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STUDY ON OPTIMIZING THE ANTENNA PARAMETERS OF A PATCH ANTENNA FOR OBTAINING DESIRED PERFORMANCE

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ABSTRACT

This paper investigates the optimization of microstrip patch antenna parameters to achieve maximum efficiency, focusing on dimensions, substrate materials, and operating frequencies. Microstrip antennas, widely used in wireless communication systems due to their low profile and ease of fabrication, are highly sensitive to design parameters that influence their efficiency, gain, and bandwidth. This study employs simulation tools and mathematical modeling to evaluate the performance of antennas under varying conditions. By analyzing the effects of substrate permittivity, patch dimensions, and feed mechanisms, the research aims to establish guidelines for achieving optimal antenna performance. Results indicate significant improvements in efficiency through precise parameter tuning, offering insights into designing antennas for next-generation communication systems

KEYWORDS: *Antenna Parameters*

Article History

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INTRODUCTION

The rapid advancement of wireless communication technologies necessitates the design of efficient antennas capable of supporting diverse applications, ranging from satellite communication to mobile networks and IoT devices. Among various antenna types, microstrip patch antennas have gained popularity due to their planar structure, lightweight, and compatibility with integrated circuits. However, their performance is highly dependent on several design parameters, including the dimensions of the patch, the dielectric constant of the substrate, and the operating frequency.

Antenna efficiency, defined as the ratio of radiated power to input power, is a critical performance metric. Achieving high efficiency is challenging due to factors such as dielectric losses, surface wave losses, and impedance mismatches. Optimizing these parameters is essential for ensuring reliable communication and minimizing energy losses in modern wireless systems.

This paper explores the key factors influencing the efficiency of microstrip patch antennas. By leveraging advanced simulation tools and analytical models, the study aims to identify optimal design configurations. The findings provide valuable guidelines for antenna engineers, facilitating the development of high-performance antennas for emerging communication standards.

NEED FOR OPTIMIZATION IN ANTENNA DESIGN

- **Improved Efficiency**: Antennas are critical for transmitting and receiving signals. Optimizing parameters ensures that maximum power is radiated, minimizing energy losses due to dielectric or surface wave losses, especially in microstrip antennas.
- **Enhanced Bandwidth**: Modern communication systems demand antennas with broader bandwidths to handle higher data rates. Optimization helps improve bandwidth while maintaining signal integrity.
- **Size Constraints**: Compact and efficient antenna designs are crucial for portable devices, IoT applications, and embedded systems. Optimization helps achieve high performance within tight size limitations.
- **Frequency Adaptability**: Different applications operate at different frequencies. Optimization ensures the antenna resonates effectively at the desired operating frequency, reducing mismatch losses.
- **Impedance Matching**: Mismatched impedance leads to power reflection and reduced efficiency. Optimization fine-tunes the feed and patch dimensions for better impedance matching with the transmission line.

PARAMETERS CONSIDERED IN ANTENNA FOR OPTIMIZATION

Antenna

Antennas are essential components in wireless communication, including mobile phones and televisions. They convert electric power into electromagnetic waves, such as radio waves, and vice versa. Wireless devices like routers, wireless modems, game controllers, and Bluetooth devices also have antennas. Antennas are structures that help bridge the transition between guided waves and free space, converting electric power into electromagnetic waves. Infrared communication is an exception, but both devices rely on antennas. Antennas convert signals from transmission lines or guiding devices like co-axial cables into electromagnetic energy for transmission through free space. They can be used for both transmission and reception of radiation, collecting electrical signals and accepting radio waves from space.

Antenna Beam Width

Antenna beam width determines the expected signal strength given the direction and radiation distance of an antenna. The beam width will vary given several different factors such as the antenna type, design, orientation and radio frequency. Understanding beam width and how it influences a test environment is critical to accurate and repeatable tests.

