A Novel Chebyshev Series Fed Linear Array with High Gain and Low Sidelobe Level for WLAN Outdoor Systems

Tang The Toan [1], Nguyen Minh Tran [2], and Truong Vu Bang Giang [3]

[1] University of Hai Duong, Haiduong, 170000, Vietnam
toantang@uhd.edu.vn

[2] Sungkyunkwan University, Suwon, 16418, KOREA
minhtran.uet@gmail.com

[3] Vietnam National University, Hanoi, 100000, Vietnam
giangtvb@vnu.edu.vn

Abstract **─** In this paper, we propose a novel linear microstrip array antenna with high gain and low sidelobe level (SLL) for outdoor WLAN applications. The array antenna includes of two main parts: a linear array and a reflector. Specifically, the array is linearly constructed with 10 elements; those are placed on Rogers RT/Duroid 5870tm substrate with the dimensions of 422×100×10.15 mm^3. Furthermore, to acquire the SLL reduction, a series fed network is designed to have the output signals being proportional to the Chebyshev distributions (with the preset SLL of -30 dB). On the optimization of the single element, Yagi antenna theory is applied by adding two directors above each element to increase its directivity. Additionally, we put a reflector at the back side of the proposed array. Simulation results indicate that the array operates well at 5.5 GHz with the high gain of 17.5 dBi and a low SLL of -26 dB. A prototype has been fabricated and measured to validate the simulation results. Good agreement between simulation and measurement data have been obtained. This proves that the presented array antenna can be a good candidate for WLAN applications.

Index Terms **─** Fan-beam, linear array, low sidelobe.

I. INTRODUCTION

Printed antenna arrays are usually used in telecommunication systems such as point to point and point to multipoint, in radar microwave, and millimeter systems. However, combining antenna elements in an array may lead to larger in size and the side lobe level (SLL) will be high, which is the main drawback of such kind of antenna. The high SLL in the array may be caused by: tolerances in fabrication, mutual coupling between radiating elements, limitations in feasibility of feeding network realization, surface wave effect as well as parasitic radiation from a feeding network.

Several techniques to reduce the SLL of the array have been investigated and proposed in the literature [1-3]. In the digital beamforming (smart antennas) or radar systems, Binomial, Chebyshev and Taylor distributions have been commonly applied in power excitation of the array to get low SLL. In the ordinary arrays, the same thing can be achieved by designing the feeding network which has output power corresponding to these distributions. Among several types of array feeding structures, there are two common types of feeding network for the array: corporate fed and series fed. The discontinuities, bends and power dividers in the corporate fed array may cause spurious radiation that raises the SLL to high levels, especially in large arrays. In some cases, a single high-directive element is used to avoid the spurious effect of the feeding network [4, 5]. In opposite with the corporate one, the series fed, which employs shorter and fewer transmission lines, leads to an array antenna with smaller size, lower attenuation loss and spurious radiation from the feed lines.

Recently, several attempts have been done to suppress the SLL in the printed array antennas [6-16]. A novel aperture coupled microstrip antenna array has been proposed in [8]. The antenna consists of a total 100 microstrip elements that are arranged in two rows of 50 elements, with element spacing of 0.51 free-space wavelength. A SLL of -20.9 dB has been obtained. However, due to using a large number of elements, the size of the whole array is considerably large while the SLL is not low. In [13], Saputra et al. have introduced a sidelobe suppression method for X-band antenna array by designing a novel feeding network with Chebyshev distribution. The array operates at 9.3 GHz and can give -19.4 dB SLL. As the complexity of the feeding network and the limited number of elements, the gain is only 12.3 dBi and the SLL is still high. Another 6 elements array antenna with linear series fed has been presented in [12]. A wideband of 6.5 % has been obtained, but the SLL

