Journal of Advanced Marine Engineering and Technology, Vol. 47, No. 2, pp. 78~83, 2023
J. Advanced Marine Engineering and Technology (JAMET)
https://doi.org/10.5916/jamet.2023.47.2.78

ISSN 2234-7925 (Print)
ISSN 2765-4796 (Online)
Original Paper

Calculation of optimum feed-line impedance of series-fed microstrip antennas using the image parameter method and Bloch theory

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(Received December 21, 2022 ; Revised January 19, 2023 ; Accepted March 19, 2023)

Abstract: In millimeter-wave bands, microstrip array antennas are used for various communications and sensors because of their lightweight and low cost. A series-fed method that can reduce the length of a feed line as much as feasible is preferable over a parallel feed method to reduce the loss in a microstrip array antenna. However, the characteristic impedance, which is simple to fabricate without a theoretical analysis or comprehension, is primarily chosen and applied to the feed line of the microstrip array antenna. In this paper, we propose an optimal feedline selection method for a series-fed microstrip array antenna using the image parameter method and Bloch theory, both of which are used in filter design in microwave engineering. A typical 79 GHz band series-fed microstrip array antenna has a gain of 14.7 dB with a preferred feed line of 100 Ω, whereas a gain of 17.3 dB with the characteristic impedance calculated using the image parameter method and Bloch theory. The proposed method resulted in a 1.3 dB increase in antenna gain. These results are preliminary from the simulations, and prototypes will be fabricated in the future to verify the proposed method.

Keywords: Array antenna, Feed line, Microstrip antenna, mmWave

1. Introduction

In the past, the millimeter-wave (mmWave) band was primarily used for military radar systems; however, it has recently been developed and expanded for civilian use, such as vehicle radars **[1]**. Furthermore, as 5G communication began service in the mmWave band, market attention has focused on the mmWave band **[2]**.

Various types of antennas have been used in the mmWave bands, such as microstrip patch antennas, slotted waveguide antennas, and antennas with lenses or reflectors. Reflector antennas generally have a very low loss, but they have a large volume and limited bandwidth because they require separate layers for reflection and an excitation antenna for the incident. Slotted array waveguide antennas are highly efficient, can easily distribute open-surface power, and are structurally robust. However, combining antennas with other radiofrequency (RF) modules is difficult, and the antenna size becomes extremely small at high frequencies in the sub-THz band, making manufacturing difficult **[3]**. However, microstrip patch antennas are lightweight owing to their thin substrates **[4]-[7]**. Nevertheless, certain drawbacks exist, including a low power-handling capability, low gain, and narrow bandwidth. In particular, conductor and dielectric losses rapidly increase at high frequencies above the microwave band, limiting its use. However, as hardware performance and signal processing algorithms improve, antenna gain requirements are reduced. Consequently, this has regained the popularity of microstrip array antennas in the mmWave band **[8]**.

The majority of losses in microstrip antennas are caused by dielectric and conductor losses that are proportional to the total printing pattern length. Therefore, the shorter the length of the entire feed line, the smaller the loss. The series feeding method is preferred over the parallel feeding method in mmWave microstrip array antennas that are vulnerable to loss **[9][10]**.

In the series feeding method for microstrip array antennas, the characteristic impedance is often used as an approximate value rather than an accurately calculated value. A feed line of 100 Ω, the feed line width for fabrication convenience, is commonly used in series-fed microstrip array antennas operating at 77 GHz or 79 GHz **[11]-[13]**. That is, theoretical research or analysis on

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the feed line width of the series feeding method is lacking.

A microwave filter is a two-port network with a periodic structure that has a frequency response at a specific point in the RF owing to attenuation in the stopband, providing transmission at frequencies within the passband **[14]**. The image parameter method and Bloch theory are used to design the input and output impedances of a filter with a periodic structure. In this study, using the image parameter method and Bloch theory, we attempt to determine the optimal feed line for a series-fed microstrip array antenna with several radiating elements arranged in a periodic structure.

