Supplementary Material

AnIMAGE: A MATLAB-based tool for generating microstrip antennas with complex shapes.

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A bird-like Antenna

In the third scenario, a microstrip antenna with a bird silhouette patch was created with AnIMAGE and numerically evaluated in CST STUDIO. As with prior examples (see manuscript), an image of a bird's silhouette was imported into AnIMAGE, as shown in Figure S1. Then, the microstrip patch antenna was developed using the proposed software. In the layout, a **Side length** of 50 mm, a **Resolution factor** of 2.0, and an **Image Scale** of 1.0 were chosen for this purpose. Furthermore, FR4, with a dielectric permittivity of 4.3 and a thickness of 1.6 mm, was chosen as the dielectric substrate once more. Figure S1 illustrates that a copper layer thickness of 0.035 mm was entered. Thus, the area of the microstrip patch with bird shape was 670.0962 mm^2. On the other hand, the bottom layer was made up of a continuous copper foil with the same dimensions of the dielectric substrate, and a coaxial feed port was inserted at the coordinates X=19 mm and Y=18 mm, as shown in Figure S1.

Using the aforementioned configuration, we successfully exported the structure to CST STUDIO, as shown in Figure S2(a). This structure is clearly complex, making it difficult to build directly in CST STUDIO without the assistance of AnIMAGE. Notably, the bird's legs emerge as one of the most intricately designed components within the structure. Moving forward, we proceeded to evaluate the electromagnetic performance of the antenna. The resulting return losses for this specific example are presented in Figure S2(b). Analysis of the data reveals a resonant frequency of 4.85 GHz and a bandwidth of 48 MHz by this bio-inspired antenna.

Moreover, the radiation pattern of the bird-inspired antenna was calculated using CST STUDIO. The co-polarization and cross-polarization radiation patterns at 4.85 GHz are illustrated in Figure S2(c). Upon examination, it becomes evident that the antenna exhibits higher directivity in the co-polarization scenario compared to the cross-polarization pattern. Specifically, the co-polarization radiation pattern attains a maximum gain of 6 dB at 22°, whereas the cross-polarization pattern only reaches -0.393 dB at 67°. Finally, the gain and total efficiency of this particular configuration were estimated across a frequency range of 3 GHz to 8 GHz. The obtained results for both parameters are illustrated in Figure S2(d). Remarkably, the findings consistently indicate that the antenna performs optimally at a frequency of 3.85 GHz. At this specific frequency, the antenna achieves a remarkable gain of 6.27 dB and an impressive total radiation efficiency of 94.9%. These results further validate the suitability of this antenna for applications where the frequency of 4.85 GHz is desirable, due to its exceptional performance in terms of gain and radiation efficiency.

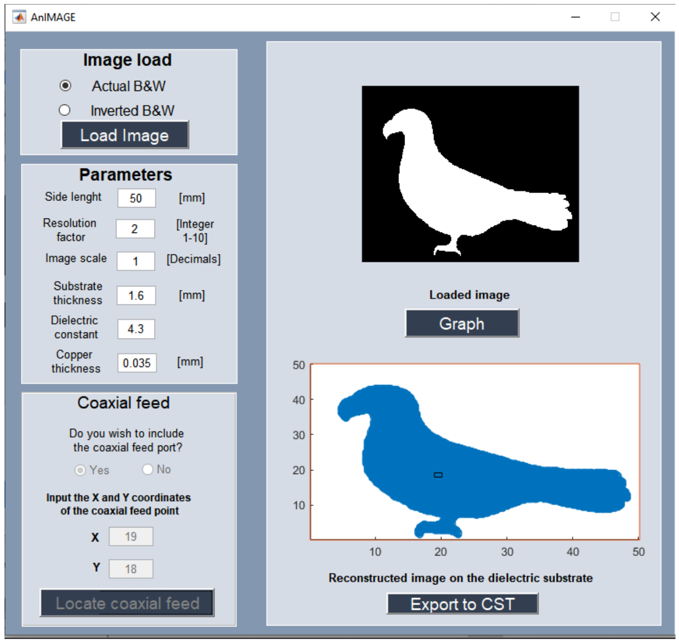

Fig. S1: An image interface with the configuration utilized in the reconstruction of a bird-like antenna.