Submitted On: November 6, 2017
Accepted On: April 6, 2019

and the gain acquired are still not good, which are -20 dB and 14.2 dBi, respectively. Lower SLLs have been tackled and obtained in [9, 14]. By using the optimized distribution coefficients through differential evolution algorithm, a wideband and lower SLL have been achieved in slot antenna with series fed network in [9]. The antenna includes of 10 elements which are arranged in a series feeding network. The SLL and half power beam-width (HPBW) are -25.3 dB and 8.4^0, respectively. However, the gain achieved is only 14.5 dBi. In addition, the authors in [14] have proposed a low SLL and wideband series fed dielectric resonator antenna (DRA) array. The proposal can get a very low SLL of -30 dB and high gain of 19 dBi. Nevertheless, the large number of elements (up to 22 dielectric resonators have been used) result in a large size. Besides, the fabrication could be complicated as complex design techniques have been used. Similarly, two other DRA arrays have been introduced in [11, 16]. The array [16] works at 60 GHz, while the counterpart operates at 7.4 GHz. The SLL are -27.7 dB and -23 dB, respectively. Bayderkhani and Hassani have presented two linear series fed Yagi-like array samples in [10, 15]. The arrays have 22 similar Yagi line elements, which can provide the gain of 15.3 dBi and the SLL of about -27 dB. In spite of using a huge number of single elements and the Chebyshev distribution with the SLL preset to -35 dB, the gain and the SLL is not noticeably good. Hassani and his other colleagues have continuously proposed two other low SLL arrays [6, 7]. The sample in [7] has the SLL of 20 dB, while the lower SLL (-33.2 dB) has been obtained in [6]. However, the gain in [7] is remarkably high with 18.2 dB compared to just -15.9 dBi in [6].

In this paper, a high gain, low SLL, microstrip linear antenna array will be introduced. The design procedure from single element, feeding network and the complete array will be specifically demonstrated. The array consists of 10 single elements, which are double-sided printed dipoles (DSPD). The low SLL is obtained by designing the series fed network with the output power corresponding to the Chebyshev coefficients (preset SLL of -30 dB). As can be seen from the simulation results, the antenna operates well at 5.5 GHz with the bandwidth of 212 MHz. Moreover, a high gain of 17.5 dBi has also been acquired, while the SLL is low at -26 dB. Fabrication and measurement have been done, and simulated results have been validated with the corresponding measured data. Good agreements between simulation and measurement have been shown.

II. ANTENNA DESIGN AND STRUCTURE

A. Design of the single element

To build an array, a single element should be first selected and designed. In this work, to guarantee the requirements in both size and performance, DSPD has been used as the single element of the array. In authors' previous work [17], we have presented and analyzed this kind of antenna in details. Figure 1 gives the proposed DSDP used as single elements in the array construction. The length of the feed line and the patch can be given by approximately a quarter of the wavelength ($\lambda_g/4 = c/4f_0\sqrt{\varepsilon_r}$). The width of the patch can be calculated by equation (1):

$$Z_a \approx 90\frac{\varepsilon_r^2}{\varepsilon_r-1}\left(\frac{L}{W}\right)^2, \quad (1)$$

where, $Z_a = \frac{Z_0^2}{Z_{in}}, Z_{in} = 50\ \Omega$

$$Z_{0(\text{parallelstrip})} = 2Z_{0(microstrip)}\left(h = \frac{d}{2}\right).$$

In this paper, the DSDP is placed on the Roger RT/Duroid 5870tm (thickness of 1.575 mm and ε_r = 2.33), and has been adjusted to work at 5.5 GHz with the impedance Z_d = 100Ω at the center frequency. The final dimensions of the single element are given in Table 1.

The simulated S_{11} and radiation pattern of the DSDP are shown in Fig. 2 and Fig. 3, respectively. It is clear that the DSDP can work well at 5.5 GHz with the gain of 5.27 dBi. This DSDP will be used as the single element of the array in this work.

Table 1: The parameters of the single element

Parameters	Value (mm)	Parameters	Value (mm)
W_{e1}	0.8	L_{e1}	8.5
W_{e2}	9.1	L_{e2}	6.0
W_{e3}	10.0	a	2.5

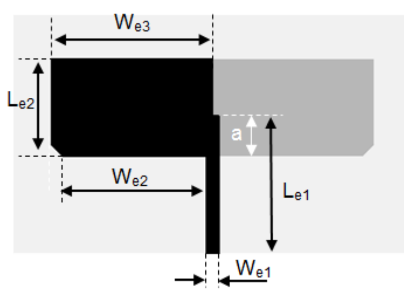


Fig. 1. The proposed single element.

