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Bandwidth Improvement of Center-Fed Series Antenna Array Targeting for Base Stations in Offshore 5G Communications

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ABSTRACT A 1 × 12 center-fed series antenna array, with a novel probe feeding structure to broaden the bandwidth, is designed for 5G base stations deployed in the land for offshore maritime communications. The improvement of the bandwidth is achieved through a combination of folding and replacing the center feed line to a lower layer away from patch radiators. By moving the center feed line to the lower layer beneath radiators, serious mutual-coupling and corresponding parasitic effect between the feed and radiators are reduced, facilitating better transmission and also resulting in better matching to the 50-Ω coaxial probe. Moreover, a vertically folded-U structure is proposed to be inserted in part of the feed line, to provide a section of a high impedance microstrip line and further broaden the impedance bandwidth. A simulation study is performed on the geometry of the center feed line to investigate how the antenna performance can be controlled. The antenna array design procedure is outlined and a prototype with over 20% bandwidth, which can fully cover the 4.8–4.99 GHz 5G spectrum band, is fabricated and measured for impedance matching, radiation pattern, and broadside gain. For both S-parameter and far-field results, good correspondence is achieved between simulation and measurement. The proposed series-fed antenna array with coaxial feed is very suitable to be deployed in base stations with 1-D beam steering capability.

INDEX TERMS Series-fed antenna, probe feeding, bandwidth improvement, 5G offshore communications.

I. INTRODUCTION

Since the beginning of the 21th century, with the rapid progress of science and technology, land telecommunications have been developed from electric to optical, wired to wireless, analog to digital, and first generation (1G) to fifth generation (5G) systems. However, on the vast ocean, due to the volatile environment and difficulties in construction, maritime communications lags behind the development of those land-based ones. In recent years, along with increased maritime activities and booming marine economies, research on new generation maritime communication systems has attracted more and more attentions.

Now, the 5G mobile and wireless communication is under trial running stage. The beam-steering system, which is recognized as one key technology in 5G, has gained significant interest as it is one of the most innovative and effective solutions to realize the aforementioned 5G vision and requirements [1]–[3]. This technology can significantly expand the communication range and enhance the transmission capacity, and enables 5G systems to be deployed for rural areas with sparsely distributed users [4], [5], in which the offshore area is one typical scenario.

For a beam-steering system, a large number of antennas is required at the base station [6]. In order to reduce the hardware complexity, the subarray technology is recommended [7]. As an example, the series-fed structure was utilized for the subarray design in a prototype of 5G communication system in [8]. Such a series-fed array employs shorter line length in comparison with corporate-fed arrays, leading to an antenna with less space on substrate, lower attenuation loss, and less spurious radiation from feed lines [9].

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FIGURE 1. Illustration of 1-D beam steering in the horizontal plane required in based stations for offshore maritime communications.

Meanwhile, series feeding structures with feed located at the center are more recommended [10], since this arrangement can avoid the beam squint problem so as to ensure a stable link within target areas. However, series patch antenna arrays with center-located feed are inherently narrow in bandwidth [10], [11], whose typically bandwidth is less than 4%. The bandwidth can be enhanced by using other types of radiators [10], [12]. However, the polarization direction of designs presented in [10] and [12] is perpendicular to their series feeding lines. When deploying them in base stations with beams steered in the horizontal plane as in Fig.1, the generated beams are horizontally polarized, which are not suitable for base-station applications due to large loss brought by induced currents in the ground/sea along its transmitting path.

In this paper, several series-fed patch antenna arrays with novel center-located feeding networks are proposed. Polarization directions of these antennas are parallel to their corresponding feeding lines, which can meet the requirement of base stations with 1-D beam steering capability for offshore 5G communications. Different structures are investigated and compared with emphasis on impedance bandwidth improvement. The structure with a vertical-U shaped section is chosen for application, due to its bandwidth broadening ability and good engineering reliability. A prototype with 12 patch elements is fabricated and achieves over 20% impedance bandwidth, fully covering the 4.8-4.99 GHz 5G spectrum band. Simulated and measured results are presented and discussed.

II. REFERENCE ANTENNA DESIGN

A conventional series-fed microstrip patch antenna array with center-located coaxial probe-feed is designed first, to be referred as a reference antenna. Afterwards, modifications can be performed on this antenna to improve its impedance bandwidth.