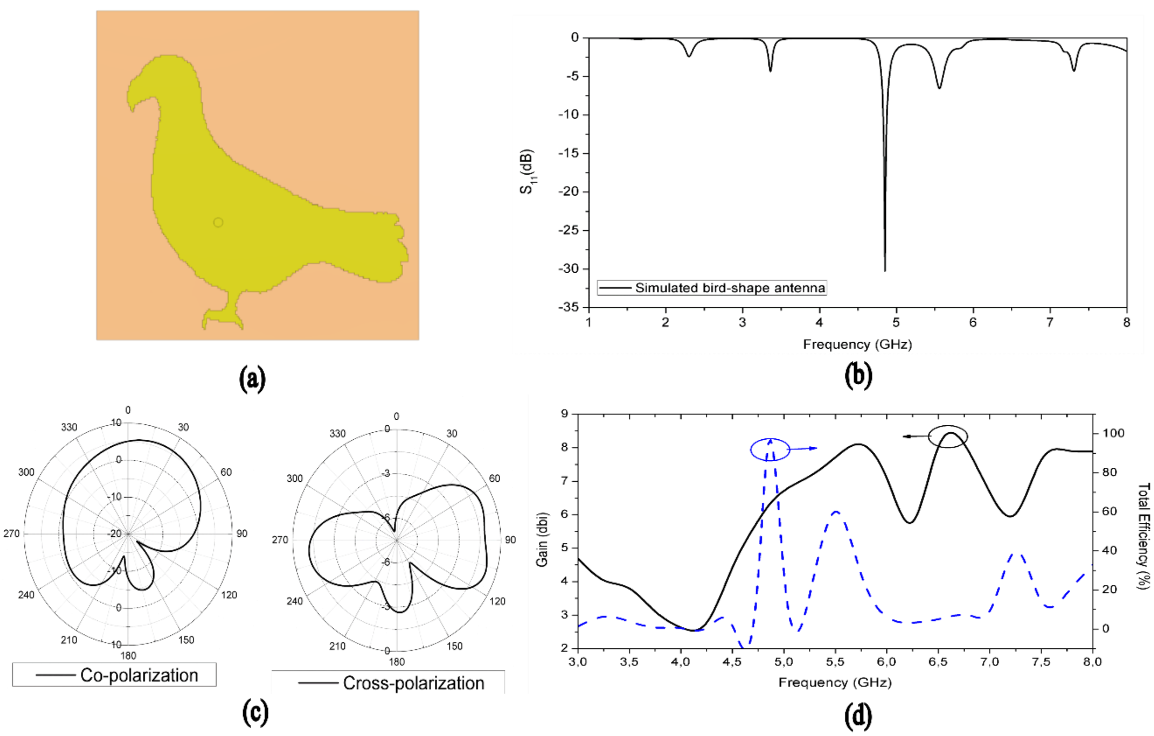

Fig. S2: (a) Schematic of the proposed bird-like antenna reconstructed using AnIMAGE tool. **(b)** Return losses of the bird-like antenna. **(c)** Comparison of co-polar and cross-polar radiation patterns of the bird-like antenna at 4.85 GHz. **(d)** Gain and total efficiency of bird-like antenna.

Papaya Leaf-like Antenna

In this final example, a configuration that uses a microstrip line as a feeding mechanism to achieve an antenna with exceptional electrical characteristics is addressed. The main objective in this case is to develop a setup with a wide bandwidth. To accomplish this, AnIMAGE was employed to design a microstrip antenna featuring a Papaya leaf-shaped patch, which was subsequently evaluated numerically in CST STUDIO.

To create the microstrip patch, an image of a Papaya leaf was imported into AnIMAGE, as shown in Figure S3. For this specific setup, we chose a **Side length** of 13 mm, a **Resolution factor** of 1.0, and an **Image scale** of 1.0 to ensure accurate representation. In line with prior examples, we used FR4 with a permittivity of 4.3 and a thickness of 1.6 mm as the dielectric substrate. A copper layer thickness of 0.035 mm was also specified, resulting in a microstrip patch area of 70.9633 mm^2, as shown in Figure S3. Subsequently, the designed microstrip patch file was exported to CST STUDIO for further analysis. However, it is important to note that in this specific case, a microstrip line with a width (W_f) of 2.8 mm and a length (L_f) of 29.2 mm was employed as part of the configuration as is shown in Figure S4(a). Similarly, modifications were made directly in CST STUDIO to adjust the width (W_{sub}) and length (L_{sub}) of the substrate. This was done to showcase the feasibility of working with antennas that lack symmetry.