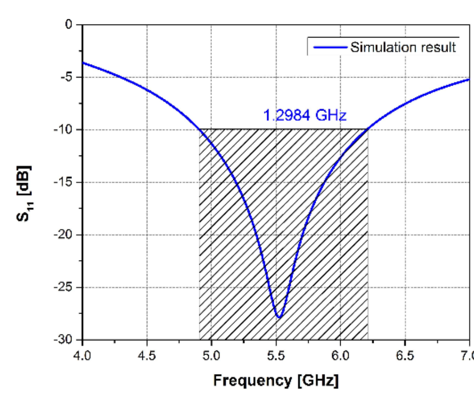


Fig. 2. Simulated S_{11} of the DSPD.

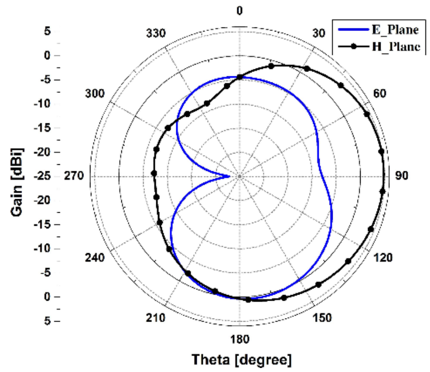


Fig. 3. Radiation pattern of the DSPD.

B. Design of the feeding network

This section will present the procedure to design the feeding network using in the array. The series fed network for the linear array is designed to match with the single element in the previous section to form a 10×1 array antenna. The Chebyshev distribution with preset SLL of -30 dB has been utilized as the output coefficients' target. In order to obtain the Chebyshev distribution in the series fed network, different shunt stubs have been added to the feed line so that the amount of signal flowing out each output port can be easily controlled. The operation and the equivalent circuit of the stub in the antenna are given in the Fig. 4. According to [18], the equivalent shunt capacitor of shunt stub can be calculated by:

$$Y_{in} = \mathrm{j}Y_c \tan\left(\frac{2\pi}{\lambda_g} l\right) \approx jY_c\left(\frac{2\pi}{\lambda_g} l\right) = j\omega\left(\frac{Y_c l}{v_p}\right), \qquad (2)$$

where Y_c is the equivalent admittance of the stub, l is the length of the stub v_p is the phase velocity, λ_g is the wavelength in the substrate.

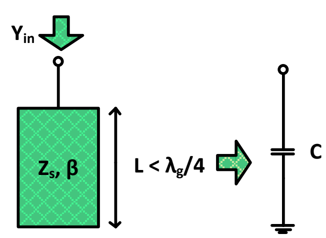
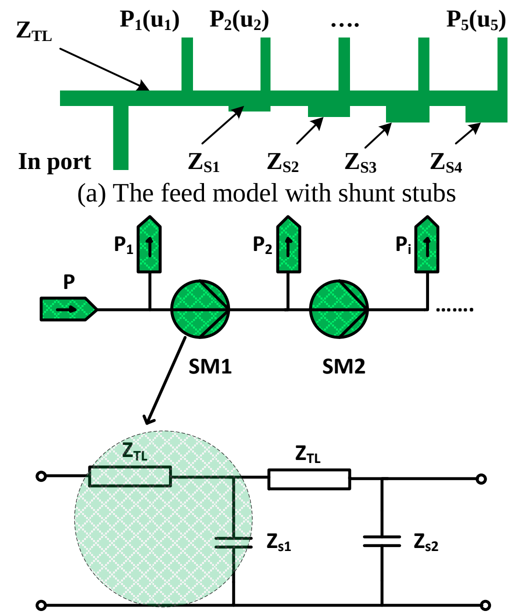


Fig. 4. The equivalent capacitor of shunt stub.

As the symmetrical properties of Chebyshev distribution, the proposed feeding network has a mirror like structure. Indeed, the feed has a main line which is fed by the 50Ω line at the center. To form the symmetrical geometry, the same feeding line and shunt stubs are equally distributed on each side of the central line. These stubs serve as shunt capacitors and play as impedance matching to control the output amplitude excited at each element. Due to the effect of shunt stubs in the impedance matching point, the S parameters at each port related to the input port will be easily handled. It means that the energy flowing out each output port can be controlled [19]. The feed model at one side and the equivalent circuit are shown Fig. 5.



(a) The feed model with shunt stubs

(b) The equivalent circuit

Fig. 5. The series fed network and its equivalent circuit.

In this work, the feeding network has been designed for 10×1 antenna array with the Chebyshev amplitudes corresponding to SLL of -30 dB. The Chebyshev amplitudes for 10 elements are given in the Table 2.

