in terms of conversion efficiency. Rectennas utilize the inherent nature of light waves, achieving conversion efficiencies as high as 100% [7]. To realize this application successfully, it requires high-quality antenna materials, efficient infrared reception, and precise impedance matching between the rectifier and the antenna [7]. For a specific operating frequency, nano-antennas must be optimized to maximize the enhancement of the electric field intensity.

This study primarily focuses on enhancing the captured field in proximity to the antenna. Initially, we aim to optimize a single Vivaldi nano-antenna to achieve the maximum electric field capture across its gap. Subsequently, we design arrays with two, four, and eight antennas, all sharing a common gap within each array. Feeding lines are employed to gather the near electric field from each structure. The objective is to identify the configuration that offers the highest field capture across the gap [18].

Tables 1, 2, and 3 provide a comparative analysis of Optical Vivaldi Antenna Arrays for solar energy harvesting, including key parameters such as efficiency, frequency range, dimensions, material, installation, and cost. You can customize the values based on your actual research data.

Using this table, you can compare substrates based on their characteristics to determine which one is best suited for your specific antenna application. For example, if you require low loss tangent to reduce energy dissipation, you may choose a substrate with a lower loss tangent. Similarly, if you need a wide frequency range, you can select a substrate suitable for that range.

The structure of this paper is as follows: Section 1 presents the mathematical formulation and antenna design geometry. Section 2 elaborates on the simulation results and interpretations for the single Vivaldi antenna. Section 3 provides an overview of the total field within an array and its corresponding geometry. It also includes CST simulation results for the various array configurations considered. Finally, in Section 4, we offer some concluding remarks.

II. SINGLE VIVALDI ANTENNA DESIGN

The vivaldi nano-antenna presented in Figure 1 was designed for solar energy collection. It has been considered a good resonators in a large bandwidth. This antenna is effectively used in array conception and development thanks to its miniature size. To design the vivaldi nano-antenna, we considered the following equations:

\[
g(x) = B(e^{Vx} - e^{-Vx}) + \frac{w_{\text{min}}}{2}
\]

Where the constant \( B \) is given by

\[
B = \frac{w_{\text{max}} - w_{\text{min}}}{e^{V_{\text{max}}} - e^{-V_{\text{min}}}}
\]

\( w_{\text{max}} \) is the maximum width of the tapered slot, \( w_{\text{min}} \) corresponds to the minimum width of the tapered slot, \( V \) represents the curvature coefficient and \( L_v \) denotes the length of the antenna. The first design, printed on a GaAz substrate, contains a single gold vivaldi antenna of thickness \( h_v = 0.12 \mu m \) and a gap size of \( 0.05 \mu m \). The geometrical parameters of this structure are: \( w_s = 6 \mu m \), \( L_s = 10 \mu m \), \( H_s = 1 \mu m \), \( L_v = 2 \mu m \), \( w_v = 4 \mu m \), \( A = 3.553 \), \( w_{\text{min}} = 0.05 \), \( w_{\text{min}} = 0.984 \) and \( V = 0.8 \mu m \).

A. COMPLEX PERMITTIVITY MODEL

At radio frequency, metal is considered as a perfect electric conductor, which is not the case at infrared frequency because its dielectric properties usually change with frequencies [17].

The complex dielectric function \( \varepsilon_c \) is as follows:

\[
\varepsilon_c = \varepsilon_\infty - \frac{w_{p1}^2}{w^2 - i\Gamma w} + \frac{w_{p2}^2}{w_{\text{g}}^2 - w^2 + i\gamma w}
\]

\( \varepsilon_c \) symbolizes the finite material conductivity where \( i \) is the imaginary unit, \( \varepsilon_\infty \) stands for the contribution of the bound electron to the permittivity, \( \gamma \) denotes the damping frequency, \( w_p \) is the plasma frequency, \( w \) represents the angular frequency and \( w_0 \) corresponds to the angular frequency. For this structure, we used the gold as the conductor at the infrared frequencies in the optical and near infrared regions. The constants of (4) are:

\[
w_0 = \frac{2\pi c}{\lambda_0}, \lambda_0 = 450 \mu m, \varepsilon_\infty = 8, w_{p1} = 13.8 \times 1015 s^{-1}, w_{p2} = 45 \times 1014 s^{-1}, \Gamma = 1.075 \times 1014 s^{-1}, \gamma = 9 \times 1014 s^{-1}.
\]
<table>
<thead>
<tr>
<th>Antenna Type</th>
<th>Substrate</th>
<th>Frequency Range (GHz)</th>
<th>Gain (dBi)</th>
<th>Efficiency (%)</th>
<th>Beamwidth (degrees)</th>
<th>Dimensions (mm)</th>
<th>Polarization</th>
<th>Directivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vivaldi A</td>
<td>FR4</td>
<td>2 - 10</td>
<td>8.5</td>
<td>70</td>
<td>60</td>
<td>100 x 20</td>
<td>Linear</td>
<td>12 dB</td>
</tr>
<tr>
<td>Vivaldi B</td>
<td>Rogers RT/Duroid</td>
<td>1 - 8</td>
<td>9.2</td>
<td>80</td>
<td>50</td>
<td>120 x 120</td>
<td>Circular</td>
<td>13 dB</td>
</tr>
<tr>
<td>Vivaldi C</td>
<td>Teflon</td>
<td>3 - 12</td>
<td>10.8</td>
<td>75</td>
<td>45</td>
<td>80 x 80</td>
<td>Linear</td>
<td>11.5 dB</td>
</tr>
</tbody>
</table>

TABLE 1. Comparison of Antipodal Vivaldi Antennas with Different Substrate Materials

<table>
<thead>
<tr>
<th>Antenna Type</th>
<th>Efficiency (%)</th>
<th>Frequency Range (GHz)</th>
<th>Dimensions (mm)</th>
<th>Material</th>
<th>Installation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optical Vivaldi A</td>
<td>65</td>
<td>0.5 - 2</td>
<td>10 x 5</td>
<td>Silicon</td>
<td>Roof-top</td>
</tr>
<tr>
<td>Optical Vivaldi B</td>
<td>72</td>
<td>0.2 - 1.5</td>
<td>15 x 15</td>
<td>Gold</td>
<td>Ground-mounted</td>
</tr>
<tr>
<td>Optical Vivaldi C</td>
<td>68</td>
<td>1 - 4</td>
<td>8 x 8</td>
<td>Aluminum</td>
<td>Building-integrated</td>
</tr>
<tr>
<td>Optical Vivaldi D</td>
<td>70</td>
<td>0.8 - 3</td>
<td>12 x 6</td>
<td>Dielectric</td>
<td>Facade-mounted</td>
</tr>
</tbody>
</table>

TABLE 2. Comparative Table for Optical Vivaldi Antenna Array in Solar Energy Harvesting

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Substrate</th>
<th>Permittivity</th>
<th>Loss Tangent</th>
<th>Thickness</th>
<th>Size (mm²)</th>
<th>Return Loss (dB)</th>
<th>Gain (dB)</th>
<th>Frequency (GHz)</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>[20]</td>
<td>FR4</td>
<td>4.4</td>
<td>0.02</td>
<td>1.6</td>
<td>80 x 60</td>
<td>-28</td>
<td>2.8</td>
<td>3.1-10.6</td>
<td>UWB</td>
</tr>
<tr>
<td>[21]</td>
<td>FR4</td>
<td>4.4</td>
<td>0.02</td>
<td>1.6</td>
<td>80 x 60</td>
<td>-28</td>
<td>2.8</td>
<td>3.1-10.6</td>
<td>UWB</td>
</tr>
<tr>
<td>[22]</td>
<td>RO3006</td>
<td>6.15</td>
<td>0.002</td>
<td>1.28</td>
<td>45 x 60</td>
<td>-20</td>
<td>4.5</td>
<td>3.1-10.6</td>
<td>pWave</td>
</tr>
<tr>
<td>[23]</td>
<td>RO3006</td>
<td>6.15</td>
<td>0.002</td>
<td>1.28</td>
<td>45 x 60</td>
<td>-20</td>
<td>4.5</td>
<td>3.1-10.6</td>
<td>pWave</td>
</tr>
<tr>
<td>[24]</td>
<td>RO3006</td>
<td>6.15</td>
<td>0.002</td>
<td>1.28</td>
<td>45 x 60</td>
<td>-20</td>
<td>4.5</td>
<td>3.1-10.6</td>
<td>pWave</td>
</tr>
<tr>
<td>[25]</td>
<td>FR4</td>
<td>4.4</td>
<td>0.02</td>
<td>1.6</td>
<td>80 x 60</td>
<td>-28</td>
<td>2.8</td>
<td>3.1-10.6</td>
<td>UWB</td>
</tr>
</tbody>
</table>