How Beam Width is Measured

To calculate an antenna beam width, it is first important to understand directional antennas and antenna gain. Gain is more than increased signal strength. It is directly associated with antenna directionality: increased signal strength in one direction is obtained by reducing signal strength in another. Antenna gain is referenced against a theoretical, pure omni directional antenna that radiates power equally in all directions, in the shape of a perfect sphere. Gain is measured in decibels (dB), which is a logarithmic scale since radio frequency (RF) power drops logarithmically with distance. All of these components of gain are important to consider during product testing to ensure that tests are correct, accurate and repeatable. The half-power value, also called the -3 dB point, which is represented by the red lines in below figure determines and defines the main RF lobe and its width, or beam width.

Accounting for Different Antennae and Frequencies

Antennas have a specific beam width pattern, but this pattern is not consistent across all frequencies. When testing, consider the frequency of operation to account for beam width differences. Higher frequencies have a narrower beam width and are more directional. The divergence of the beam is related to frequency by a formula, making it easy to account for these effects. A typical test setup in an anechoic chamber with a log periodic antenna, where its beamwidth at 1 m covers 0.536 m2 of testing area.

This demonstrates the necessity of calculating the required testing distance relative to beamwidth and antenna. Antenna design plays a crucial role in selecting the best antenna for each test, considering factors like resonant frequency, bandwidth, polarization, and gain. Log periodic antennas have wide-frequency bandwidth and directionality, and their beamwidth is used for half-power testing. The half-power beamwidth and distance to the device under test provide the necessary information for setting up a test environment.

Gain

Gain: The extent to which an antenna focuses energy. In general, gain is measured and directivity is calculated Efficiency (dB) = Directivity (dB) – Gain (dB).

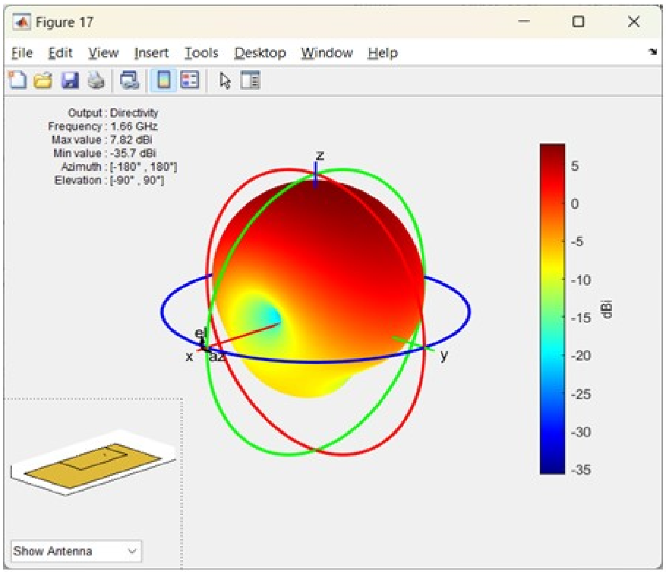

Figure 1: Gain Plot of Antenna with Matlab 5-A

In a transmitting antenna, the gain describes how well the antenna converts input power into radio waves headed in a specified direction. In a receiving antenna, the gain describes how well the antenna converts radio waves arriving from a specified direction into electrical power. When no direction is specified, gain is understood to refer to the peak value of the gain, the gain in the direction of the antenna's main lobe. A plot of the gain as a function of direction is called the antenna pattern or radiation pattern

Antenna Measurements

An isotropic radiator is a theoretical point source of electromagnetic energy that radiates uniformly in all directions. The absolute power used is an isotropic radiator, and the measured gain relative to it is expressed in dB. Directivity, calculated using antenna pattern or design parameters, should always be greater than the actual measured gain.