Table 2: Chebyshev amplitude weights for 10×1 linear array (SLL = -30 dB)

Element No.	u_1	u_2	u_3	u_4	u_5
Amplitude	1	0.8780	0.6692	0.43	0.2575
Characteristic Impedances	Z_{TL}	Z_{s1}	Z_{s2}	Z_{s3}	Z_{s4}
Element No.	u_6	u_7	u_8	u_8	u_{10}
Amplitude	1	0.8780	0.6692	0.43	0.2575
Characteristic Impedances	Z_{TL}	Z_{s5}	Z_{s6}	Z_{s6}	Z_{s8}

The impedance of the shunt stubs (Z_{s1}, Z_{s2} ,..., Z_{s4}) can be determined using theory given in [20] as follow: Z_{s1}/Z_{TL} = u_2/u_1 = 0.8780; Z_{s2}/Z_{TL} = u_3/u_1 = 0.6692; Z_{s3}/Z_{TL} = u_4/u_1 = 0.4300; Z_{s4}/Z_{TL} = u_5/u_1= 0.2575. For determining the value of impedances and the value of shunt stubs, the main line should be first selected. The different values of the main line have been simulated, and the results are given in Fig. 6. The wider bandwidth has been achieved with the main line impedance of 178Ω. Hence, the main line has been designed with the impedance of 178Ω. Eventually, these values of Z_{si} have been calculated as given in Table 3.

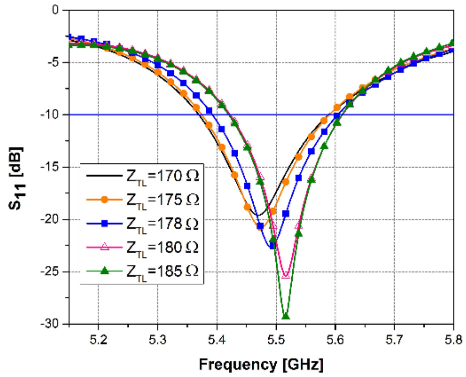


Fig. 6. The simulated reflection coefficient of different main line impedances.

Table 3: Characteristic impedances of the series fed network

Characteristic impedances	Z_{TL}	Z_{s1}	Z_{s2}	Z_{s3}	Z_{s4}
Value (Ω)	178	156.11	118.98	76.454	45.78
Characteristic impedances	Z_{TL}	Z_{s5}	Z_{s6}	Z_{s7}	Z_{s8}
Value (Ω)	178	156.11	118.98	76.454	45.78

Figure 7 shows the final series fed network of 10 elements designed on Roger RT/Duroid 5870tm substrate (the height of 1.575 mm and the permeability of 2.33) with the dimensions of 55×385×1.575 mm^3. Synthesized parameters of 10×1 series fed network is given in Table 4 [21].

Table 5 gives the simulated amplitude and phase data at each output port. It is clear that the simulated amplitude coefficients coincide with the Chebyshev distribution with small negligible differences. The normalized radiation pattern of simulated coefficients from the feed and the corresponding one from theory have been presented in Fig. 8. This series fed network can be combined with single elements to construct a linear antenna array which has the SLL suppressed to -27 dB.

Table 4: Synthesized parameters of 10×1 series fed network

Parameters	Value (mm)	Parameters	Value (mm)
d	38.8	w_{s4}	7.00
l_s	3.75	W_1	2.00
w_{s1}	1.14	W_2	0.80
w_{s2}	3.30	g	7.20
w_{s3}	5.13		

Table 5: The simulated amplitudes and phases of the series fed network

Element No.	u_{1-6}	u_{2-7}	u_{3-8}	u_{4-9}	u_{5-10}
Amplitude	1.0000	0.9238	0.6726	0.4150	0.1863
Phase	-50.48^0	-53.67^0	-53.10^0	-55.75^0	-51.12^0

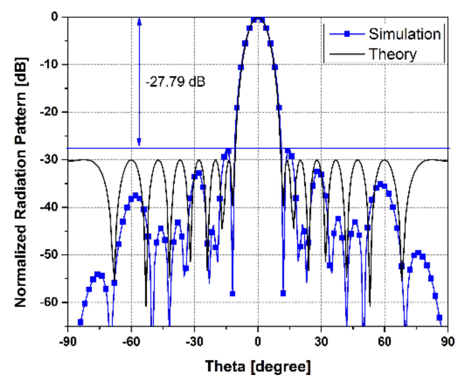


Fig. 8. Normalized radiation patterns with respect to the output power coefficient (solid line) and theoretical one (dotted line) [21].