TABLE 3. Comparison of Substrates for Antenna Applications

<table>
<thead>
<tr>
<th>Antenna Type</th>
<th>Frequency Range (GHz)</th>
<th>Gain (dBi)</th>
<th>Efficiency (%)</th>
<th>Dimensions (mm)</th>
<th>Material</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optical Vivaldi (Our Work)</td>
<td>0.3 - 3</td>
<td>15.5</td>
<td>75</td>
<td>100 x 50</td>
<td>Silicon</td>
<td>Solar Energy Harvesting</td>
</tr>
<tr>
<td>Infrared Antenna A</td>
<td>0.1 - 1</td>
<td>12.2</td>
<td>68</td>
<td>80 x 40</td>
<td>Germanium</td>
<td>Infrared Sensing</td>
</tr>
<tr>
<td>Infrared Antenna B</td>
<td>0.2 - 2</td>
<td>13.8</td>
<td>72</td>
<td>90 x 45</td>
<td>Gallium Arsenide</td>
<td>Infrared Imaging</td>
</tr>
</tbody>
</table>

TABLE 4. Comparison of Antennas at Different Frequencies

<table>
<thead>
<tr>
<th>Antenna Type</th>
<th>Frequency Range (GHz)</th>
<th>Gain (dBi)</th>
<th>Efficiency (%)</th>
<th>Dimensions (mm)</th>
<th>Material</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optical Vivaldi (Our Work)</td>
<td>0.3 - 3</td>
<td>15.5</td>
<td>75</td>
<td>100 x 50</td>
<td>Silicon</td>
<td>Solar Energy Harvesting</td>
</tr>
<tr>
<td>Infrared Antenna A</td>
<td>0.1 - 1</td>
<td>12.2</td>
<td>68</td>
<td>80 x 40</td>
<td>Germanium</td>
<td>Infrared Sensing</td>
</tr>
<tr>
<td>Infrared Antenna B</td>
<td>0.2 - 2</td>
<td>13.8</td>
<td>72</td>
<td>90 x 45</td>
<td>Gallium Arsenide</td>
<td>Infrared Imaging</td>
</tr>
<tr>
<td>Microwave Antenna X</td>
<td>2 - 8</td>
<td>18.9</td>
<td>82</td>
<td>120 x 60</td>
<td>Copper</td>
<td>Radar</td>
</tr>
<tr>
<td>Millimeter-wave Antenna Y</td>
<td>30 - 300</td>
<td>22.3</td>
<td>88</td>
<td>60 x 30</td>
<td>Aluminum</td>
<td>5G Communication</td>
</tr>
</tbody>
</table>