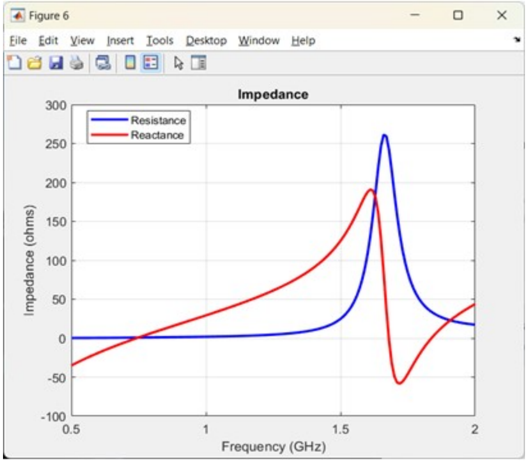

Figure 2: Impedance Curve Using Matlab

The antenna impedance (in ohms) is the impedance value seen at the antenna terminals. This does not mean the DC resistance, but the radiation resistance (whose job is to convert the incoming signal to radiation) which varies with the frequency. As a result, using the antenna outside of its designed frequency will change its feed point impedance to an incorrect value.

The antenna impedance (resistive and reactance components vary with the occurring frequency range)

Universal Spectral Dipole Source

Applied Electromagnetic Technology, LLC (AET) offers the Universal Spherical Dipole

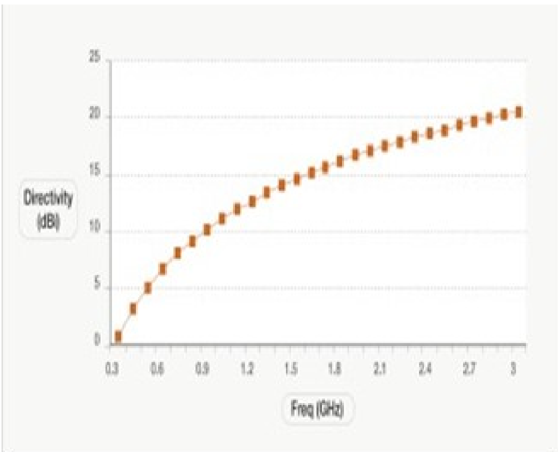

Figure 3: Directivity Vs Frequency

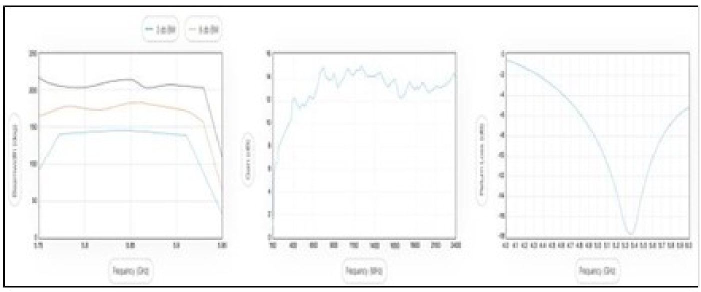

Figure 4: Bandwidth, Gain, Pattern Loss.

Source (USDS), a broadband electric field comb generator RF source with Quasi-Peak detector test functionality.

The USDS is traceable to the Precision Spherical Dipole Source (PSDS) design, developed by NIST. It is ideal for RF emission site comparisons, shielding measurements, quasi-peak detector verification, and verification of RF laboratory equipment. The USDS's spherical dipole antenna offers a highly uniform radiation pattern, easy use, and a small, 10 cm size for shielding effectiveness tests

Figure 5: USDS.

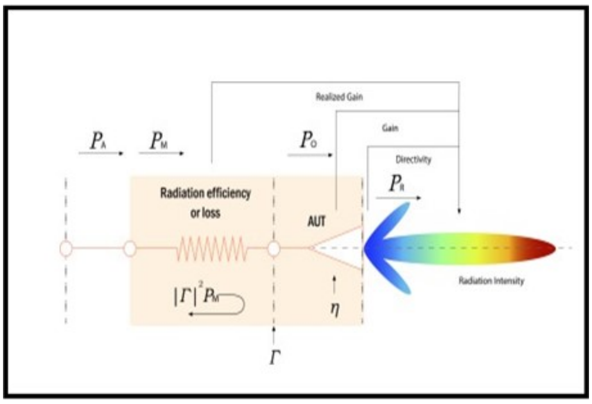

Figure 6: Radiation Efficiency Plot.