The reference antenna array operating at 4.9 GHz is shown in Fig. 2. 12 rectangle patch elements are placed on a 20-mil thick Roger RO4003C substrate, whose dielectric constant ε_r is 3.55 and loss tangent is 0.0027. These elements are grouped into two 6-element subarrays, which are connected in the middle to a coaxial probe with an 180° phase shifter. Within each antenna subarray, a section of meander line is inserted between adjacent elements, to ensure an equal phase distribution and therefore a broadside radiation pattern. The length of resonant patches is $\lambda_g/2$, while the width of them is optimized to achieve 100-Ω input impedance for each 6-element subarray. The characteristic impedance of the microstrip line in the phase shifter is 100 Ω, to match with 6-element subarrays at both sides and the 50-Ω coaxial probe. Detailed parameters are as below: S=21.6 mm, W=14.5 mm, L=25.4 mm, K=1.7 mm, P=6.7 mm, g=4.492 mm.

Simulated reflection coefficient of this reference array is shown in Fig. 3. A poor impedance matching is observed, although each part of this array has been properly designed. The major reason is that, the relative large width of the 100-ohm microstrip line (P=6.7 mm) in the 180° phase shifter leads to a small spacing between adjacent transmission lines & radiators around, resulting in serious mutual-coupling as well as parasitic effect. This is validated by observing the input impedance at the coaxial probe, which is strongly reactive [around −j50 Ω as illustrated in Fig. 4] at resonant frequencies (f_1&f_2).

III. INVESTIGATION ON DIFFERENT PROBE FEEDING STRUCTURES FOR BANDWIDTH IMPROVEMENT

In this section, three improved feeding structures with different geometries are investigated, analyzed and compared.

A. END-FOLDED 3-DIMENSIONAL PROBE FEEDING STRUCTURE (TYPE I)

To minimize the coupling between different sections within the 180° phase shifter, the relative large width of the 100-Ω microstrip line needs to be narrowed. In order to maintain its characteristic impedance, one possible approach is to lower this shifter closer to the ground as shown in Fig. 5(a) and (b). Two vertical metallic plates with dimensions of $L_3 \times W_1$ are included to connect the phase shifter and the two 6-element subarrays. In this case, the width for 100-Ω microstrip line required in the phase shifter is narrowed from P=6.7 mm to W_2=1.7 mm. Parameters of this improved feeding structure (type I) are: L_3=4 mm, W_1=7.6 mm, L_4=5.8 mm, W_2=1.7 mm. It can be observed that, much larger spacing between adjacent lines is now achieved and leads to a weaker mutual coupling. Moreover, the phase shifter is lower than nearby radiators with a distance of L_3, which also contributes to a smaller mutual coupling between them. As shown in Fig. 3, a bandwidth ranging from 4.75 to 5.02 GHz for $|S_{11}|$ <−10 dB is achieved for this improved antenna array, which can meet the 4.8-4.99 GHz 5G spectrum band. However, this achieved bandwidth leaves almost no margins for fabrication tolerance. By analyzing its input impedance as in Fig. 6, it is found that this poor impedance matching can be attributed to large resistances at resonances of 4.8 and 5.1 GHz, which are 70 Ω and 110 Ω, respectively.

B. END-FOLDED 3-DIMENSIONAL PROBE FEEDING STRUCTURE WITH CONSTRICTED LINE (TYPE II)

Based on the above analysis, in order to further improve the impedance matching and broaden the bandwidth, one

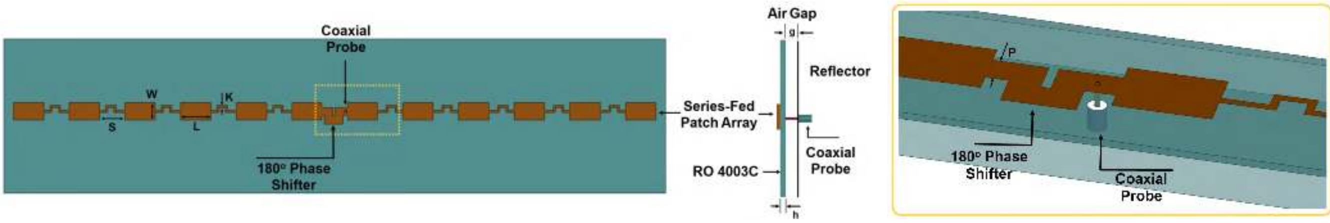

FIGURE 2. Microstrip series-fed antenna array (reference antenna).

