SERIES FEED FAN-BEAM ANTENNA ARRAY WITH A LOW SIDELOBE LEVEL FOR POSITIONING SYSTEM

Nguyen Thi Kim Ngan[1], Bui Thi Duyen[2], Tran Thi Lan[3], Le Minh Thuy[1*]

Abstract: *In this paper, a novel antenna array at 5GHz is presented with a low sidelobe level and wide impedance bandwidth for indoor positioning applications . The antenna array has the size of 450 ×57×0.8 mm^3 with the high gain of 14.5dBi and the low SLL of -18 dB at 5GHz. The series feed using Unequal Split T-Junction is proposed with the Chebyshev-amplitude distribution to improve SLL. Besides the 180^0 phase and amplitude distribution, by deploying driven elements above each single antenna element, the radiation pattern and the gain of the antenna aray are significantly improved.*

Keywords: Microstrip Antenna Array; Low Sidelobe Level (SLL); Chebyshev Distribution; Printed Yagi-Antenna.

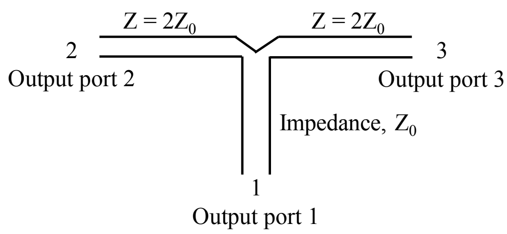
1. INTRODUCTION

Printed antennas are widely used in telecommunications systems such as indoor and outdoor wireless LANs, RF positioning andmicrowave radar systems due to low cost, light weight, great reproducibility and the capability of integration with other microwave circuits. In position applications, high gain antennas are necessary to increase the transmitting and receiving distance. In general, the high gain can be achieved by combining antenna elements into an array. An important application that can take the advantage of phased arrays is automotive collision avoidance radar or adaptive cruise control technology [1]. However, combining antenna elements in an array leads to a large size and the high SLL that are main disadvantages of array antennas. The SLL is defined for telecommunication systems by international standards and recommendations [2]. The high SLL in the array may be caused by: mutual coupling between radiating elements, surface wave and parasitic radiation from the feeding network [3, 4]. Thus, solutions to reduce the SLL for antenna arrays is one challenge. Several techniques to reduce the SLL of the array have been investigated and proposed in [2], which has given some methods to reduce the SLL in microstrip array to handle the excitations for each single element in the array in such a way that the amplitude decreases gradually from the center to the end of two sides in an array. Binomial, Chebyshev and Taylor distributions have been commonly applied in power excitation of the elements to get low SLL. Contemporaneously, there are two common types of feeding network for array: parallel feed and series feed. In contrast to the parallel feed, the series feed, which is designed by shorter transmission line, leads to array antenna with smaller size, lower attenuation loss and spurious radiation from the feed lines. Recently, several works have been done to suppress the SLL in the printed array antennas [3-9]. In the papers [3, 5], low SLL of microstrip antennas has been studied and managed by using Chebyshev excitation amplitude theory, a SLL of -26 dB (with preset SLL of 30 dB) but the gain is only 17.5 dBi at 5.5 GHz. Using the differential evolution algorithm (DEA), low SLL series-fed microstrip antenna arrays of unequal inter-element spacing (IES) was investigated in [6], the SLL of -25.3 dB with the peak gain of 14.5 dBi. New excitation amplitudes based on Gaussian distribution was used to improve the radiation characteristics of millimeter-wave patch array antenna operating at 30 GHz in [7, 8]. Nevertheless, the fabrication could be complicated. In addition, the authors in [9] have proposed a low SLL and wideband series fed dielectric resonators antenna (DRA) array. This proposal had a very low SLL of -30 dB and high gain of 19 dBi. However, the large number of antenna elements up to 22 results in a large size and complex design. Other works related to the reduction of SLL and fan beam were also presented in [10-12]. The proposed fan beam 1antenna array in [10, 12] used 4 elements. Antenna in [10] had 33^0 of beamdidth in horizonal and 65^0 in vertical at 9.32 GHz but the peak gain was not presented and the patch antenna element gave low efficiency. In [11], the proposed array of 10 yagi-antennas with the dimension of 22×100×10.15 mm^3 using Duroid 5880T was presented with the peak gain of 14.2 dBi, this peak gain was incread to 17.5 dBi using reflector but the antenna element size is quite large.