To enhance the performance of the antenna, the ground plane was modified by introducing defects on both sides. Additionally, a rectangular strip was integrated onto the defected ground, as illustrated in Figure S4(b). For a comprehensive understanding of the antenna's design, please refer to the specific parameters outlined in Figure S4, which are also summarized in Table S1. These design specifications provide valuable insights into the key features and characteristics of the proposed antenna.

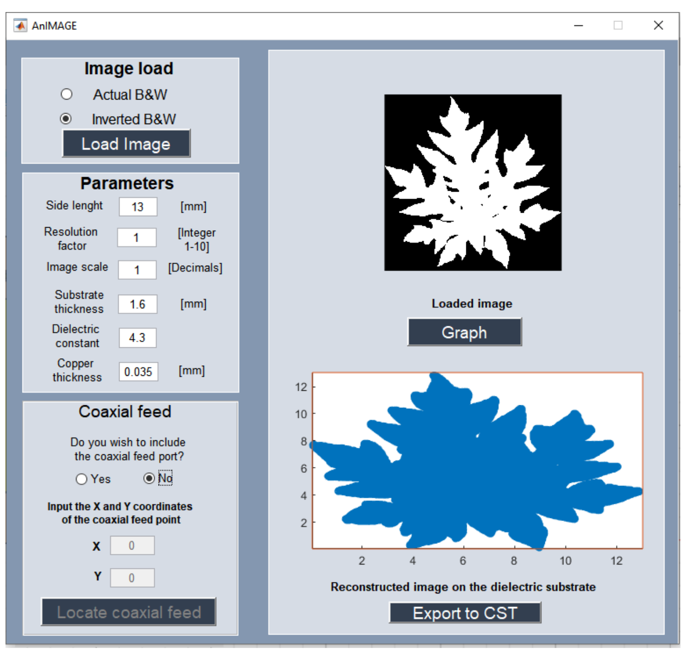

Fig. S3: An image interface with the configuration utilized in the reconstruction of a Papaya leaf-like antenna.

The electrical performance of the proposed configuration was thoroughly evaluated using CST STUDIO through numerical simulations. The obtained results, illustrated in Figure S5(a), demonstrate the remarkable characteristics of the antenna. Notably, the proposed configuration showcases an impressively wide bandwidth, operating efficiently from 1.99 GHz to 6.36 GHz, with a bandwidth of 4.37 GHz. This finding is particularly significant as microstrip antennas typically have much narrower bandwidths, often less than 200 MHz. The gain and total efficiency of this bio-inspired configuration were estimated across a frequency range of 1 GHz to 8 GHz. The obtained results for both parameters are illustrated in Figure S5(b). The results show that the papaya leaf-shaped antenna has outstanding efficiency, regularly exceeding 94.5% across its operating range. Furthermore, the antenna exhibits the greatest gain at 5.7 GHz, an Industrial, Scientific, and Medical (ISM) frequency. This frequency range holds significant importance and relevance across various applications, further enhancing the attractiveness and versatility of the antenna design.