Effect of Meatal used for Antenna Design

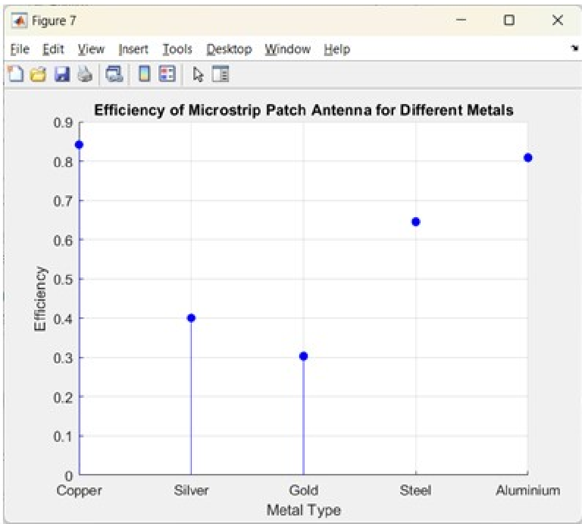

Figure 7: Efficiency Plot for Metals.

Conductivity

- **Higher Conductivity:** Metals with higher electrical conductivity, such as copper, silver, and aluminum, are more efficient in transmitting electromagnetic signals. High conductivity reduces resistive losses, allowing more of the input power to be radiated as electromagnetic waves.
- **Lower Conductivity:** Metals with lower conductivity, like stainless steel or brass, result in higher resistive losses, leading to reduced antenna efficiency. The energy lost as heat due to resistance reduces the power available for radiation.

Surface Roughness

- **Smooth Surfaces:** A smoother metal surface reduces the skin effect, where high-frequency currents flow primarily on the surface of the conductor. Smoother surfaces have lower resistance, which leads to lower energy loss and higher efficiency.
- **Rough Surfaces:** Metals with rougher surfaces increase resistance due to the skin effect, which in turn decreases the antenna's efficiency by causing greater power losses.

Thermal Conductivity

- **High Thermal Conductivity:** Metals with high thermal conductivity, like copper, can dissipate heat more effectively. This property is essential in high-power antennas, where excessive heat can cause inefficiency or damage.
- **Low Thermal Conductivity:** Metals with poor thermal conductivity may overheat during operation, leading to increased resistance and reduced efficiency.

Magnetic Properties

- **Non-Magnetic Metals:** Most efficient antennas are made from non-magnetic metals like copper and aluminum. These metals do not interact with magnetic fields, ensuring stable performance across different frequencies.
- **Magnetic Metals:** Ferromagnetic metals like iron can introduce unwanted inductance and affect the magnetic field distribution, which can degrade antenna efficiency.

Efficiency of Antennas

The efficiency of antennas is influenced by their shape, which determines factors such as radiation pattern, bandwidth, and impedance matching. Here are some common antenna shapes along with relevant formulas to evaluate their efficiency:

1. Dipole Antenna

- **Efficiency Formula:**

$$\eta = \frac{R_r}{R_r + R_l}$$

  - η: Efficiency of the antenna
  - R_r: Radiation resistance (typically around 73 ohms for a half-wave dipole)
  - R_l: Loss resistance (includes resistive losses due to the material, connections, etc.)

