High-Gain Design Microstrip Antenna for Weather Radar on Aircraft at the 9.4 GHz Frequency

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Abstract

The use of radar in aviation primarily centers around aircraft weather radar systems, which provide real-time monitoring of weather conditions surrounding the aircraft. Antennas play a crucial role in enabling detection within these radar systems. This article is dedicated to research efforts focused on developing a microstrip antenna design using array techniques to achieve high gain. The research methodology follows Thiagarajan's 4D approach, encompassing the Define, Design, Develop, and Disseminate stages. To optimize performance, the research encompasses the creation of various antenna designs, including single patches, 1x2, 4x4, and 8x4 arrays, employing feed and coaxial insert enumeration methods. Additionally, comparisons are drawn between two substrates, specifically FR-4 and Rogers RT-5880. Parameters under scrutiny encompass gain, VSWR, return loss, bandwidth, and radiation patterns. The design process for microstrip antennas involves intricate dimensional calculations and array method selection, followed by a detailed application-based design. The results consistently demonstrate VSWR values below 2 and return loss values below -10 dB for microstrip antenna designs on both FR-4 and Rogers RT-5880 substrates. The most significant gains were achieved by an 8 x 4 array design employing the insert feed enumeration method on a Rogers RT-5880 substrate, reaching an impressive 17,979 dBi. The widest bandwidth is observed in the design of the 1x2 array using the Rogers RT-5880 substrate, reaching 651.1 MHz. Moreover, it is evident that an increase in the number of patches in the array corresponds to an increase in gain. Notably, Rogers RT-5880 material demonstrates a superior capacity to produce higher gain compared to FR-4 substrates.

Keywords: Microstrip, High Gain, Array, FR-4, Rogers RT-5880

INTRODUCTION

In the aviation sector, radar technology enables the surveillance of a broader and extended range of objects. Radar systems are pivotal in detecting and pinpointing objects by transmitting electromagnetic waves and subsequently analyzing the incoming signals. As outlined in [1]–[3] According to Annex 10 Volume IV, radar's primary function is to determine the aircraft's position in terms of both range and azimuth. An example of radar used during flight is the aircraft weather radar, which offers real-time weather monitoring for pilots. These weather radar systems excel in detecting various elements, including rainfall intensity and adverse weather conditions such as storms, in the vicinity of the aircraft. To support the detection process, the aircraft's weather radar system necessitates crucial devices in the form of antennas [4]. An antenna serves as a vital electronic component responsible for transmitting and receiving electromagnetic waves [5], [6]. When functioning as a transmitter, the antenna acts as an electromagnetic transducer on cable transmission lines, converting electrical energy into electromagnetic waves. Conversely, in its receiver role, the antenna is responsible for transforming incoming electromagnetic waves into electrical signals.

Microstrip antennas are typically composed of PCB material, featuring multiple sheets, each with distinct functions. This component comprises a conductive patch separated by a substrate, which serves both as an insulating layer and a separator from the groundplane or base layer situated beneath it [7]–[9]. Microstrip antennas offer several advantages, including their compact form, dual-frequency capabilities, and seamless integration with other equipment. This article outlines the design of microstrip antennas operating at 9.4 GHz, utilizing array techniques in conjunction with arrays functioning at the same 9.4 GHz frequency. The substrate materials employed for this antenna design encompass FR-4 and Rogers RT-5880. Consequently, based on this comprehensive description, a scientific paper is planned with the title "Design of a 9.4 GHz Aircraft Weather Radar Microstrip Antenna Using Array Techniques." Prior studies have also delved into high-gain antennas, including: [10]–[15]

The objective was to create a rectangular microstrip antenna using array techniques and to evaluate its performance using various substrate materials, specifically FR-4 and Rogers RT-5880. This assessment encompassed parameters like VSWR, gain, return loss, bandwidth, and radiation patterns. Furthermore, the study aimed to compare the gain outcomes of microstrip antennas employing FR-4 and Rogers RT-5880 substrates.

METHOD

This study follows a research and development (R&D) approach, utilizing a 4D development model, which comprises four distinct stages: Define, Design, Develop, and Disseminate.

a. Define

In this study, the Define stage encompasses the conduction of a needs analysis and the collection of relevant information pertaining to the requirements for the development of rectangular microstrip antennas using array techniques for weather radar applications operating at a frequency of 9.4 GHz. In this Define stage, crucial aspects to consider involve the delineation of design attributes and an extensive review of existing literature. The specifics of these design characteristics are presented in Table 1.