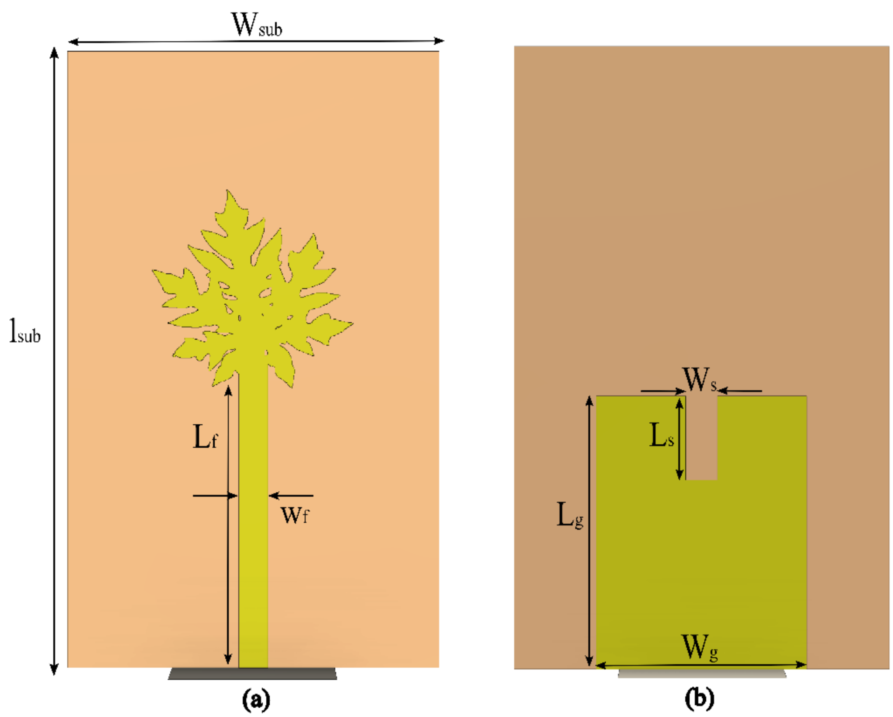

Fig. S4: Schematic of the proposed Papaya leaf-like antenna with feedline (a) Front view. (b) Bottom view.

Table 1: Dimensions of the proposed Papaya leaf-like antenna

Parameter	Description	Value
W_f	Width of the feedline	2.8 mm
L_f	Length of the feedline	29.2 mm
W_s	Width of the rectangular strip	4.3 mm
L_s	Length of the rectangular strip	8.0 mm
W_{sub}	Width of the substrate	35.7 mm
L_{sub}	Length of the substrate	59.3 mm
W_g	Width of the ground plane	23.3 mm
L_g	Length of the ground plane	23.3 mm

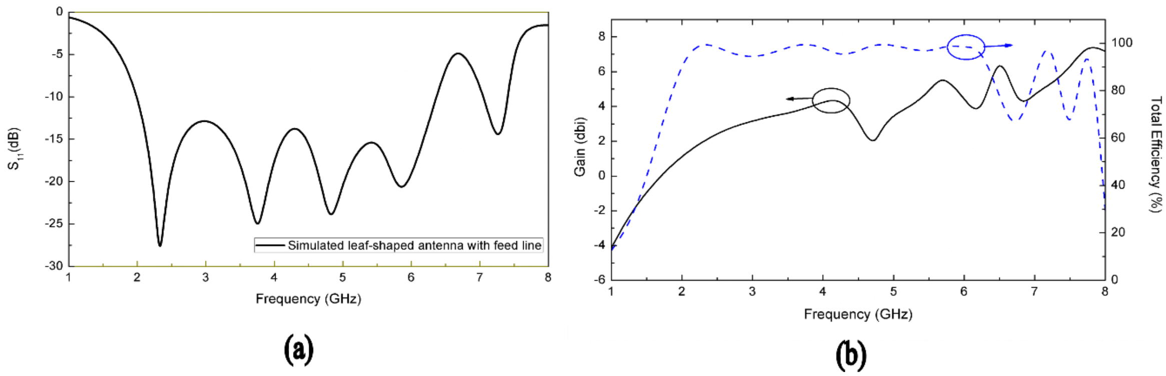

Fig. S5: (a) Return losses of the Papaya leaf-shaped antenna with feedline. **(b)** Gain and total efficiency of the Papaya leaf-shaped antenna with feed line.

Finally, the CST STUDIO was employed to calculate the co- and cross-polarization radiation patterns of the papaya leaf-inspired antenna at various frequencies: 2.45 GHz, 3.75 GHz, 4.418 GHz, and 5.7 GHz. At 2.45 GHz, both the co- and cross-polarization patterns exhibited similar behavior, with minimal differences observed as is shown in Figure S6(a). The analysis of the collected data revealed an omnidirectional pattern, with a maximum gain of 2.32 dB at -176°. Similar characteristics were observed at 3.75 GHz (see Figure S6(b)), where the radiation pattern maintained a similar shape for both polarizations, but with a higher gain of 3.9 dB at -161°. At 4.418 GHz, the radiation pattern remained omnidirectional for both polarization states and exhibited a synergistic behavior akin to the 2.45 GHz pattern as is depicted in Figure S6(c). The maximum gain achieved was also comparable, reaching 2.36 dB at 15°. The final frequency analyzed was 5.7 GHz as is indicated in Figure S6(d), chosen due to the previously demonstrated maximum gain shown in Figure S5(b). As expected, at this frequency, the antenna exhibited a more directive radiation pattern for both polarizations. For instance, the co-polarized radiation pattern demonstrated a higher gain at 33°, reaching 5.27 dB in that direction. Conversely, the cross-polarized radiation pattern exhibited a higher gain at 141°, allowing the antenna to radiate with a gain of 4.7 dB.