2. Monopole Antenna

- **Efficiency Formula:**

$$\eta = \frac{R_r}{R_r + R_g + R_l}$$

  - R_r: Radiation resistance (typically 36.5 ohms for a quarter-wave monopole)
  - R_g: Ground resistance (depends on ground plane size and quality)
  - R_l: Loss resistance

3. Microstrip Patch Antenna

- **Efficiency Formula:**

$$\eta = \frac{P_{\text{rad}}}{P_{\text{rad}} + P_{\text{loss}}}$$

  - P_{rad}: Radiated power
  - P_{loss}: Power lost in the substrate, conductive losses, and surface wave losses

- **Efficiency in Terms of Quality Factor (Q):**

$$\eta = \frac{Q_r}{Q_r + Q_l}$$

  - Q_r: Quality factor due to radiation
  - Q_l: Quality factor due to losses

4. Helical Antenna

- **Efficiency Formula:**

$$\eta = \frac{C \cdot R_r}{C \cdot R_r + R_l}$$

  - C: A constant that depends on the shape and spacing of the helix (typically around 140 ohms for axial mode)
  - R_r: Radiation resistance
  - R_l: Loss resistance (including conductor and dielectric losses)

5. Yagi-Uda Antenna

- **Efficiency Formula:**

$$\eta = \frac{R_r}{R_r + R_l}$$

  - R_r: Radiation resistance of the driven element (can vary depending on element length and spacing)
  - R_l: Loss resistance (including losses from the driven element, parasitic elements, and boom)

6. Loop Antenna

- **Efficiency Formula:**

$$\eta = \frac{R_r}{R_r + R_l}$$

  - R_r: Radiation resistance, which is very small for small loops (proportional to A^2, where A is the loop area)
  - R_l: Loss resistance (typically higher in small loops due to conductor losses)

7. Horn Antenna

- **Efficiency Formula:**

$$\eta = \frac{G}{G_{\max}}$$

  - G: Actual gain of the horn antenna
  - $G_{\max}$: Maximum theoretical gain, which depends on the aperture size and operating frequency
  - Horn antennas typically have high efficiency due to minimal resistive losses and good impedance matching over a wide bandwidth.

8. **Parabolic Reflector Antenna**

- **Efficiency Formula:**

$$\eta = \frac{A_e}{A_p}$$

  - A_e: Effective aperture area, which represents the actual area contributing to the radiation
  - A_p: Physical aperture area (the physical size of the reflector)
  - **Overall Efficiency:** Also affected by spillover losses, diffraction losses, and surface inaccuracies. The total efficiency is:

$$\eta = \eta_{\text{spillover}} \times \eta_{\text{diffraction}} \times \eta_{\text{surface}}$$

  - Parabolic reflectors are highly efficient for high-gain applications, especially at microwave frequencies.

9. **Slot Antenna**

- **Efficiency Formula:**

$$\eta = \frac{R_r}{R_r + R_l}$$

  - R_r: Radiation resistance of the slot
  - R_l: Loss resistance (including conductor losses and any dielectric losses from surrounding materials)
  - Slot antennas are often efficient due to their simple structure and the ability to integrate them into surfaces.

10. **Log-Periodic Dipole Array (LPDA)**

- **Efficiency Formula:**

$$\eta = \frac{R_r}{R_r + R_l}$$

  - R_r: Radiation resistance, which varies across the array
  - R_l: Loss resistance, including losses due to the feeding network and element interactions
  - The efficiency is generally high because LPDAs are designed for broadband operation, minimizing frequency-dependent losses.

11. **Biconical Antenna**

- **Efficiency Formula:**

$$\eta = \frac{R_r}{R_r + R_l}$$

  - R_r: Radiation resistance, which can vary depending on the cone angle and length
  - R_l: Loss resistance (affected by the material of the cones and connections)
  - Biconical antennas have good efficie ↓ over a broad frequency range, making them ideal for broadband measurements.

12. Spiral Antenna

- **Efficiency Formula:**

$$\eta = \frac{R_r}{R_r + R_l}$$

  - R_r: Radiation resistance, typically lower for electrically small antennas
  - R_l: Loss resistance, which includes losses due to the spiral structure and substrate material
  - Spiral antennas are known for their wide bandwidth and circular polarization, with efficiency depending on the design and operating frequency.