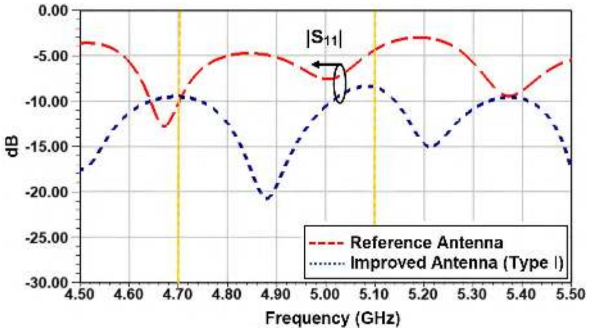

FIGURE 3. Simulated $|S_{11}|$ of the reference antenna array.

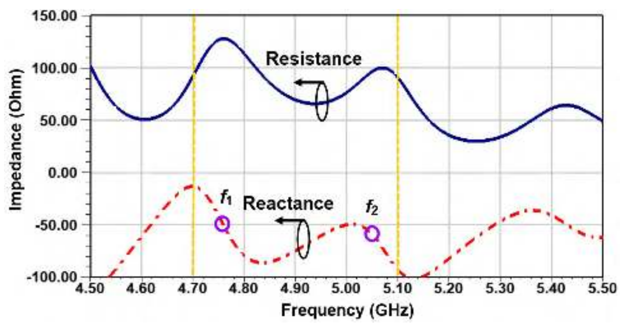

FIGURE 4. Simulated input impedance of the reference antenna array.

needs to lower the resistance at resonant frequencies. The key issue is to design an impedance transformer, which should be compact enough to be integrated in the phase shifter illustrated in Fig. 5(b). To resolve this issue, a novel approach by increasing the characteristic impedance of part of the 100-Ω mircostrip line to a higher value is proposed. This can be done by constricting part of the 100-Ω mircostrip line with a length of L_5 from W_2 to W_3 shown in Fig. 5(c). Fig. 7 illustrates its corresponding working mechanism and details are provided as follows:

Step 1: Before this constriction, the normalized value of the input impedance is assumed to be I_1, for the antenna subarray on the left portion of the probe feeding position *A* [shown in Fig.5 (b)].

Step 2: Then, when tracing back towards the radiator to position *B* marked in Fig. 5(c), the normalized value can be assumed to be I_2, whose value will be I_2 after re-normalized by a larger characteristic impedance of the microstrip line with a width of W_3.

Step 3: Next, when moving from position *B* to *C*, the normalized value will become I_3'.

Step 4: After a re-normalization by 100-Ω, I_3' changes into I_3 and finally turns into I_4 when again reaching position *A*.

By conducting these 4 steps of impedance transformations, input impedance of the antenna subarray on the left can be reduced from I_1 to I_4, subsequently resulting in smaller input impedance for the whole antenna array. As observed in simulation results plotted in Fig.8 and Fig. 9, the bandwidth improvement after utilizing the above approach with parameters of W_3=0.7 mm and L_5=2.8 mm is verified. It is seen in Fig.8 that, resistances at resonant frequencies decrease to 55 Ω and 85 Ω, respectively. Compared with results of type I array in Fig. 9, $|S_{11}|$ notches at 4.7 and 5.1 GHz are improved to be smaller than −10 dB with this modification. However, it is worth mentioned that, this constricted line with a width of only 0.7 mm is of easy brittleness. Such a weak link is not applicable for applications requiring high reliability. Therefore, further improvement is required and proposed in the following part.

C. END-FOLDED 3-DIMENSIONAL PROBE FEEDING STRUCTURE WITH VERTICAL-U (TYPE III)

As analyzed above, the impedance matching improvement using the high-impedance in the above design is at the cost of reliability. To overcome this constraint, modifications should be carried out to the constricted microstrip line, by inserting a vertical-U shaped section into the phase shifter as plotted in Fig. 5(d). In this proposed structure, its width is identical to the 100-Ω microstrip line. However, due to the higher spacing between this section and the ground, much larger characteristic impedance for the microstrip line with a length of L_6 can be achieved larger than 100-Ω, providing the same impedance transformer function illustrated in Fig. 6. Parameters of this vertical-U section are L_6=2.1 mm and L_7=3 mm. Simulated results shown in Fig. 8 present a close reduction on resistances as achieved by the type II structure. The −10 dB impedance bandwidth is predicted to be 630 MHz [shown in Fig. 9], which is sufficient for the required 4.8-4.99 GHz 5G spectrum band.