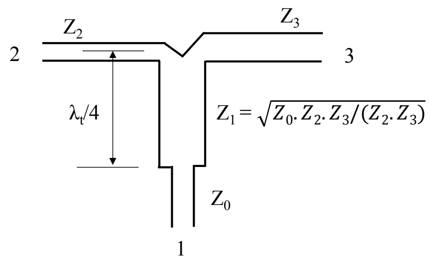
In this paper, a high gain, low SLL microstrip linear antenna array with a simple series feed network is presented. The design procedure from a feeding network, and a single element to a complete array is demonstrated. The array consists of 10 single elements, which are printed Yagi antennas. The low SLL is obtained by designing the series feed network with the output power amplitudes corresponding to the Chebyshev coefficients with the preset SLL of -20 dB. As can be seen from the simulation results, the antenna operates well at 5 GHz with the SLL of -18 dB and the peak gain of 14.5 dBi.

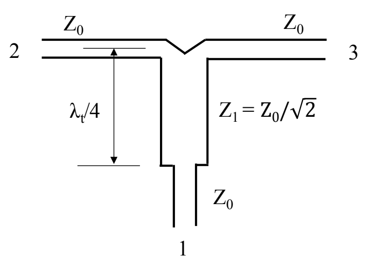
2. FEEDING NETWORK DESIGN

2.1. Theory of T-junction Power Divider



a) Basic T-junction





b) Quater-wave-match T-junction *c) Unequal-split-T-junction*

***Figure 1.** The structure of T-junctions.*

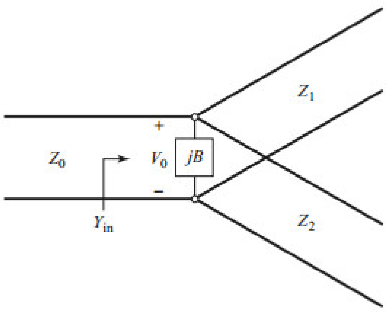
The series feed network is designed to feed 10 antenna elements of the proposed antenna array. The Chebyshev distribution with the preset SLL of -20 dB is utilized as the output coefficients's target. In order to obtain the Chebyshev distribution in the series feed network, the theory of T-junction power divider is used. The T-junction power divider is a simple three-port network for power division or power combining, and it can be implemented in any type of transmission line medium [13]. There are two types of T-junctions: quater-wave-match T-junction and unequal-split T-junction. The relationship between the input and output impedances of the T-junctions are shown in figure 1.

The lossless T-junction dividers can be modeled as a junction of three transmission lines, which shown as figure 2 (a). In general, there may be fringing fields and higher order modes associated with the discontinuity at such a junction, which leads to stored energy. That can be accounted for by a lumped susceptance B. The T-junction divider is matched to the input line of characteristic impedance Z_0 when Equation (1) is satisfied.

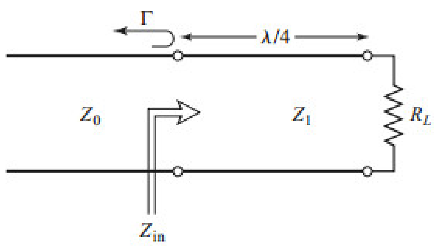
$$Y_{in} = jB + \frac{1}{Z_1} + \frac{1}{Z_2} = \frac{1}{Z_0} \tag{1}$$

If the transmission lines are assumed to be lossless (or low loss), the characteristic impedances are real. Then, if B = 0, equation (1) is simplified as Equation (2).

$$\frac{1}{Z_1} + \frac{1}{Z_2} = \frac{1}{Z_0} \tag{2}$$



(a)



(b)

Figure 2. *(a) Transmission line model of a lossless T-junction divider (b) The quarter-wave matching transformer.*