13. Patch Antenna (Rectangular)

- **Efficiency Formula:**

$$\eta = \frac{R_r}{R_r + R_l + R_d}$$

  - R_r: Radiation resistance of the patch
  - R_l: Loss resistance (including conductor and dielectric losses)
  - R_d: Losses due to surface waves, particularly in high-permittivity substrates
  - Patch antennas are popular for their ease of fabrication and good efficiency, especially in compact designs.

14. Reflectarray Antenna

- **Efficiency Formula:**

$$\eta = \frac{P_{\text{radiated}}}{P_{\text{incident}}}$$

  - P_{radiated}: Power radiated by the reflectarray
  - P_{incident}: Power incident on the reflectarray from the feed source
  - Reflectarray antennas combine features of reflectors and arrays, offering high efficiency for beam-steering applications.

General Factors Affecting Efficiency across Different Shapes

- **Radiation Resistance (RrR_rRr)**: Represents the power radiated by the antenna. Higher radiation resistance generally leads to higher efficiency.
- **Loss Resistance (RlR_lRl)**: Represents the power lost due to resistive heating, dielectric losses, and other non-radiative losses. Lower loss resistance improves efficiency.
- **Antenna Quality Factor (Q):** Indicates the bandwidth over which the antenna operates efficiently. Lower QlQ_lQl (loss quality factor) improves efficiency.

Directivity

Directivity is a measure of how concentrated the radiation pattern of an antenna is in a particular direction compared to an isotropic antenna, which radiates equally in all directions. It is a key parameter in antenna theory and design, as it indicates the ability of an antenna to focus energy in a specific direction.

Definition of Directivity

Directivity (D) is defined as the ratio of the maximum power density (in the most focused direction) to the average power density radiated in all directions.

$$D = \frac{U_{\max}}{U_{\text{avg}}} = \frac{4\pi U_{\max}}{P_{\text{total}}}$$

U max Maximum radiation intensity (power per unit solid angle) in the direction of the strongest radiation.

Uavg: Average radiation intensity over all directions.

Ptotal: Total radiated power by the antenna.

Expressing Directivity in Decibels

Directivity is often expressed in decibels (dB) for convenience:

DDdB=10log10D

Isotropic Antenna

An isotropic antenna, which radiates equally in all directions, has a directivity of 1 (or 0 dB).

Typical Directivity Values for Different Antennas

- **Dipole Antenna:** The directivity of a half-wave dipole is approximately 2.15 dB.
- **Monopole Antenna:** For a quarter-wave monopole, the directivity is approximately 5.15 dB.
- **Patch Antenna:** A typical rectangular microstrip patch antenna has a directivity in the range of 6-9 dB.
- **Yagi-Uda Antenna:** The directivity varies but can range from 7 dB to over 20 dB depending on the number of elements.
- **Parabolic Reflector Antenna:** The directivity can be very high, often exceeding 30 dB, depending on the size of the reflector.
- **Horn Antenna:** Typically has a directivity ranging from 10 dB to over 20 dB.

Relation between Directivity and Beamwidth

There is an inverse relationship between directivity and beamwidth (the angular width of the main lobe of the radiation pattern

$$D \approx \frac{41253}{\text{HPBW}_\theta \times \text{HPBW}_\phi}$$

HPBWθHalf-power beamwidth in the horizontal plane.

HPBWϕHalf-power beamwidth in the vertical plane.

The narrower the beamwidth, the higher the directivity.

Directivity and Gain

Gain (G) is related to directivity but also takes into account the efficiency (η\etaη) of the antenna: G=η×D

η\eta Efficiency of the antenna, accounting for losses due to resistance, material imperfections, etc.