2. Proposed methods

2.1 Image parameter method

Consider a two-port network characterized by its ABCD parameters, as shown in **Figure 1**. Image impedance Z_{i1} is the input impedance at port 1 when port 2 is terminated with Z_{i2}, and image impedance Z_{i2} is the input impedance at port 2 when port 1 is terminated with Z_{i1}.

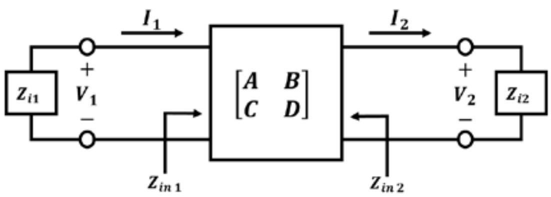


Figure 1: Two-port network terminated in its image impedance

In a two-port network, the two ports are matched when terminated with their image impedance. In terms of the ABCD parameters of the network, the image impedances of ports 1 and 2 are expressed in **[14]** as follows:

$$Z_{i1} = \sqrt{AB/CD}\ , \tag{1}$$

$$Z_{i2} = \sqrt{BD/AC}\ . \tag{2}$$

If the network is symmetric, $A = D$ and $Z_{i1} = Z_{i2}$.

2.2 Bloch theory

Consider a periodic loading line of infinite length, as shown in **Figure 2**. Depending on the frequency and normalized susceptance values, the periodic line represents passbands or stopbands and thus can be considered as a type of filter. Each unit cell of this line consists of a transmission line of length d with shunt susceptance b that is normalized to characteristic impedance Z_0; k is the propagation constant. Here, I_n and I_{n+1} represent the currents on both sides of the nth and n+1th unit cells, respectively. Similarly, V_n and V_{n+1} represent the voltages on both sides of the nth and n+1th unit cells, respectively.

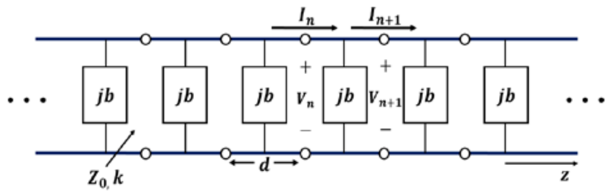


Figure 2: Periodically loaded transmission line's equivalent circuit

If the finite line comprises a cascade connection of identical two-port networks, we determine the relationship between the voltages and currents on both sides of the nth unit cell using the ABCD matrix as follows:

$$\begin{bmatrix} V_n \\ I_n \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} V_{n+1} \\ I_{n+1} \end{bmatrix}. \tag{3}$$

The characteristic impedance at the end of the unit cell is called the Bloch impedance that is expressed in **[14]** as follows:

$$Z_B^{\pm} = \frac{-2BZ_0}{A - D \mp \sqrt{(A+D)^2 - 4}}\ . \tag{4}$$

For symmetric unit cells, $A = D$; thus, **Equation (4)** can be simply expressed as follows:

$$Z_B^{\pm} = \frac{\pm BZ_0}{\sqrt{A^2 - 1}}\ , \tag{5}$$

where ± solutions imply the characteristic impedance of traveling waves in positive and negative directions. Except for the sign, these impedances are the same for symmetric networks. However, (5) can be used for periodic structures; but the structure need not have infinite unit cells.

3. Simulation results

To apply the proposed methods, HFSS, a commercial finite element method simulation tool for electromagnetic structure analysis, was used to analyze the radiating elements and design the antenna. Isola Astra MT77 was used as a substrate, and it had a relative permittivity (ε_r) of 3.0, loss tangent ($\tan\delta$) of 0.0017, and thickness (h) of 0.127 mm.