The output line impedances Z_1 and Z_2 can be selected to provide various power division ratios. The quarter-wave transformers can be used to bring the output line impedances back to the desired levels. If the output lines are matched, the input line will be matched. figure 2 (b) illustrates a quarter-wave transformer. The load resistance R_L and the feed line characteristic impedance Z_0 are both real and assumed to be known. These two components are have the characteristic impedance Z_1 and length $\lambda/4$. It is desired to match the load to the Z_0 line using the $\lambda/4$ line. From [13], the input impedance Z_{in} can be found as equation (3):

$$Z_{in} = Z_1\left(\frac{R_L + jZ_1 \tan\beta l}{Z_1 + jR_L \tan\beta l}\right) \quad (3)$$

If $l = \lambda/4$ then $\beta l = (2\pi/\lambda)(\lambda/4) = \pi/2$, which leads to:

$$Z_{in} = \frac{(Z_1)^2}{R_L} \quad (4)$$

Let г reaches the minimum value, then $Z_{in} = Z_0$ and :

$$Z_1 = \sqrt{Z_0 Z_L} \quad (5)$$

So a quarter-wave-matched-T Junction with Z_0 = 50 ohm input impedance and two equal output ports of Z_0 = 50 ohm, the impedance of the quarter-wave-transformer is determined by equation (6):

$$Z_1 = Z_0/\sqrt{2} \quad (6)$$

2.2. Feeding Network Design

In this paper, the Chebyshev distribution is applied to calculate the output power amplitude for each element in the array [2]. The 1-10 feeding network consists of a main line fed by the 50 Ω line at the center, unequal T-junctions to control the output power amplitude excited at each the element and quarter-wave–transformers to be matched with antenna element impedance. The Chebyshev output power amplitudes for 10 antenna elements are calculated and listed in the table 1. The feeding model at one side is shown in figure 3.

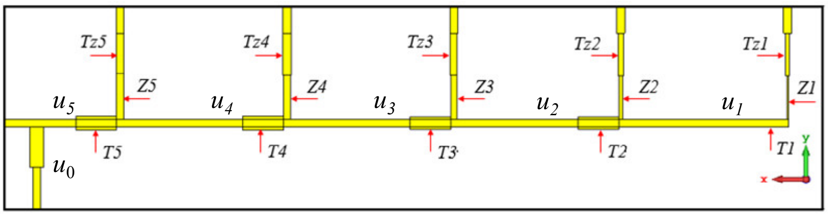


Figure 3. *Feeding network model at one side with unequal T-junctions.*

The impedances of the unequal T-junctions (Z_1, Z_2,... Z_{10}) and the impedances of the quater-wave transformers at figure 3 are determized by $Z_5/Z_0 = u_5/u_0 = 1$, $Z_4/Z_0 = u_4/u_0 = 0.931$, $Z_3/Z_0 = u_3/u_0 = 0.8024$, $Z_2/Z_0 = u_2/u_0 = 0.6311$, $Z_1/Z_0 = u_1/u_0 = 0.4392$. After caculating the impedances of the unequal T-junctions, the impedances of quater-wave T-junctions ($T_1, T_2 ... T_{10}$, $T_{z1}, T_{z2}, ... T_{z10}$) are also determined and are shown in table 2 and table 3, respectively:

Table 1. *Chebyshev amplitude distribution for 10 antenna elements (SLL = -20dB).*

Element	Amplitude (V)	Amplitude (dB)
u_1 & u_{10}	0.4392	-7.9424
u_2 & u_9	0.6311	-5.6570
u_3 & u_8	0.8024	-3.8873
u_4 & u_7	0.9310	-2.5171
u_5 & u_6	1	0