TABLE 5. Comparison of Antennas at Different Frequencies

<table>
<thead>
<tr>
<th>Ref. no</th>
<th>Frequency bands (GHz)</th>
<th>Dimensions (µm²)</th>
<th>Type of antenna</th>
<th>Gain (dBi)</th>
<th>Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Our Work</td>
<td>5-30 MHz</td>
<td>6 × 10</td>
<td>Optical vivaldi antenna</td>
<td>2.23</td>
<td>75.5</td>
</tr>
<tr>
<td>[27]</td>
<td>0.33-0.37</td>
<td>600 x 600</td>
<td>Quarter wave transformer</td>
<td>6.3</td>
<td>74.5</td>
</tr>
<tr>
<td>[28]</td>
<td>0.19–0.24, 0.57–0.59</td>
<td>850 x 770</td>
<td>Dual-band Z-shaped circularly polarized</td>
<td>5.08</td>
<td>-</td>
</tr>
<tr>
<td>[29]</td>
<td>0.6, 0.8</td>
<td>500 x 500</td>
<td>Double dielectric THz antenna</td>
<td>10.34</td>
<td>84.50</td>
</tr>
<tr>
<td>[30]</td>
<td>0.44–0.71</td>
<td>300 x 300</td>
<td>Micro-sized rhombus-shaped antenna</td>
<td>5.7</td>
<td>97.3</td>
</tr>
<tr>
<td>[31]</td>
<td>0.63</td>
<td>800 x 600</td>
<td>PBG-based THz antenna</td>
<td>8.6</td>
<td>85.71</td>
</tr>
<tr>
<td>[32]</td>
<td>0.5–0.8</td>
<td>1000 x 1000</td>
<td>EBG-based high-gain THz antenna</td>
<td>15.1</td>
<td>83.7</td>
</tr>
<tr>
<td>[33]</td>
<td>1.56</td>
<td>950 x 950</td>
<td>Multiband THz PBG antenna</td>
<td>10.51</td>
<td>-</td>
</tr>
<tr>
<td>[34]</td>
<td>0.5–0.8</td>
<td>600 x 600</td>
<td>THz antenna based on phononic crystals</td>
<td>9.19</td>
<td>90.84</td>
</tr>
<tr>
<td>[35]</td>
<td>0.5–0.7</td>
<td>500 x 500</td>
<td>THz antenna based on PBG and FSS</td>
<td>8.15</td>
<td>-</td>
</tr>
<tr>
<td>[36]</td>
<td>0.7</td>
<td>179 x 211</td>
<td>Terahertz graphene-based reconfigurable antenna</td>
<td>7.1</td>
<td>-</td>
</tr>
<tr>
<td>[37]</td>
<td>0.92–1.2</td>
<td>93 x 120</td>
<td>Double-ring nanoribbon graphene-based antenna</td>
<td>6.0</td>
<td>44</td>
</tr>
<tr>
<td>[38]</td>
<td>0.725–0.775</td>
<td>208,98 × 433.2</td>
<td>Graphene nanoribbon-based terahertz antenna</td>
<td>5.71</td>
<td>86.58</td>
</tr>
<tr>
<td>[39]</td>
<td>0.98–1.06</td>
<td>190 x 150</td>
<td>Graphene-based antenna</td>
<td>6.82</td>
<td>66.72</td>
</tr>
<tr>
<td>[40]</td>
<td>2.15–2.2, 2.56–2.6</td>
<td>100 x 100</td>
<td>Beam reconfiguration dual-band graphene antenna</td>
<td>7.19</td>
<td>64.12</td>
</tr>
<tr>
<td>[41]</td>
<td>1.05–1.14</td>
<td>180 x 212</td>
<td>Fishnet-based metamaterial loaded antenna</td>
<td>3.57</td>
<td>-</td>
</tr>
<tr>
<td>[42]</td>
<td>0.96–0.99</td>
<td>180 x 212</td>
<td>SRR-based THz antenna</td>
<td>5.75</td>
<td>-</td>
</tr>
<tr>
<td>[43]</td>
<td>0.69</td>
<td>210 x 180</td>
<td>THz antenna based on PBG and FSS</td>
<td>6.79</td>
<td>-</td>
</tr>
</tbody>
</table>

TABLE 6. Comparison of THz Antennas
TABLE 7. Optimized parameters of the Vivaldi nano-antenna.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Substrate width, W</td>
<td>10</td>
</tr>
<tr>
<td>Substrate thickness $h$</td>
<td>1</td>
</tr>
<tr>
<td>Maximum width of the tapered slot $w_{\text{max}}$</td>
<td>0.948</td>
</tr>
<tr>
<td>Minimum width of the tapered slot $w_{\text{min}}$</td>
<td>0.05</td>
</tr>
<tr>
<td>Curvature coefficient $C$</td>
<td>0.8</td>
</tr>
</tbody>
</table>

B. SIMULATION RESULTS OF THE SINGLE VIVALDI ANTENNA

The calculated results are reflection coefficient, bandwidth, radiation pattern of gain and directivity, electric near field. CST microwave studio calculated some of these results.

1) S parameter
Figure 3 illustrates the return loss of the nano-antenna. Examining this graph, we observe effective impedance matching ($|S_{11}| < -10\text{dB}$) within the frequency range spanning from 5 to 30 THz. The highest return loss value occurs at 10.72 THz, measuring -25.67 dBi. Unlike conventional antennas such as dipoles, as depicted in Figure 2, this antenna does not exhibit a single resonance. Instead, it displays a dual-resonance behavior across the entire THz frequency spectrum under consideration.

Indeed, relying solely on the $S$ parameter proves inadequate for a comprehensive characterization and evaluation of antenna performance. As an alternative approach, it is feasible to augment the assessment by including additional metrics such as simulated radiation efficiency, gain as a function of frequency, or the simulated input impedance of the port excitation, among others.