3.1 Calculating feed-line impedance through unit cell analysis

Among the various radiating element shapes, the simplest rectangular patch was selected as the radiating element in this study. Because the electromagnetic field is concentrated between the signal pad and the ground pad, a lumped port, which is more suitable than a wave port, was used for the analysis. As shown in **Figure 3**, two lumped ports were attached to both sides of the radiating element, and the design parameters of the radiating element were optimized to resonate at an operating frequency of 79 GHz and maximize the antenna gain of a single radiating element. The optimized design parameters a, b, A, and B were 1.06 mm, 0.79 mm, 2.37 mm, and 3.18 mm, respectively.

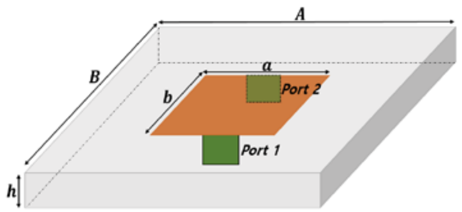


Figure 3: Simulation setup for S parameters of a rectangular radiating element

To obtain the ABCD parameters, we assumed the radiating element to be a unit cell and converted the S parameters of the optimized radiating element, as shown in **Figure 4**, to the ABCD parameters.

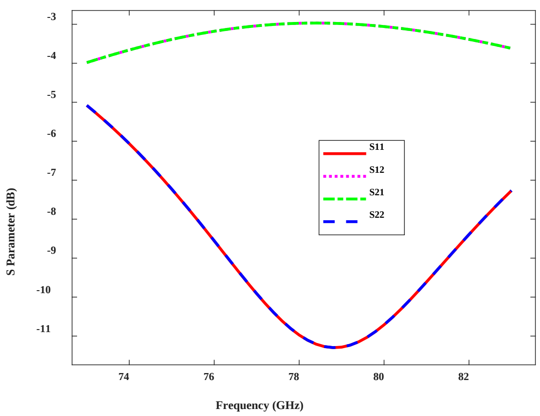


Figure 4: Simulated reflection coefficient of the unit cell

By substituting the complex values of the ABCD parameters in **Table 1** into **Equations (1)** and **(4)**, we obtained the image and Bloch impedances. The result of the image impedance was the same as that of the Bloch impedance, and the absolute and real values of the calculated optimum impedance were 119 Ω and 90 Ω, respectively.

Table 1: ABCD parameters of the unit cell at 79 GHz

A	B	C	D
$-0.95-0.24j$	$8.05-82.6j$	$-0.01-0.00j$	$-0.94-0.24j$

3.2 Performance of a series-fed microstrip array antenna depending on the feed line

A conventional microstrip array antenna is required to verify the effect of the feed line on the performance of a series-fed microstrip. As shown in **Figure 5,** the rectangular radiating elements were arranged on the dielectric substrate at half-wavelength intervals ($\lambda_g/2$) and directly connected to the feed line. Therefore, all the radiating elements had the same phase characteristics. The end radiating element was connected to the inset-type feed line to match the feed line to the input impedance of the radiating element. Therefore, the inset-related parameters, w_i and *depth*, depended on the feed line. The series-fed microstrip array antenna consists of 16 identical rectangular radiating elements and a single inset-fed radiating element.