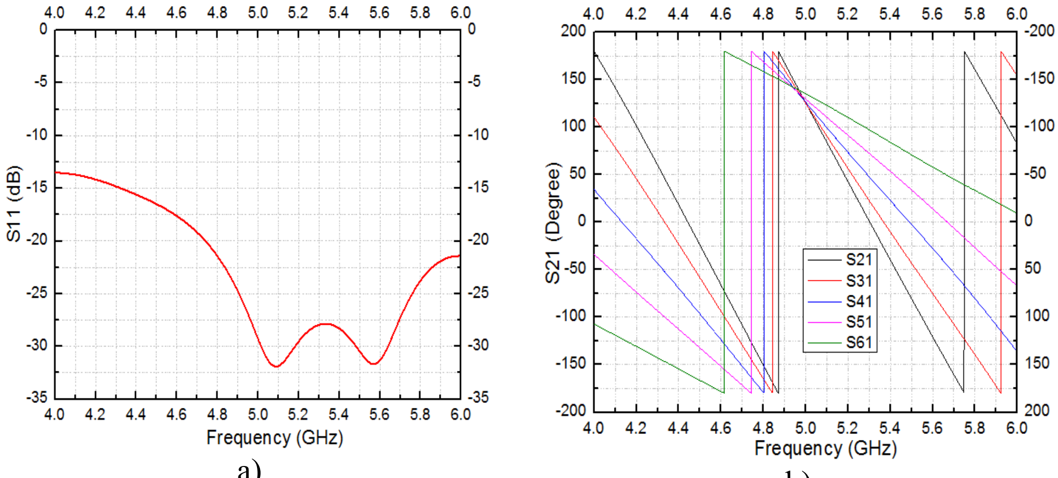
Table 2. *Impedance and dimension of T-Junctions.*

Feed element	Amplitude (V)	Impedance (Ω)	Value of width (mm)
Z_1 & Z_{10}	0.4392	113.84	0.28
Z_2 & Z_9	0.6311	79.227	0.75
Z_3 & Z_8	0.8024	62.313	1.2
Z_4 & Z_7	0.9311	53.706	1.58
Z_5 & Z_6	1	50	1.75

Table 3. *Dimension of the quarter-wave –transformers.*

Transformer	Value of width (mm)	Transformer	Value of width (mm)
T_1	2.98	T_{z1}	1.75
T_2	2.924	T_{z2}	1.68
T_3	2.77	T_{z3}	1.48
T_4	2.58	T_{z4}	1.19
T_5	0.8343	T_{z5}	0.8343

The simulated reflection coefficient S_{11} of the proposed feeding network is illustrated in figure 4 (a), showing that the feeding network works well in a wide range from 4 GHz to 6 GHz and having a good impedance matching. The excited phases at then antenna elements are nearly the same as shown in figure 3 (b) and table 4. The excited ampllitude of antenna elements u_1&u_{10}, u_2&u_9, u_3&u_8, u_4&u_7, u_5&u_6 are from 0.4392 to 1 according to the Chebyshev distribution . The power at the element 1 and 10 are smaller than the power at element 5 and 6 up to 50%. It is clear that the simulated amplitude coeficients in figure 4 (a) meet well with the desired Chebyshev distribution with a small negligible difference, but the signal is greatly attenuated due to the use of T-Junctions and quater-wave transformer. There may be fringing fields and higher order modes associated with the discontinuity at such a junction, which leads to the attenuated energy.



a) b)

Figure 4. *(a)Reflection coefficient of the feeding network*
(b) Phases of elements in the feeding network.

3. THE PROPOSED ARRAY ANTENNA

3.1. Printed Yagi Antenna Element

The printed Yagi antenna originated from the Yagi-Uda antenna by Huang in 1991 [14] is chosen in this paper. Its structure consists of a folded half-wavelength dipole and an approximately quater-wavelength rectangular director to improve the gain and the front-to-back ratio. Besides, it is low profile, low-cost and has light weight, small size. These advantages make it suitable to be integrated into circuits as well as to be easily fabricated. Many contributions have been done in the design and optimization of the printed Yagi-antenna for specific applications [15-17]. In [13], the Invasive Weed Optimization (IWO) method is applied to design and optimize a printed Yagi antenna, the optimization goals are set to reach an antenna with a VSWR less than 1.5 and high gain radiation pattern. PSO (Particle swarm optimization) has been used to optimize gain, impedance and bandwidth of Yagi–Uda array in [16]. In our proposal, two directors are used to increase the directivity. Moreover, the Yagi antenna element is miniaturized by bending its arms as shown in figure 5 (a).