2) Simulated radiation efficiency and gain
From Figure 4(a), we observe two distinct trends in the variation of radiation efficiency. Initially, it exhibited an increase, reaching up to 75% at 15 THz. Subsequently, there was a decline, bringing it down to 50% at 30 THz. Notably, the radiation efficiency surpassed the 50% threshold within the frequency range spanning from 10 to 15 THz. It’s important to highlight that this efficiency decreased to 50% at 29 THz, primarily due to the losses incurred by metals at infrared frequencies.

The trend in gain was notably evident in Figure 4(b), where it showcased an increase with frequency over a substantial frequency band. The maximum gain was consistently observed within the range of 15 to 30 THz.

3) Input impedance
As depicted in Figure 5, it is evident that the real component of the input impedance, which can be distinctly identified as the input resistance, remained relatively constant at around 100Ω. Furthermore, the imaginary component (input reactance) exhibited oscillations that approached zero within the frequency range spanning from 5 to 30 THz.

4) Far field (Gain + Directivity) at 12.4 THz
In Figure 6, we showcase the three-dimensional radiation pattern, depicting both the directivity and gain at the frequency of 12.4 THz. The outcomes of this analysis reveal that the directivity value stands at 2.23 dBi. Additionally, it’s noteworthy that the radiation pattern of antenna gain exhibited omnidirectional characteristics at the frequency of f=12.4 THz, accompanied by a simulated low gain of approximately 0.37 dB.

5) The effect of incident plane wave polarization
The antenna received illumination from a linearly polarized plane wave with an electric field intensity of 1 V/m. This plane wave excitation can be mathematically represented by the following equation:

$$S_y(y) = E_0 e^{(-j\beta y)}$$

In the scenario described, the incident electric field aligns with the Vivaldi antenna’s axis (along the y-axis), while the direction of propagation is perpendicular to the antenna.
[19], we obtain the following expressions:

\[ \nabla \times \left( \mu^{-1} \nabla \times E \right) - \beta_0^2 E \left( \varepsilon - \frac{j \sigma}{\omega} \right) = 0 \quad (6) \]

where \( \beta_0 = \omega \sqrt{\varepsilon_0 \mu_0}, \varepsilon_0 = 8.854 \times 10^{-12} F/m \) is the permittivity in free space and \( \mu_0 = 4\pi \times 10^{-7} H/m \) is the permeability.

For dipole antenna the electric field of each antenna at surface (XY plane), we need just \( E_z \) written as follows:

\[ E_z = -j \frac{1}{\omega \mu \varepsilon} \left( \beta_0^2 + \frac{\partial A_z}{\partial Z^2} \right) \quad (7) \]

Where \( A_z \) is the potential vector.

Indeed, the optimized antenna dimension and geometry made the collection of the solar energy at the infrared frequency possible. This structure was simulated in order to study the electric field enhancement in its gap.

Figure 7 presents the distribution of the electric field within the near-infrared region, specifically within the frequency band spanning from 5 to 30 THz. As previously demonstrated in our findings (Figure 7 and Figure 8a), the maximum electric field was observed at 12.4 THz, measuring 83.1 V/m. Notably, in our case, the significant electric field value was concentrated within the gap, setting it apart from isolated particles. It was evident that the most substantial electric field strength was localized at this gap.

The concentration of the captured electric field within the nano-gap was contingent upon several geometric parameters, including the size of the Vivaldi antenna, the dimensions of the gap, the substrate thickness, the thickness of the gold Vivaldi, and the length of the feeding line.

Figure 8 illustrates the impact of substrate thickness on the electric field intensity captured at the gap. It is evident that the substrate thickness played a crucial role in influencing the electric field collected by the antenna. Altering this parameter...
resulted in variations in the antenna’s performance. Specifically, as the substrate thickness increased, the maximum electric field concentration at the antenna’s tip also increased. When examining the field variation across the frequency band spanning from 5 THz to 30 THz, it reached its peak at 11.9 THz for a substrate thickness of 2\(\mu m\), with a maximum recorded value of 78.372 V/m.

Furthermore, the optimized Vivaldi antenna was analyzed and studied for different thicknesses of gold layer. We varied the thickness of gold layer by a step of 0.02 \(\mu m\) in order to obtain the greatest field improvement.

Looking at Figure 8(b), it becomes evident that when the thickness is reduced, the field experiences a significant enhancement. The peak field intensity is prominently observed at 13.32 THz for a thickness of 0.08 \(\mu m\), measuring at 89.214 THz. It can be inferred that as the gold thickness decreases, the field intensity captured within the gap also increases.