If an antenna is 100% efficient, its gain equals its directivity

RESULTS AND DISCUSSION

In frequency optimization using fixed dimensions:

Using steepest ascent optimization:

len = 0.34; % Logarithmic value, actual length will be 10^len

bre = 0.67; % Logarithmic value, actual width will be 10^bre

% Initial frequency and step size for steepest descent

initial_frequency = 1.5e9;

step_size = 5e6; % Smaller step size for faster convergence

tolerance = 1e-4; % Larger tolerance for quicker termination

The optimal value of frequency of operation and maximum effieciency was obtained as:

Optimized Frequency: 1500000000 Hz

Efficiency: 0.96159

Dimension Optimization for Fixed Frequency of Operation

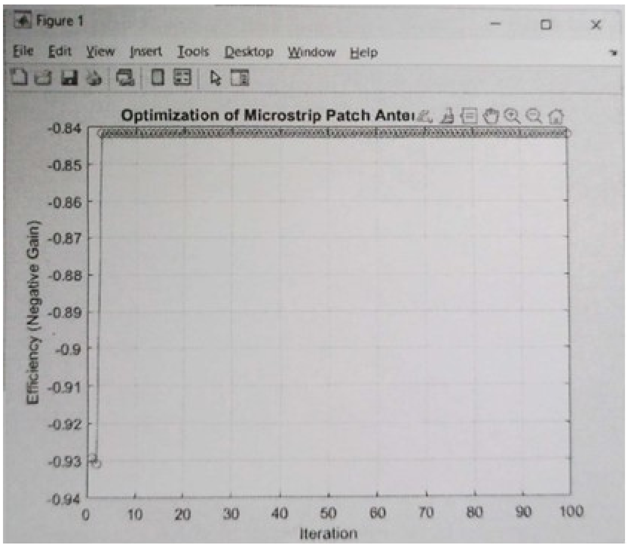

Figure 8: Optimizing Microstrip Patch.

Gradient ascent for antenna dimensions

Provided 0.01 * 0.01 m

With optimal efficiency of 0.8417

Variation of Efficiency as a Function of Dimensions

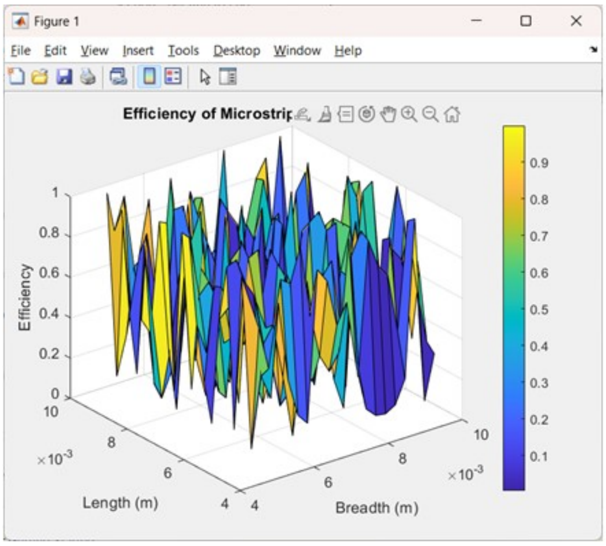

Figure 9: 3D Plot of Efficiency Contour.