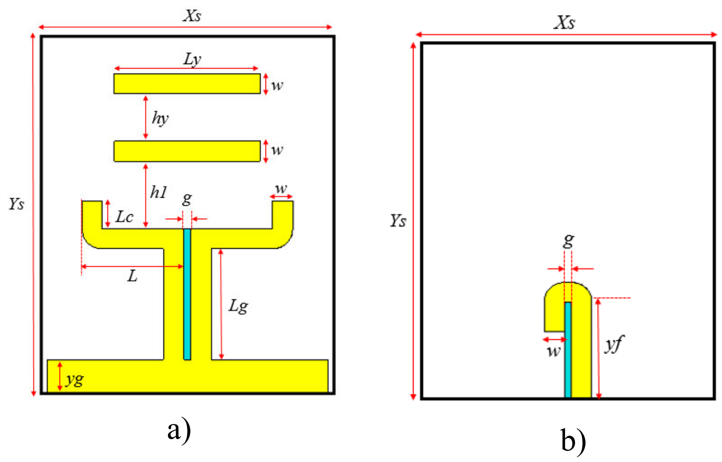
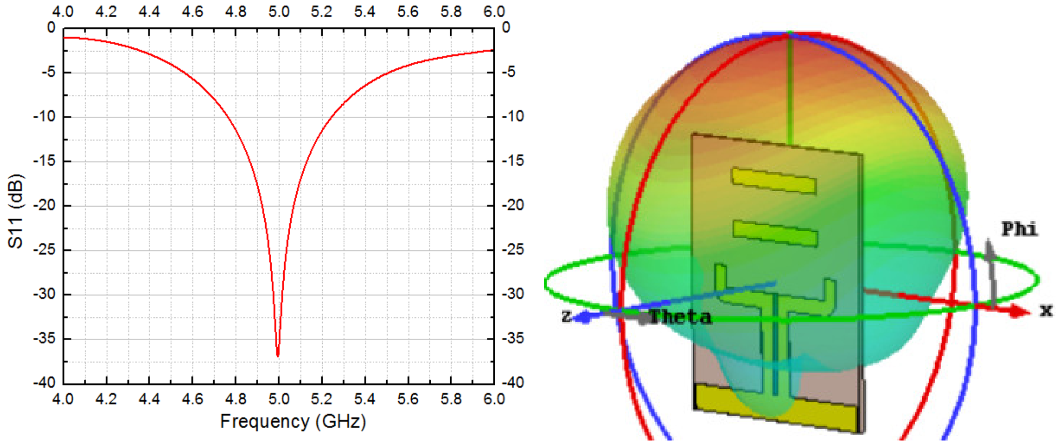


Figure 5. *The proposed Yagi antenna (a) Top layer (b) Bottom layer (L_g = 12, y_g = 3.5; L_c = 5, L = 16.8, h_y = 7, L_y = 15, w = 2.1, g = 0.7, h_1 = 7, y_f = 10, X_s = 30, Y_s = 37).*

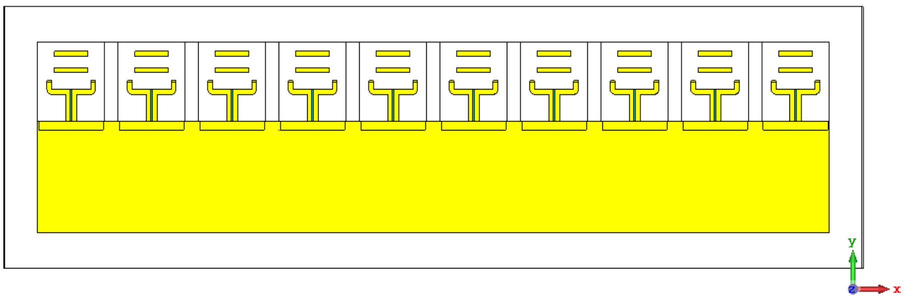
Two element directors are added above the arms of the Yagi antenna element. The distance between two directors and their length are optimized based on PSO algorithm in [16]. The distances h_y between directors should be 0.1λ and 0.45λ, and the length L_y of each element varies between 0.15λ and 0.35λ to increase the gain while the input impedance of the antenna and banwidth maintain good. The J-shaped balun in figure 5 (b) based on Robert's research [18] is applied to overcome weak impedance matching of the I-shaped balun. The Yagi antenna element works by coupling from the J-shaped balun to its two arms. The proposed Yagi antenna element is printed on a Rogers 4003C substrate with the relative permittivity of 3.55 and the thickness of 0.8 mm. The total size of each element antenna is 30×37×0.8 mm^3. The reflection coefficient S11 is -37 dB at 5 GHz as shown in figure 6 (a). The peak gain of 7.6 dBi is obtained as shown in figure 6 (b) while the radiation efficiency is very high up to 96.2 %. The antenna gain of an array can be increased if the element antenna gain is increased. This Yagi antenna gain can be increased up to 9.5 dBi by just adding more the directors while the beamwidth is smaller and the antenna size in y direction will be increared. The suitable beamwidth and peak gain must be determined according to the antenna array application requirement.