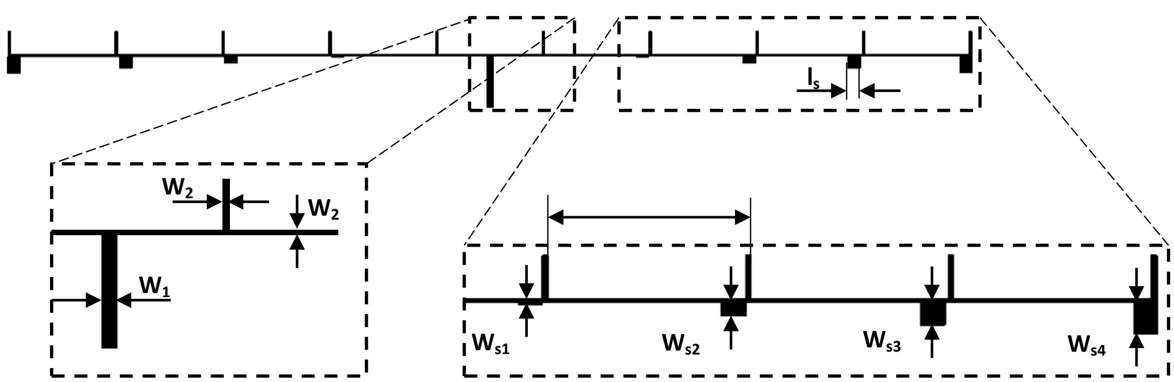


Fig. 7. 10×1 series fed network [14].

C. Design of the array

The array structure is obtained by combining optimized single elements and the series fed network developed in the previous sections.

So as to increase the gain, two techniques are being applied in the design of the array. Firstly, as the inspiration of Yagi theory, directors are being added into the elements of the array [20]. Hence, according to the theory given in [20] that the directors in Yagi antenna should be around 0.4λ to 0.48λ, each single element has been integrated with three directors, which have the same size of 2.5×15 mm ($0.42\lambda_g \times 0.07\lambda_g$), at both sides of the DSDP. The number of directors can be designed larger subject to the trade off between gain and dimensions required in the array. The simulated results of the gain and the SLL with respect to the sample with and without directors will be specifically presented and discussed. Secondly, a reflector is being placed at the back of the main array with the distance of $g \approx \lambda_g/4$ (as shown in Fig. 9 (c)) so as to boost up the gain of the whole array. The overall size of the proposed array is 422×100×10.15 mm^3 as given in Fig. 9.

The optimized array has been fabricated and measured in the laboratory as shown in the Fig. 10. In Section 3, the detailed results will be compared and discussed.

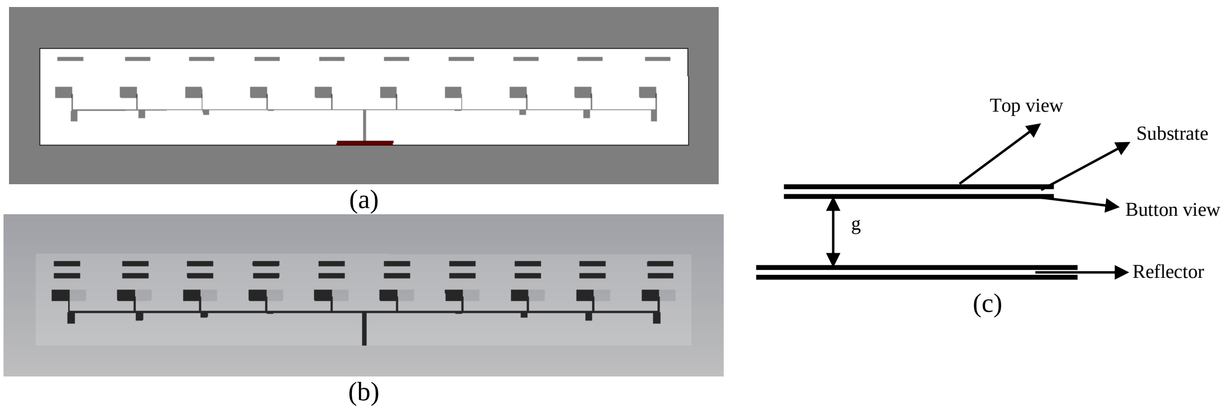


Fig. 9. Structure of the proposed array: (a) top view, (b) button view, and (c) side view.