IV. MEASUREMENT AND DISCUSSIONS

To verify the above design and simulated results, a prototype was built and measured. Fig. 10 shows the fabricated

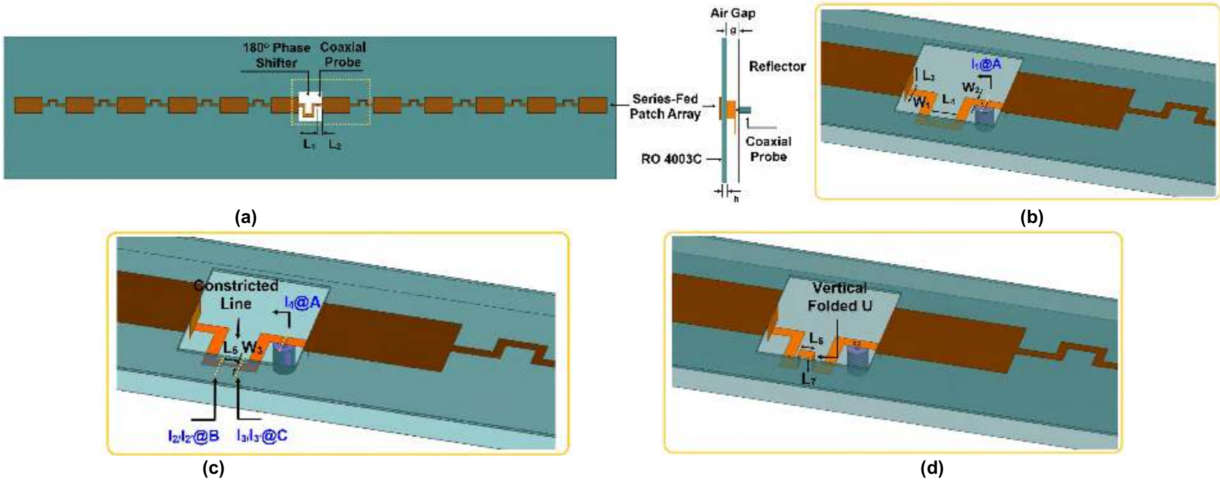

FIGURE 5. Improved microstrip series-fed antenna array with different probe feeding structures. (a)&(b) type I, (c) type II, and (d) type III.

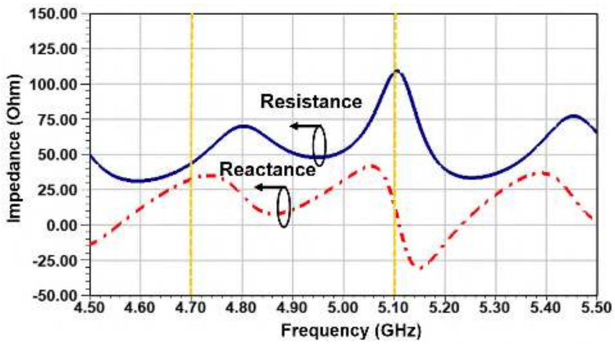

FIGURE 6. Simulated input impedance of the improved antenna array (type I).

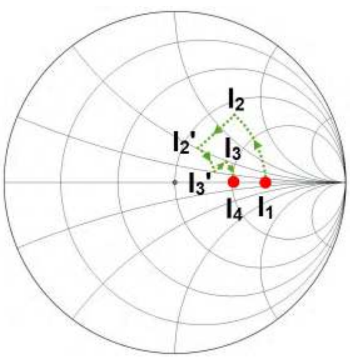

FIGURE 7. Working mechanism of the improved impedance matching illustrated in Smith Chart.