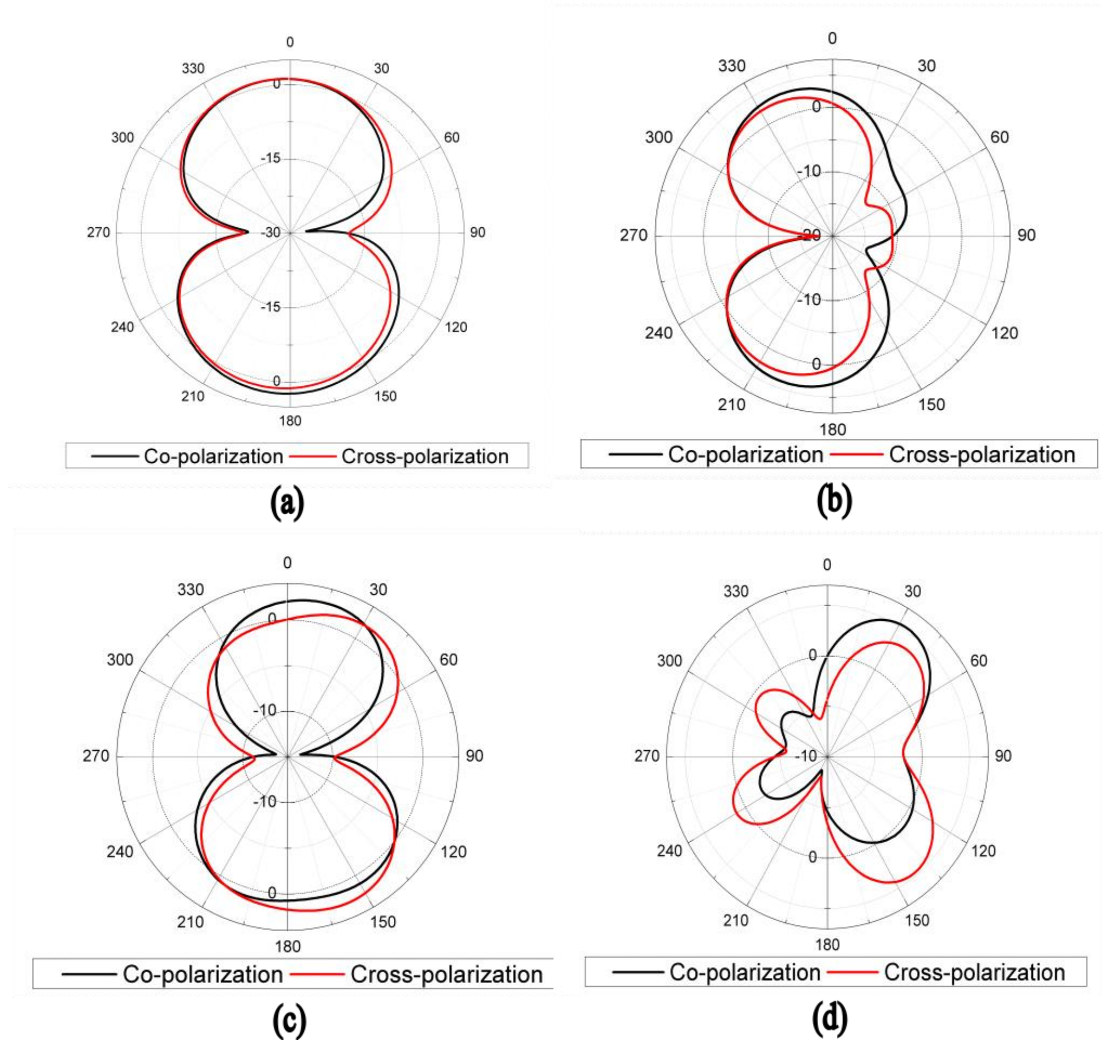

Fig. S6: Comparison of co-polar and cross-polar radiation patterns of the Bird-shape microstrip antenna. (a) at 2.45 GHz. (b) at 3.75 GHz. (c) at 4.818 GHz. (d) at 5.7 GHz.