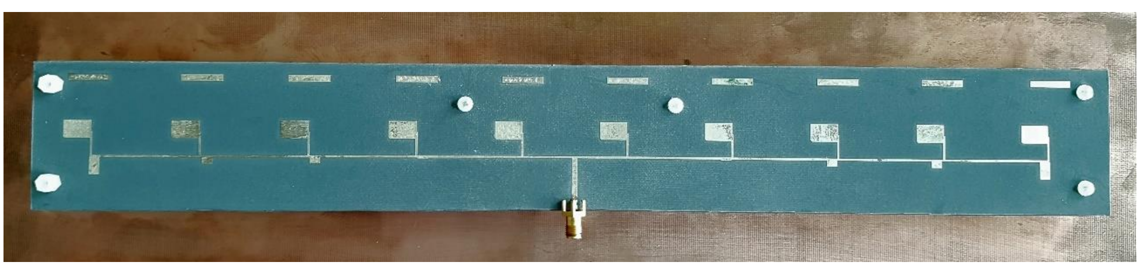


Fig. 10. Fabricated antenna array.

III. RESULTS AND DISCUSSION

A. Simulation results

In this work, the element and array are simulated using the CST Studio Suite 2016 in the notebook computer with the configuration as given in Table 6. The total time required to completely run the simulation in this computer is nearly 10 minutes.

Figure 11 shows the simulated S_{11} of the array. The proposed antenna operates at 5.5 GHz with the bandwidth of 212 MHz at -10 dB of S_{11}. Though the single element can provide wide bandwidth (about 1.3 GHz bandwidth), the constructed array antenna can just operate at a part of the full bandwidth of the applications. This may result from the effect of the feed or the mutual coupling between the elements when combined.

Table 6: Computer configuration

Brand Name	Lenovo - T440S
Max Screen Resolution	1600 x 900 pixels
Processor	2.1 GHz Intel Core i7
RAM	8 GB DDR3L SDRAM
Memory Speed	1600 MHz
Hard Drive	256 GB Serial ATA-600
Graphics Coprocessor	Intel HD Graphics 4400
Operating System	Windows 10

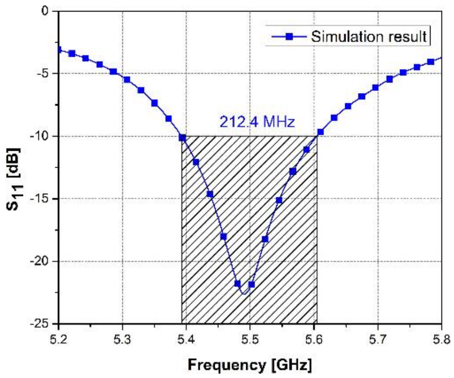


Fig. 11. Simulated S_{11} of the array [15].

The radiation pattern, gain and SLL over the operating frequency have also been demonstrated in Figs. 11 and 12. As can be seen from Fig. 12, a narrow HPBW of 10.4^0 is acquired over 5.4 GHz - 5.65 GHz band.

The stable gain at about 17 dBi, and the SLL, which is lower than -20 dB, are obtained over the bandwidth as given in Fig. 13. At 5.5 GHz, the gain of 17.5 dBi and low SLL of -26.0 dB have been acquired. In comparison with those from theory and the feeding in [21], the SLL of the array in this paper is 1.79 dB higher (see Fig. 8). It proves the capability of applying the series fed network to simultaneously obtain high gain and low SLL arrays.

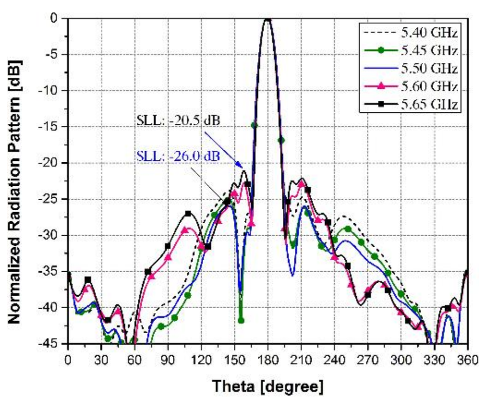


Fig. 12. The radiation pattern over different frequencies.