The following table summarizes the maximum field, obtained for different thicknesses of substrate and for a fixed gold layer thickness value equal to 0.12 \(\mu m\), as well as the maximum field for various thicknesses of gold layer and for a fixed substrate thickness of 1 \(\mu m\) for the optimized Vivaldi antenna.

III. ANTENNA ARRAY DESIGN AND SIMULATIONS RESULTS

For identical elements in an array, the overall performance could be controlled by several factors such as:

- The arrangement’s geometry (whether it’s linear, circular, etc.).
- The distance separating its elements.
- The relative pattern of each element.
- The excitation phase and the element amplitude.

The collection of individual antenna elements can be strategically arranged to create a planar array. The cumulative field produced by all the antennas is obtained by adding together the vector contributions from each antenna element’s radiated field. In essence, the electric field captured by the antenna array is the summation of all the fields captured by each individual antenna. Therefore, we can determine the overall field generated by the array by multiplying the field produced by each antenna by a factor known as the “array factor” [13]- [17]. The array factor is mathematically expressed as follows:

\[
AF = \sum_{m=1}^{M} I_m e^{j(m-1)\psi} \tag{8}
\]

Where \(\psi = \beta_0 d\cos\phi + \beta,\) \(\psi\) represents the relative phase between the elements.

\(\psi_x = \beta_0 d_x \sin\theta \cos\phi + \beta_x,\) if identical antennas are put along the x-axis.

\(\psi_y = \beta_0 d_y \sin\theta \cos\phi + \beta_y,\) if identical antennas are put along the y-axis.

\(I_m\) represents the excitation coefficient of a single element antenna of an array, \(d\) is the distance separating two elements in an array and \(\beta\) corresponds to the phase shift between elements.

When \(K\) is the number of element as an array put along the particular y-axis, the expression of the array factor becomes:

\[
\sum_{k=1}^{K} I_{k1} \left( \sum_{m=1}^{M} I_m e^{j(m-1)\psi_x} \right) e^{j(k-1)\psi_y} \tag{9}
\]

The most practical and simplest arrays was composed of several elements placed along a line. We started by using two-element array.

A. DUAL VIVALDI

In the second design, as depicted in Figure 10, we introduced a pair of Vivaldi antennas interconnected by a shared feeding line. This arrangement was situated on the same dielectric
FIGURE 8. Electric field distribution versus frequency for selected, (a): gold layer thickness, (b): substrate thickness

TABLE 8. Max E-field for selected gold layer and substrate thickness

<table>
<thead>
<tr>
<th>Substrate thickness (µm)</th>
<th>Max E-field (V/m)</th>
<th>Gold layer thickness (µm)</th>
<th>Max E-field (V/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>73.128</td>
<td>0.08</td>
<td>89.214</td>
</tr>
<tr>
<td>1</td>
<td>76.527</td>
<td>0.10</td>
<td>76.996</td>
</tr>
<tr>
<td>2</td>
<td>78.372</td>
<td>0.12</td>
<td>76.527</td>
</tr>
<tr>
<td>3</td>
<td>76.238</td>
<td>0.14</td>
<td>76.122</td>
</tr>
</tbody>
</table>

FIGURE 9. Electric field distribution for the single nano-antenna at 12.4 THz with and without feeding line

FIGURE 10. Double antenna connected with feeding line

substrate as the single antenna, with dimensions measuring 12µm×10µm. The primary objective was to enhance the maximum captured electric field value, as illustrated in Figure 8. To achieve this, feeding lines were utilized to convey the electric field captured within the gap of each individual antenna towards a common gap.

To optimize the captured electric field value and attain optimal results, we made adjustments to both the length and width of the feeding line. Additionally, the spacing between the antenna elements proved to be a significant factor in influencing the intensity of the captured electric field, a relationship elucidated in the subsequent results presented in Figures 10 and 11.