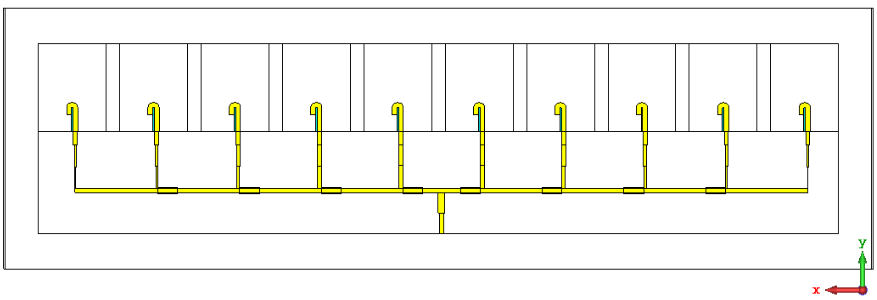
(a) *(b)*

Figure 6. *The Yagi antenna element: (a) Reflection coefficient (b) 3D pattern.*

3.2. The proposed array antenna



(a) Top layer



(b) Bottom layer

Figure 7. *The proposed array antenna model.*

The array structure is created by combining 10 single elements and 1-10 series feed network designed in the previous sections as shown in figure 7. The distance between the elements in the antenna array is λ, and the overall size of 450×57×0.8 mm^3.

Table 4. *Phase and amplitude excitation of the proposed array.*

Element	Phase (degree)	Amplitude (dB)
u_1 & u_{10}	126	-16
u_2 & u_9	125.5	-14
u_3 & u_8	126	-13
u_4 & u_7	130	-9
u_5 & u_6	135	-6

The simulated reflection coefficient of the proposed array antenna is shown in figure 8, where the wide bandwidth of 27.7 % can be seen. From the results in figure 9, the fan beam, high gain of 14.5 dBi and the low sidelobe levels of -18 dB are obtained. Moreover, the radiation efficiency is high up to 90% at 5GHz. Thus, the proposed antenna is suitable for outdoor positioning application systems.

The results in this work have been compared with the related works from the literatures as shown in table 5. The proposed antenna is more compact than the antenna in [3] and [11]. However, the gain is a little lower but the peak gain of array can be enhanced up to 4 dB using the reflector as the work in [3] and [11] mentioned and it will be higher than the work in [3] and [11] in the case using reflector. Besides, the radiation pattern of array antenan can be changed by adding directors in the dipole-yagi element according to the antenna element design. However, for positioning system, the wide angle in horizontal from 120^0 to 150^0 is required so that the proposed antenna is determined with two directors in antenna element.