It is noticable that the SLL and gain in the case with added directors are better compared to that of the array without directors. Therefore, the benefits of high gain in Yagi antenna has been successfully leveraged and employed in this proposal, and approximate 1 dB gain higher is achieved by using 3 additional directors.

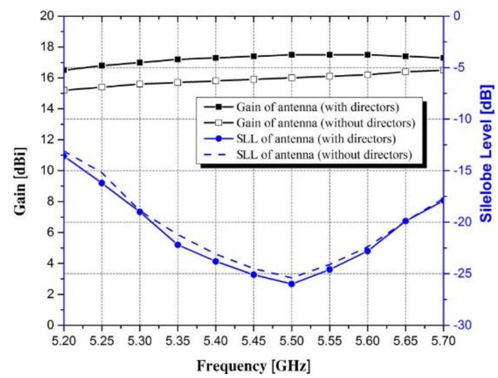


Fig. 13. The gain and SLL over the operating bandwidth.

The gain over operating frequency band of the sample with and without the reflector is shown in Fig. 14. The array with the reflector definitely has higher gain (about 3 dB) compared to the one having no reflector. Hence, the use of the reflector has a great advantage in terms of gain enhancing.

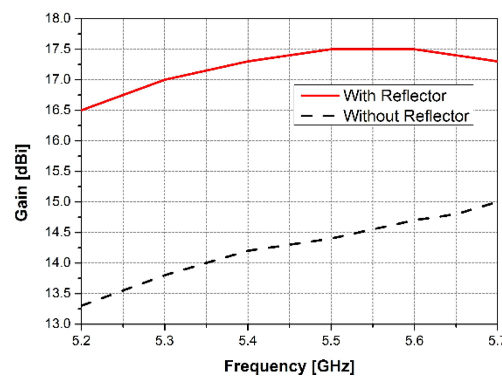


Fig. 14. Comparison of gain between the array with and without reflector.

B. Experimental results

The measurement of the prototype has been done and the measured data has been compared to that of the simulation.

Figure 15 shows the simulated and measured return loss of the antenna. It can be seen that the operating frequency of the antenna is 5.5 GHz with the bandwidth (at S_{11} = -10 dB) of 212 MHz.

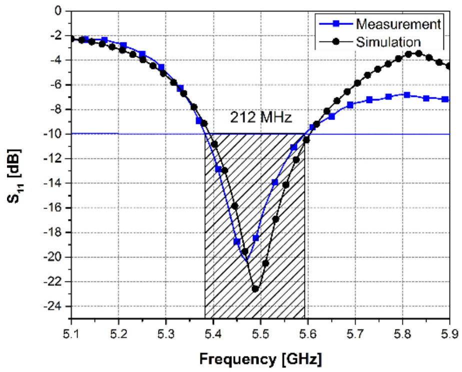
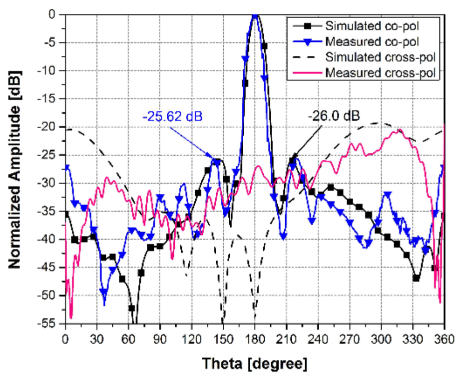
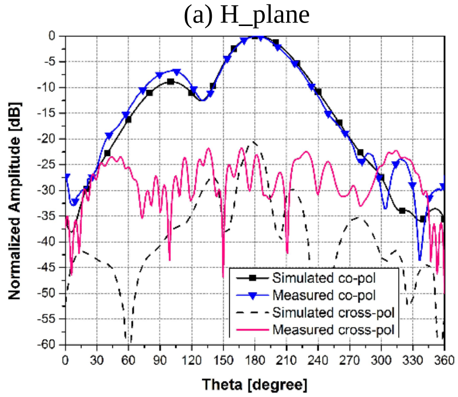


Fig. 15. The reflection coefficient of the array antenna.

The simulated and measured radiation patterns in E and H plane are also compared and presented in Fig. 16.