Table 1. Antenna Parameters

Working frequency	9,4 GHz
Parameters	**Result**
Frequency	9.4 GHz
VSWR	< 2
Return Loss	< -10 dB
Gain	> 12 dBi

b. Design

The design phase entails the creation of a rectangular microstrip antenna using array techniques, executed via an antenna simulation application. Moreover, the designed antenna is evaluated through a simulation application to verify its performance. In this phase, two types of substrates, specifically FR-4 and Rogers RT-5880, are utilized for the purpose of comparison.

Table 2. FR-4 Substrate Specifications

Characteristic	**Ideal Value**
Dielectric constant Relative(Ɛr)	4.3
Dielectric Loss Tangent(δ)	0.0265
Substrate Thickness (FR4 Epoxy)	1.6 mm
Working Frequency	9,4 GHz

Table 3. Product Specification Rogers RT-5880 Substrate

Characteristic	**Ideal Value**
Dielectric constant Relative(Ɛr)	2.2
Dielectric Loss Tangent(δ)	0.0009
Substrate Thickness (Rogers RT-5880)	1.575 mm

The initial design process commences with the calculation of the microstrip antenna using the following equation:

$$W = \frac{1}{2f_0\sqrt{\frac{\varepsilon_r+1}{2}}} \tag{1}$$

Information:
W = Patch Width
C = Air wavelength
f_0 = Working frequency
εr = Material permeability

$$\varepsilon_{eff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left[1+12\,\frac{h}{w}\right]^{-1/2} \tag{2}$$

Information:
εeff = Effective permeability
εr = Material permeability
h = Substrate thickness
W = Patch Length

$$L_{eff} = \frac{c}{2f_0\sqrt{\varepsilon_{eff}}} \tag{3}$$

Information :
εr = Material permeability
$f0$ = Working frequency
εeff = Effective permeability

$$\Delta L = 0.412h\frac{(\varepsilon_{eff}+0.3)\left(\frac{W}{h}+0.264\right)}{(\varepsilon_{eff}-0.258)\left(\frac{W}{h}+0.8\right)} \tag{4}$$

Information:
ΔL = Patch length difference
h = substrate thickness
W = Patch Width
εeff = Effective permeability

$L = L_{eff} - 2\Delta L$ (5)

Information:

L = Patch Length

ΔL = Patch length difference

$Leff$ = Effective Patch Length

Design of groundplane dimensions:

Lg=2×L (6)

Wg=2×W (7)

Information :

Lg = Groundplane length

Wg = Groundplane width

L = Patch Length

W = Patch Width

$W_f = \frac{7{,}48xh}{3{,}9484} - 1.25 \times t$ (8)

Information :

Wf = Feedline width

h = substrate thickness

t = Copper thickness

Calculations for array antennas can be performed using branching techniques, as demonstrated in the following equation:

$Z = Z0 \sqrt{N}$ (9)

Keterangan :

Z = Output Branching Impedance

Z_0 = Imput impedance

N = Number of branches

d = λ 2 (10)

Keterangan :

d = Spacing between patches

λ = Resonant frequency wavelength

Once the calculations are finalized, the subsequent phase entails designing the antenna and conducting tests through antenna simulation software. The initial step in the design process is the creation of a single antenna or a single patch with a rectangular shape, utilizing the feed insertion method for enumeration. Subsequently, the next design phase involves the development of an array antenna based on calculations conducted on the preceding single antenna patches. The array technique is employed to amalgamate antenna arrays comprising a single patch. This antenna exhibits two impedance values, specifically 50 Ohms and 70.7 Ohms.