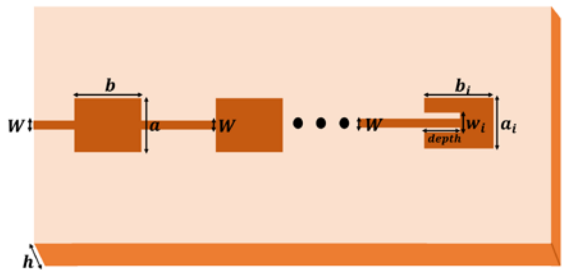


Figure 5: Geometry of a series-fed microstrip array antenna

The feed line width (W) of 119 Ω, which is the absolute value of the result obtained from the image parameter method and Bloch theory, was 0.054 mm on the Astra MT77 substrate at 79 GHz. The design parameters of the corresponding end radiating element were as follows: a_i = 0.56 mm, b_i = 1.071 mm, *depth* = 0.485 mm, and w_i = 0.137 mm. For the feed line of 90 Ω, which is the real value of the optimum impedance obtained from **Equations (1)** and **(5),** the line width (W) was 0.11 mm, and the matched end radiating elements had the following design parameters: a_i = 0.562 mm, b_i = 1.07 mm, *depth* = 0.487 mm, and w_i = 0.15 mm. When the characteristic impedance was 100 Ω, which is a common width in the literature for series-fed microstrip array antennas, the width of the feed line (W) was 0.08 mm. The design parameters for a series-fed microstrip array antenna with a characteristic impedance of 100 Ω were as follows: a_i = 0.69 mm, b_i = 1.0595 mm, *depth* = 0.5 mm, and w_i = 0.16 mm.

The simulated reflection coefficients of these series-fed microstrip array antennas are shown in **Figure 6**. The -10 dB reflection coefficient bandwidth of the simulation was 5.74 GHz at 119 Ω, 4.02 GHz at 90 Ω, and 5.52 GHz at 100 Ω. Notably, the feed line with an optimum characteristic impedance of 119 Ω increased the bandwidth by approximately 200 MHz compared with the common characteristic impedance of 100 Ω. Moreover, we note that the absolute value, rather than the real value, of the impedance obtained from the Bloch theory and image impedance method should be used as the impedance of the feed line.

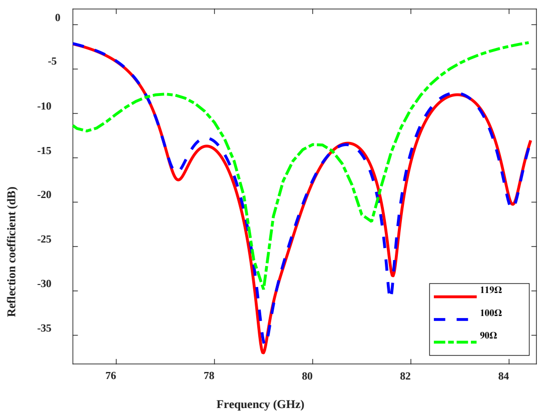
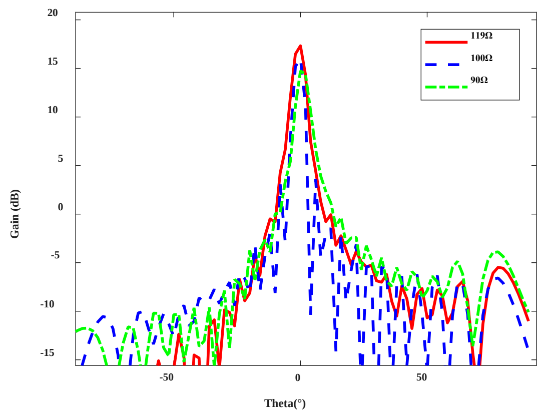


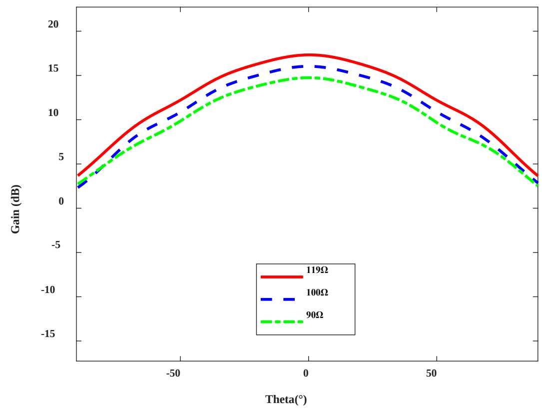
Figure 6: Simulated reflection coefficients of the antenna with respect to the operating frequencies

The radiation patterns of the E- and H-planes simulated at 79 GHz are shown in **Figure 7**. The peak gains in the E- and H-planes were 17.33 dB for the characteristic impedance of 119 Ω with a feed-line width of 0.054 mm, 14.75 dB for the characteristic impedance of 90 Ω with a feed-line width of 0.11 mm, and 16.02 dB for the characteristic impedance of 100 Ω with a feed-line width of 0.08 mm.