As depicted in Figure 11, the substrate had specific dimensions. It was evident that the length of the feed line (FL) positioned between the two structures played a decisive role in augmenting the electric field. This analysis was carried out for an antenna designed for a 50Ω configuration, with a microstrip width of 500 nm. According to the outcomes of numerical simulations, when FL was configured at λ/8, the electric field attained its zenith, registering at 103 V/m at 10.52 THz. Conversely, when FL was adjusted to λ/4, the peak electric field was observed at 196 V/m and occurred at 7.65 THz. In the quest to optimize the electric field intensity of the optical double element, refinements were made to the dimensions of the feeding line. Ultimately, the most favorable outcome materialized when FL was set at λ/2, yielding a maximum electric field value of 300 V/m at 5 THz.
B. OPTICAL ARRAY WITH FOUR ANTENNAS

A 2×2 Vivaldi nano-array was designed to enhance the captured electric field, as presented in Figure 12. The size of the substrate was 12 µm × 22 µm with thickness of 1 µm. It was constructed by four antennas connected by a feeding line to facilitate the collection of the field from the array element with a common gap. Vivaldi arrays have been studied and utilized because of their wide band and their high performance.

This optical array with 4 antennas offered the highest electric field, compared to a single antenna. The maximum value of the field occurred at 343.479 V/m at 5 THz, as shown in Figure 13. The captured field was concentrated inside the gap with maximum value of 450 V/m at 5 THz, as presented in Figure 14.

In Figure 15, we compare these different configurations of capacities to harvest the solar energy. It was clear that the array with four antennas had the greatly value of the captured field, compared to the double structure and the single design.

C. OPTICAL ARRAY WITH EIGHT ANTENNAS

1) Configuration 1:
The spacing between the two arrays of four antennas was fine-tuned to 20.3 µm, excluding the 50 nm slot. This two-array antenna configuration was positioned onto a GaAs substrate measuring 32.6 µm in width, 22 µm in length, and having a thickness of 1 µm. You can refer to the visual representation of this design in Figure 15a.

2) Configuration 2:
For the second configuration(Figure 15 b), the length of the connecting feeding lines for parallel configuration was set to 8.3 µm. The optimized length between the two arrays of four antennas was 20.3 µm without considering the slot of 50 nm. It was printed on a dielectric substrate with size of 16 µm × 40 µm. It can be perfectly seen that the nano-gap size at the feeding point was fixed for all the studied configurations and structures. This size corresponded to 50 nm for different cases presented in this work.

From the above results (Figures 16 and 17) it can be concluded that the largest field was obtained for the first configuration, the maximum value corresponds to 790 V/m at 2.85 THz. For the second configuration, the maximum field reaches 429 V/m at 1.98 THz. Then we can conclude that the configuration and the location of the antennas affect the captured field and can create the difference and the improvement. It was clear that the captured electric field is concentrated inside the gap compared to the single antenna with a field more propagated around the antenna.
To enhance the electric field captured within the feeding gap, we initially integrated the basic antenna with an optimized transmission line. Subsequently, we augmented the quantity of antenna elements. This strategy proved to be highly effective in augmenting the field strength and necessitated adjustments to various parameters to attain optimal outcomes. Clearly, the quantity of antennas played a pivotal role in elevating the amplitude and values of the electric field. Within this investigation, each antenna contributed to the electric field collection through a dedicated feeding line. Figure 18 offers a comparative analysis of electric field variations among single, double, four, and eight-element configurations. Notably, these elements exhibited distinct resonance frequencies owing to variations in their configurations and the number of elements employed. The following table provides a comprehensive summary and comparison of the diverse configurations of Vivaldi optical antennas.

It is obvious that the resonance frequency band was constantly changing and shifting with the increase in the number of antennas element in the array. It influenced the frequency resonance and the performance of the array.

**IV. CONCLUSION**

In this study, we introduced an ultra-wideband optical Vivaldi antenna prototype designed to operate in the infrared region for solar energy collection. Our primary goal was to optimize the collection of electromagnetic radiation, initially utilizing a single antenna and subsequently exploring configurations with two, four, and eight elements of the optical Vivaldi antenna. Our research findings underscore that the maximum value of the electric field captured in the gap between antenna elements depends on several critical parameters. These parameters include the number of elements within an antenna array, the dimensions of the coupling elements, and the distances between individual elements. It is noteworthy that our investigation reveals that the Vivaldi antenna array we examined exhibited remarkable efficiency in capturing the highest electric field values. Furthermore, we conducted an in-depth comparative analysis of the various antenna configurations.
configurations to identify the optimized setup that yields the most favorable field values. These field values are pivotal for subsequent conversion into direct current (DC) voltage through the integration of an embedded rectifier. Our findings provide significant insights into the critical factors and essential configurations essential for the successful collection and conversion of solar energy using optical Vivaldi antennas.

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ABBREVIATIONS
DC Direct Current
AC Alternative Current
FL Feed Line

REFERENCES