maxeff =

0.9991

18 * 10^ -2

19* 10^ -2

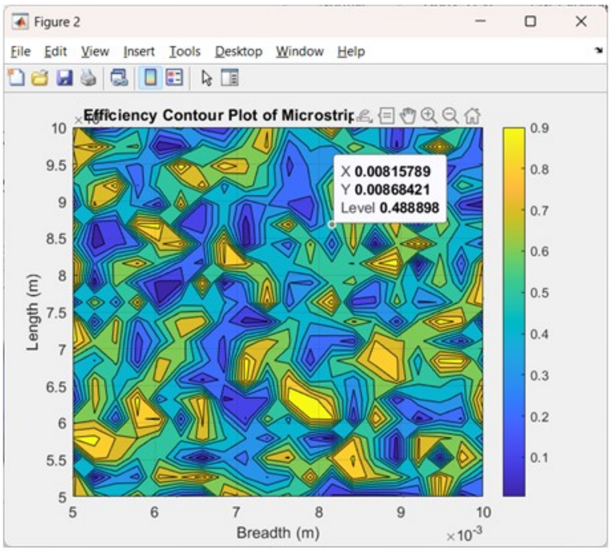

Figure 10: 2D Contour Plot of Efficiency.

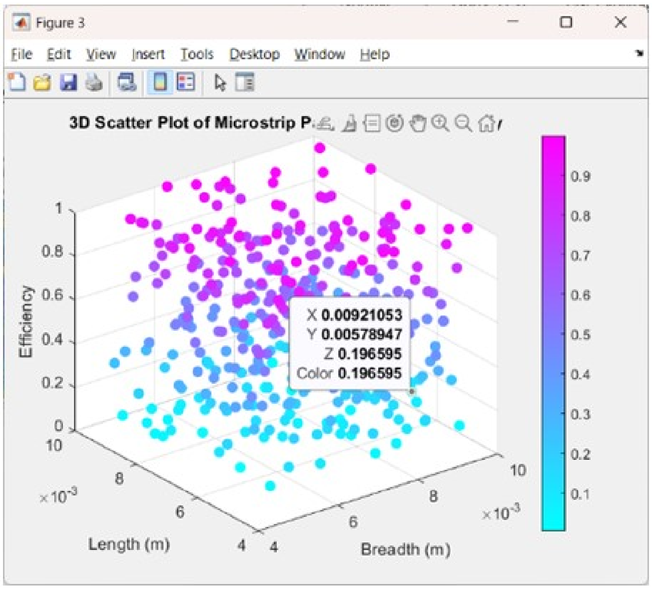

Figure 11: 3D Scatter Plot of Efficiency.

Minimum Impedance's Corresponding Frequency for Fixed Antenna Dimensions

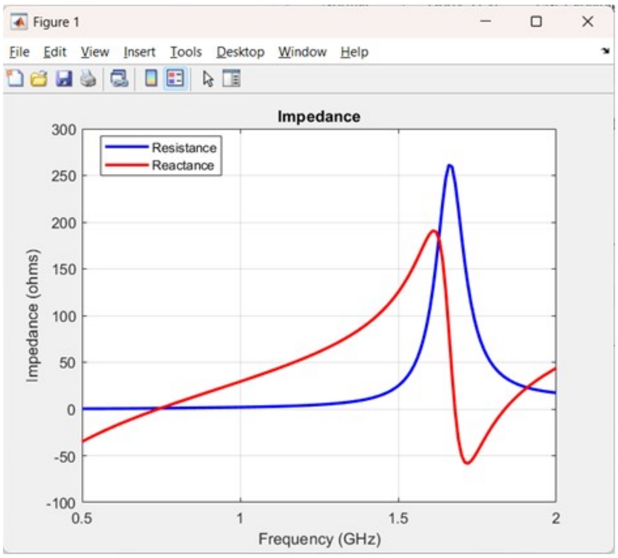

Figure 12: Impedance Plot.

Minimum Impedance

0.2338 -34.6258i

Occurring Frequency

500000000

\\ signifies the frequency of operation for lower

value of impedance found using linear

optimization

CONCLUSION

Even though all the maximizing and minimizing algorithms can be applied as a general trend the efficiency remains more at lambda/4 and lambda/2 dimensions . So for finding the small differences in magnitudes that provide higher changes in efficiency and performance improvements optimization algorithms can be used. In some cases the optimized outputs take extreme values which were neglected. It's a constantly improving and evolving domain where with more research and powerful AI tools compared to generic optimization , the performance of the estimate can be improved.

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