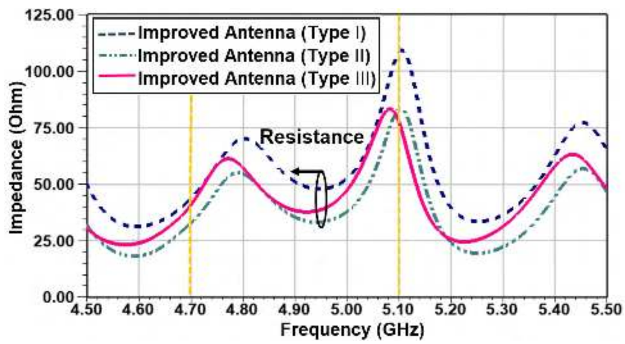

FIGURE 8. Simulated input resistances of improved antenna arrays with different feeding structures.

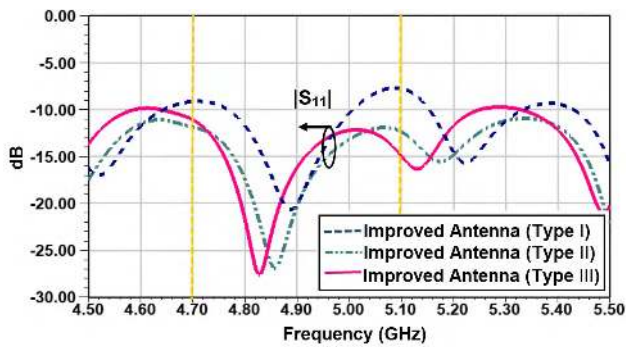

FIGURE 9. Simulated |S11| of improved antenna arrays with different feeding structures.

prototype. An ABS support printed by additive manufacturing is inserted between radiators and the ground to provide the air gap. The input impedances of the microstrip-fed antenna are measured using an Agilent E8363C vector network analyzer. Simulated $|S_{11}|$ is compared with measurement in Fig. 11. The achieved bandwidth is larger than 1000 MHz for $|S_{11}| < -10$ dB. The discrepancy between the measured and simulated $|S_{11}|$ results can be attributed to the fabrication tolerance in the assembling of the center feeding structure.

The gain and the radiation pattern were measured in an anechoic chamber, in the Institute of Microwave Communication in Nantong University. The gain measurement was conducted at the boresight of the proposed antenna array. A maximum measured gain of 19 dBi, including the connector loss,

TABLE 1. Performance comparison between proposed series-fed antenna and past works.

Ref.	Frequency	Impedance Bandwidth	Radiation Element	Feed Location	Beam Squint Problem	Polarization When Deployed in System with Horizontally Steered Beam	Implementation in Base-Station for Offshore Communication
[8]	27.9 GHz	500 MHz 1.8%	Patch	Edge	Yes	Horizontal Polarization	Not Suitable
[9]	12 GHz	180 MHz 1.5%	Patch	Center	No	Horizontal Polarization	Not Suitable
[10]	16.7 GHz	12.8 GHz 76.6%	Patch with Slotted GND	Center	No	Horizontal Polarization	Not Suitable
[11]	24.25 GHz	750 MHz 3.1%	Patch	Center	No	Vertical Polarization	Suitable
[12]	7.5 GHz	3.16 GHz 38.1%	DRA	Center	No	Horizontal Polarization	Not Suitable
This Work	4.9 GHz	1000 MHz 20.5%	Patch	Center	No	Vertical Polarization	Suitable

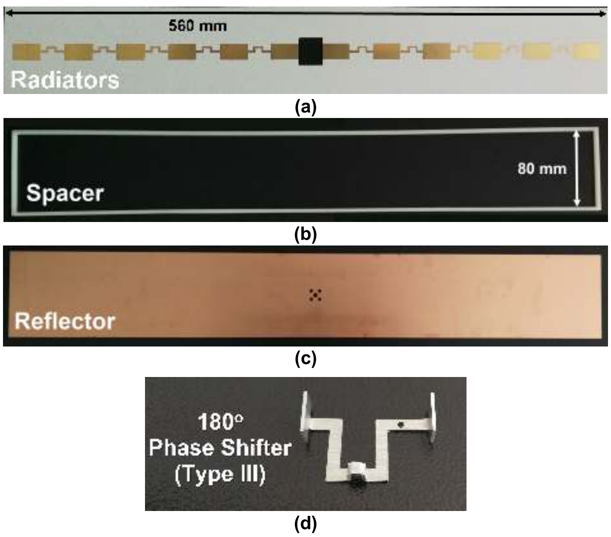

FIGURE 10. Photograph of the fabricated series-fed antenna array. (a) Radiators. (b) Spacer by 3-D printing. (c) Reflector. (d) 180o phase shifter (type III).