(a) H_plane



(b) E_plane

Fig. 16. Normalized radiation pattern of proposed array antenna at 5.5 GHz.

It is clear that simulated data have agreed well with measured ones. Indeed, the gain in simulation and measurement are 17.5 dBi and 17.1 dBi, respectively. Moreover, the low SLL in measurement has been also achieved with about -25.62 dBi compared to -26 dB from the simulation. The cross polarization in both simulation and measurement has also been given and they are both lower than -20 dB.

The results in this work have also been collated with the other works from the literature as shown in Table 7.

Table 7: The comparison between references and this work

References	[9]	[16]	[11]	[This Work]
Element no.	10×1	10×1	8×1	10×1
Size (λ)	6.01×1.1	---	---	7.7×1.83×0.19
Freq. (GHz)	9.0	60	7.54	5.5
Bandwidth (%)	1.3	36.1	31.9	3.9
Gain (dBi)	14.5	15.7	15.7	17.5
SLL (dB)	-25.3	-27.7	-23.1	-26.0
Cross-po. (dB)	-25.0	---	-30.0	-20.0

It can be seen that with the same number of elements, the proposed array has the gain of 17.5 dBi, which is higher than that of [9] with just 14.5 dBi and [16] with about 15.7 dBi. Moreover, the SLL in this work is 0.7 dBi lower than that in [9] but 1.7 dBi higher than that in [16]. In comparison with the work in [9], our array has better results in terms of both gain and SLL, but honestly the proposed array size is larger than that in [9] in term of wavelength.

IV. CONCLUSIONS

In this paper, a novel high gain and low sidelobe level linear microstrip antenna array for outdoor WLAN applications has been proposed**.** The design procedure from the single element to full array construction has been presented in details. In order to get low SLLs, Chebyshev weighting method has been deployed in the feeding network of the antenna. The Chebyshev excitation coefficients have been obtained in the feed by using the shunt stubs added at the feed line of each element. The simulated results show that the array can operate at 5.5 GHz with the bandwidth of 212 MHz and has a high gain of 17.5 dBi with the low SLL of about -26 dB. A prototype has also been fabricated and measured to validate the simulation results. It is clear from the comparison that simulated and measured data agree well with each other.

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Tang The Toan was born in 1976. He received his B.Sc. degree in Electronics and Physics, and M.Sc. degree in Electronics and Telecommunications from Hanoi National University of Education, Hanoi, VN, in 1998 and 2011, respectively. Currently, he is a Ph.D. student in the Faculty of Electronics and Telecommunications, University of Engineering and Technology, VNU.

His research interests are microstrip antennas design and analysis, electromagnetics and propagation, metamaterials.

Nguyen Minh Tran received the B.Sc. and M.Sc. in Electronics and Telecommunications Technology from the University of Engineering and Technology, VNU, Cau Giay, Hanoi, VN, in 2014 and 2016, respectively. He has served as a Research Assistant at the Laboratory of Modeling and Simulation. He is currently pursuing his Ph.D. degree in the Department of Electrical and Computer Engineering, School of Electronics and Communications Engineering, Sungkyunkwan University, Suwon, Korea.

His research interests include of microstrip antennas analysis and design, RF circuits, wireless power transfer.

Truong Vu Bang Giang received the B.S. and M.S. degree from the VNU-University of Sciences, in 1994 and 1997, respectively, and the Dr.-Ing. (Ph.D.) degree in Electrical Engineering from the Hamburg-Hamburg University of Technology, Hamburg, Germany, in collaboration with the Institute of Communications and Navigation, German Aerospace Center, in 2006.

He is now the Deputy Director of Science and Technology Department of Vietnam National University, Hanoi and as the Secretary of the National Research Program for Sustainable Development of North-West Region of Vietnam.

He is a Member of IEEE MTTs and APS. He has served as the Steering Committee (Co-Chair), Organizing Committee (Chair and Co-Chairs) or Technical Committee of ATC, REV-ECIT, VJMW, VJISAP conferences in Vietnam; Scientific and Technical Committee, International Transaction Journal of Engineering, Management, & Applied Sciences & Technologies (ITJEMAST).

His current research interests include Microstrip Antennas for Mobile and Handheld Devices; Analysis and Design of Conformal Antennas; Digital Beamforming and Beamsteering for Smart Antennas; Metamaterial Antennas; Design of RF Devices and Systems.