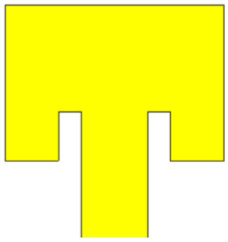

Figure 1 Single Patch microstrip antenna design

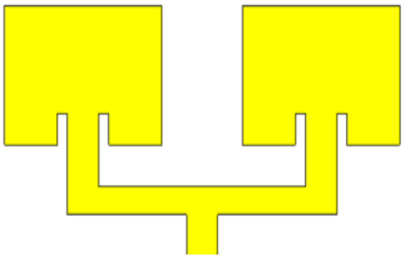

Figure 2 1 x 2 Array microstrip antenna design

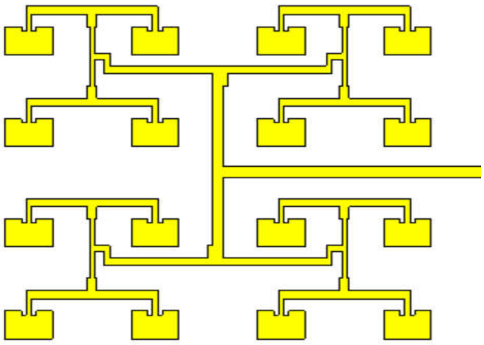

Figure 3 4 x 4 Array microstrip antenna design

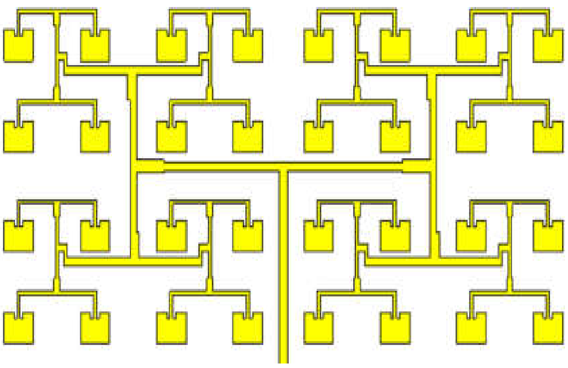

Figure 4 8 x 4 Array microstrip antenna design

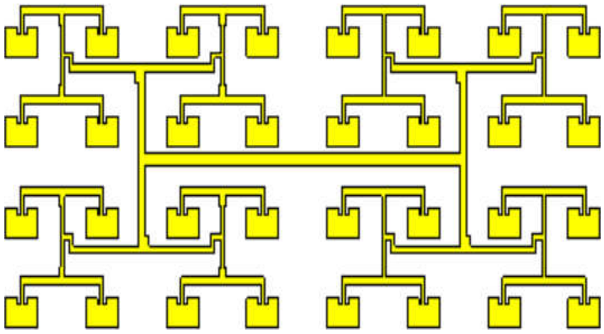

Figure 5 8 x 4 Coaxial Array microstrip antenna design

Table 4. Antenna Dimension Size

No.	Part	Symbol	Size After Optimization	
			FR-4	Rogers RT- 5880
1.	Patch Width	W	9.8 mm	12.65 mm
2.	Patch Length	L	7 mm	9.99 mm
3.	Groundplane Length	Lg	14 mm	17.5 mm
4.	Wide Groundplane	Wg	19.6 mm	19.5 mm
5.	Gap Width	Gap	1 mm	1 mm
6.	Distance Between Patches	d	16 mm	16 mm

Figure 1 serves as a representation of a single patch, serving as a reference for dimensions during the array design phase. The single patch design is the simplest in this study. Figure 2 depicts a 1 x 2 array design that employs array techniques to establish connections between antenna patches. In this design, two branches are connected to a single power source to receive voltage input. Figures 3 and 4 portray array designs with more intricate configurations, involving additional patches and branching compared to the design in Figure 2. Both Figures 4 and 5 feature the largest number of patches, each comprising 32 patches. The primary distinction between the designs in Figures 4 and 5 lies in the enumeration method; one employs the insert feed method, while the other utilizes the coaxial feed approach.

When designing arrays, the spacing between patches is calculated while considering half the wavelength of the closest distance to minimize potential interference. To ensure optimal performance of antenna equipment and alignment with the desired parameters, dimensional optimization is conducted until the desired parameters are met. This step is crucial because initial calculations provide only an estimate of the desired parameters, necessitating an optimization process after the design phase is completed. Optimization entails adjusting antenna dimensions to attain new antenna measurements.

c. Develop

Following the design stage, measurements are carried out through simulations using antenna simulation software applications. Measurement parameters encompass return loss, VSWR, gain, bandwidth, and radiation patterns. These measurements are conducted for each design, employing two types of substrates, specifically Rogers RT-5880 and FR-4.

d. Disseminate

The Dissemination Phase is the stage at which research findings are communicated to the community or relevant stakeholders, including:

1. The findings of this research are disseminated through publication in scientific journals or online platforms related to the research subject.
2. A research report containing the research findings and conclusions will be created and shared with the Surabaya Aviation Polytechnic for educational purposes. This report can also serve as a reference for future final project research related to microstrip antennas.