The simulated antenna efficiency is shown in **Figure 8**. The antenna efficiencies were 97.55%, 96.13%, and 94.98% at 119 Ω, 100 Ω, and 90 Ω, respectively. The highest antenna efficiency was obtained using a 119 Ω feed line.



(a)



(b)

Figure 7: Simulated radiation patterns at 79 GHz: (a) E-plane; (b) H-plane

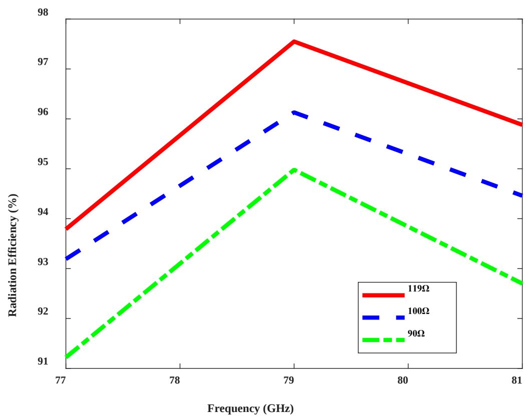


Figure 8: Simulated antenna efficiency at the operating frequency

For a feed line with a characteristic impedance of 119 Ω, the antenna gain was approximately 1.31 dB higher than that of a series-fed microstrip array antenna with a feed line of 100 Ω. Furthermore, the gain when using a feed line with a characteristic impedance of 119 Ω was approximately 2.58 dB higher than that when using a feed line with a characteristic impedance of 90 Ω. That is, when the absolute values of the optimal characteristic impedances obtained from the image parameter method and Bloch theory are applied, a larger antenna gain can be obtained than when the real values are applied.

The difference in gain between the characteristic impedances of 119 Ω and 100 Ω was linearly approximately 1.35 times; this is an effect that can theoretically reduce the number of radiating elements by 1.35 times compared with the conventional method. Therefore, the feed line of 100 Ω required 23 radiating elements to have the same gain as the series-fed microstrip array antenna with a feed line of 119 Ω and 17 radiating elements.

4. Conclusion

In this study, we propose an optimal feedline selection method for a series-fed microstrip array antenna operating in the mmWave band. A microstrip array antenna using the proposed feed-line selection method was implemented on a dielectric substrate at a center frequency of 79 GHz, and the reflection coefficient and radiation pattern were simulated. When the gain of the proposed feed-line selection method was compared to that of the conventional feed line, the gain of the proposed method was approximately 1.31 dB higher. We hope that the proposed method provides a good criterion for determining the feed lines of series-fed microstrip array antennas. In future work, we plan to fabricate conventional and designed series-fed array antennas and verify the feasibility of the proposed method by comparing our designed antenna with the conventional antenna.

Acknowledgement

This research was supported by Basic Science Research Program through the National Research Foundation of Korea(NRF) funded by the Ministry of Education(2021R1I1A3044405).

Author Contributions

Conceptualization, D.-W. Seo; Methodology, J.-Y. Ha and D.-W. Seo; Software, J.-Y. Ha; Formal Analysis, J.-Y. Ha; Investigation, J.-Y. Ha; Resources, J.-Y. Ha; Data Curation J.-Y. Ha; Writing-Original Draft Preparation, J.-Y. Ha; Writing-Review & Editing, D.-W. Seo; Visualization, J.-Y. Ha; Supervision, D.-W. Seo; Project Administration, D.-W. Seo; Funding Acquisition, D.-W. Seo.

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