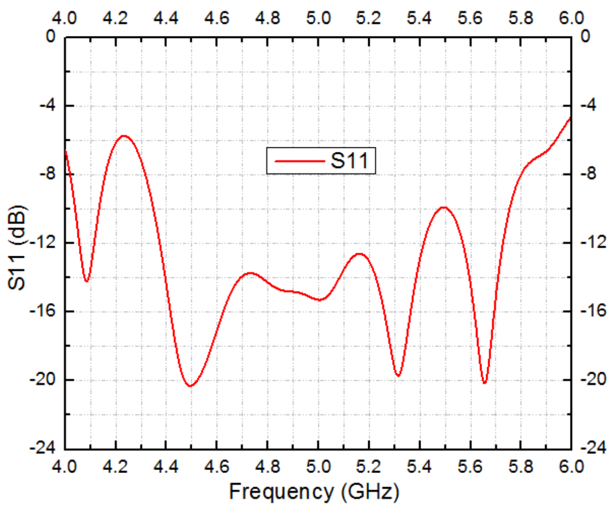
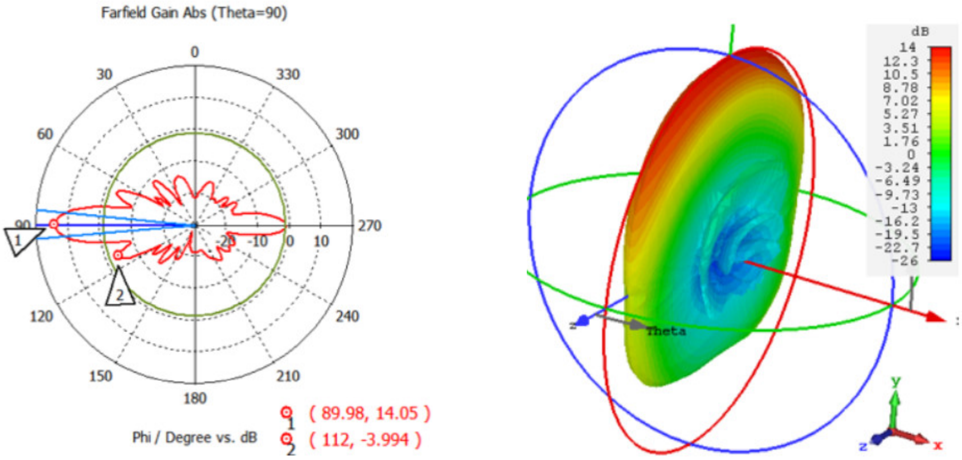


Figure 8. *Reflection coefficient of the array antenna.*



a) b)

Figure 9. *The simulation of array antenna (a) 2D radiation pattern (b) 3D radiation pattern.*

Table 5. *Comparison between the proposed antenna array and related works.*

References	**[3]**	**[6]**	**[5]**	**[11]**	**This work**
Element No	10×1	10×1	10×1	10×	10×1
Size (mm^3)	422×100×10.15	-	-	420x100x10.4	450×57×0.8
Frequency (GHz)	5.5	9	60	5.5	5
Gain (dBi)	17.5	14.5	15.7	14.2 (without reflector) 17.5 (with reflector)	14.5
Results of SLL (dB)	-26	-25.3	-27.7	-26	-18
Preset of SLL	-30	-	-30	-30	-20

4. CONCLUSION

In this paper, a novel high gain and low sidelobe level linear microstrip antenna array for positining outdoor system application have been proposed. The design procedure from the single element to the complete array antenna has been presented in details. In order to get the low SLL, the Chebyshev distribution has been used in the feeding network of the array antenna. The Chebyshev excitation coefficients have been obtained in the feed using unequal T-junctions and quater-wave transformers to get good impedance matching. The simulated results proved that the array can operate at 5 GHz with the high gain of 14.5 dBi and the low SLL of -18 dB.

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TÓM TẮT

ĂNG TEN MẢNG TUYẾN TÍNH TIẾP ĐIỆN NỐI TIẾP BÚP SÓNG DẢI QUẠT VỚI MỨC BÚP PHỤ THẤP CHO HỆ THỐNG ĐỊNH VỊ

Bài báo này đề xuất một mảng ăng ten mới hoạt động ở dải tần 5 GHz với búp sóng phụ thấp phù hợp cho các ứng dụng định vị ngoài trời. Mảng ăng ten có kích thước nhỏ gọn 450 ×57×0.8 mm^3 gồm 10 phần tử, độ tăng ích 14.5 dBi và độ nén búp phụ thấp -18 dB tại tần số 5 GHz. Ăng-ten sử dụng mạng tiếp điện 1-10 kiểu nối tiếp, phân bố biên độ ở các đầu ra tuân theo luật phân phối Chebyshev để đạt độ nén búp sóng phụ thấp. Các ăng ten chấn tử Yagi kiểu mạch in được sử dụng để tăng tính định hướng cho ăng ten mảng. Ngoài ra, độ tăng ích của ăng ten phần tử có thể được tăng bằng việc ghép thêm phần tử dẫn sóng định hướng phía trên các ăng-ten chấn tử.

Từ khóa: Mảng ăng-ten vi dải; Độ nén búp sóng phụ thấp; Đa thức Chebyshev; Ăng-ten Yagi vi dải.

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