RESULT AND DISCUSSION

The discussion encompasses various antenna parameters, including return loss, VSWR, bandwidth, gain, and radiation patterns, all of which have an impact on the signal emitted by the antenna. VSWR represents the ratio between the maximum and minimum amplitudes (|V|max and |V|min) of the standing wave. An ideal VSWR value of 1 signifies a perfect matching condition, where no signal is reflected in the channel. However, achieving this condition in practice is often challenging, and typically, acceptable VSWR values are ⩽ 2.

Antenna gain relates to the antenna's ability to focus the radiation of the signal and pick up signals from a specific direction. It is measured as the ratio between the maximum radiation level of the antenna and the radiation level of a reference antenna equipped with the same input power. Antenna gain is usually measured in decibels (dB) relative to the reference antenna, and the Friss formula can be used to calculate and express the gain in units of dBi.

Conversely, return loss represents the ratio between the amplitude of the reflected or reflected wave and the amplitude of the emitted wave. This phenomenon occurs when there is an impedance mismatch between the signal transmission line and the antenna's input impedance. An antenna is considered to have a good return loss if its value is < -10 dB, and this value can be determined through a formula that relates return loss and VSWR. The following:

$$\Gamma = \frac{VSWR-1}{VSWR+1} \quad (11)$$

$$\text{VSWR} = \frac{1+\Gamma}{1-\Gamma} \quad (12)$$

$$\Gamma = 10^{\frac{-RL}{20}} \quad (13)$$

$$\text{Return Loss} = -20 \log \left[\frac{VSWR-1}{VSWR+1}\right] \quad (14)$$

$$\text{Return Loss} = -20 \log (\Gamma) \quad (15)$$

$$\text{VSWR} = \frac{1+10^{\frac{-RL}{20}}}{1-10^{\frac{-RL}{20}}} \quad (16)$$

Information :
Γ: *Reflection Coefficient*
RL: Return Loss (dB)

Antenna bandwidth signifies the frequency range within which the VSWR or return loss value remains below a predefined threshold. Antenna radiation patterns can manifest in various forms, including isotropic, bidirectional, omnidirectional, and unidirectional patterns. These radiation patterns describe how the signal is emitted by the antenna in spherical coordinates. The outcomes of the microstrip antenna design simulations conducted using antenna simulation applications are outlined as follows:

a. Return Loss

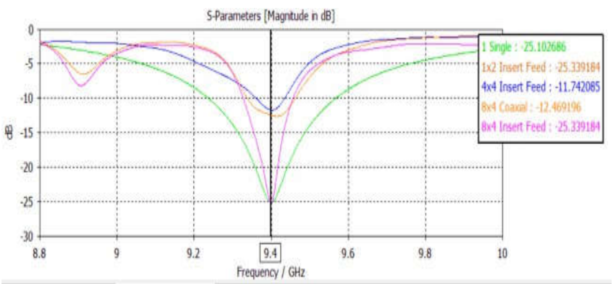

Figure 6 FR-4 Return Loss Chart

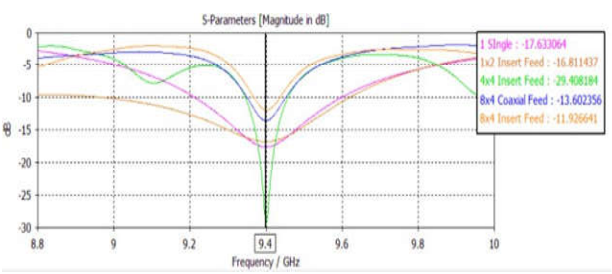

Figure 7 Rogers RT-5880 Return Loss Chart

The graphs depicted in Figure 6 and Figure 7 reveal that the return loss value in each design remains consistent, regardless of the number of patches on the antenna. All designs, whether using Rogers RT-5880 or FR-4 substrates, demonstrated optimal performance as they all achieved a return loss value of < -10 dB, meeting the minimum requirement for antenna manufacturing. This threshold of < -10 dB is determined based on the return loss and VSWR equations, accounting for a maximum VSWR value of 2 for the antenna. The most favorable return loss values are observed in the Rogers RT-5880 4 x 4 array design.

b. VSWR

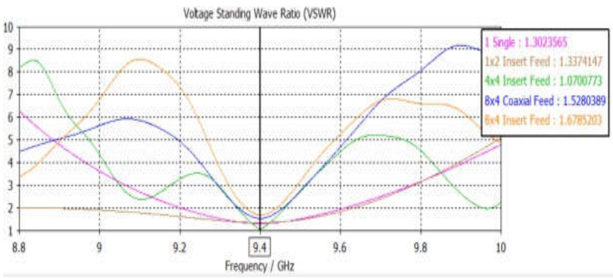

Figure 8 VSWR Rogers RT-5880 Simulation Results

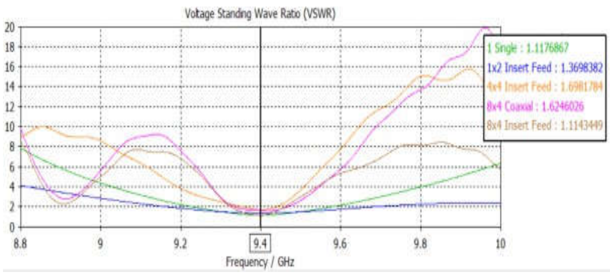

Figure 9 VSWR FR-4 Simulation Results

An examination of Figure 3 and Figure 4 disclosed that the VSWR values displayed no significant correlation with the number of patches on the antenna. However, a clear correlation emerged between the VSWR value and return loss. This relationship is apparent in the lowest return losses achieved by the 4 x 4 insert feed design on the Rogers RT-5880 substrate, which also achieved the most favorable VSWR value, approximately 1.07. In contrast, the FR-4 4 x 4 array design, associated with the highest return loss, exhibited the largest VSWR at approximately 1.624. It is important to note that all antenna designs using FR-4 substrates adhered to the standard antenna parameters, requiring VSWR values to be < 2.

c. Bandwidth

Table 5. Bandwidth and Gain Simulation Results

No.	Antenna Design	Parameters			
		Bandwidth (MHz)		Gain (dBi)	
		FR-4	Rogers RT-5880	FR-4	Rogers RT-5880
1.	Single Patch	331.6	385.6	4.02	5.667
2.	1x2 Insert Feed	480.8	651.1	5.28	9.607
3.	4x4 Insert Feed	74.9	112.5	10.36	15.699
4.	8x4 Insert Feed	129	67.9	13.57	17.979
5.	8x4 Coaxial	124.8	101.6	13.12	17.406

Table 5 demonstrates that each antenna design exhibits a distinct bandwidth value, and the inclusion of additional patches does not result in an increase in bandwidth. The 1 x 2 array design employing the Rogers RT-5880 substrate presents the broadest bandwidth, whereas the 8 x 4 array design employing the same substrate (Rogers RT-5880) yields the most limited bandwidth.

d. Gain

The simulations presented in Table 5 demonstrate that using a Rogers RT-5880 substrate results in higher gain when compared to using an FR-4 substrate. Furthermore, an increase in the number of patch elements in the antenna array corresponds to a higher gain. The choice of material or substrate for the antenna also significantly impacts the resulting gain. Rogers RT-5880 achieves superior gain due to its distinct substrate characteristics, particularly its lower dielectric constant of 2.2, while FR-4 has a dielectric constant of 4.3. This disparity affects the antenna's radiation efficiency [8]. It's worth noting that the tangent loss on FR-4 substrates is higher at 0.0265, while the tangent loss on Rogers RT-5880 is notably lower at about 0.00009. The reduced tangent loss on the Rogers RT-5880 contributes to the enhanced gain.

e. Radiation Patterns

The radiation pattern results for each antenna design using FR-4 and Rogers RT-5880 substrates revealed directional radiation patterns. These directional patterns result in a beam with higher radiation intensity in a specific area compared to others, thus creating a more focused beam in that particular region.

CONCLUSION

Based on the design outcomes and parameter comparisons from antenna simulations, the following conclusions can be drawn: Microstrip antenna designs can be developed by calculating dimensions and implementing techniques such as Wilkinson arrays and power dividers to achieve the desired parameters. All microstrip antennas, whether using FR-4 or Rogers RT-5880 substrates, exhibit VSWR values below 2, return loss values below -10 dB, and directional radiation patterns. The highest gain was attained in an 8 x 4 array design using a Rogers RT-5880 substrate, achieving an impressive 17,979 dBi. The bandwidth in each design is satisfactory, with the Rogers RT-5880 substrate in the 1x2 design having the highest bandwidth at 651.1 MHz. Gain increases with the number of patches used in each design. The use of Rogers RT-5880 material results in higher gain compared to FR-4, as demonstrated by consistently higher gain values in all designs using Rogers RT-5880 material compared to FR-4. This research received support from Surabaya Aviation Polytechnic.

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