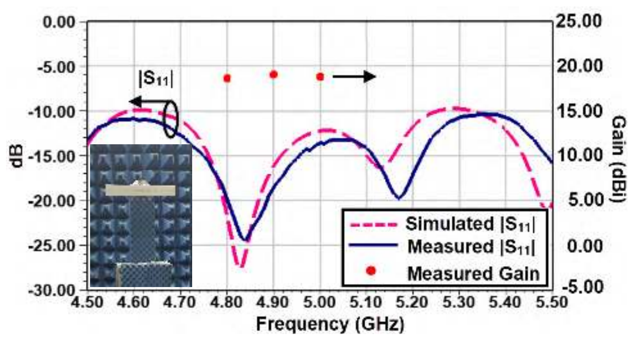

FIGURE 11. Simulated and measured reflection coefficients and measured gain of the proposed series-fed antenna array.

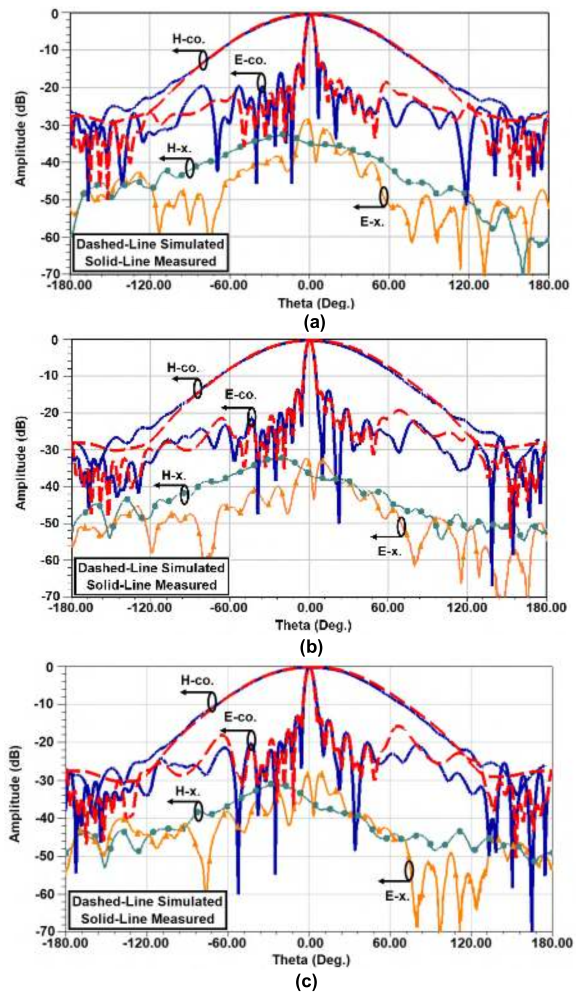

FIGURE 12. Simulated and measured radiation patterns of the series-fed antenna array at (a) 4.8 GHz, (b) 4.9 GHz, and (c) 5 GHz.

is obtained within the passband as shown in Fig. 11. Radiation patterns at 4.8, 4.9 and 5 GHz were measured and plotted in Fig.11, respectively. The 3-dB beamwidth is 5° for E-plane, while it is 72° for H-plane. Measurement results are similar to those in the simulation. Meanwhile, main beams at the above frequencies are all pointing to broadside direction, indicating an almost none beam-pointing varying with frequency.

A comparison is conducted with past works of series-fed antenna arrays in Table 1. It is seen that, the proposed geometry of antenna array can meet design specifications required in based stations with horizontally steered beams, including impedance bandwidth, beam direction and polarization direction, and therefore is suitable to be deployed in offshore maritime 5G communication systems.

V. CONCLUSION

A center-fed series antenna array, in which a novel coaxial probe feeding is proposed and implemented, is reported in this paper for 5G base-station applications. The proposed antenna array consists of 12 radiators, in order to provide an enough link budget for offshore maritime communications. Measures of lowering the phase shifter and utilizing high impedance lines are proposed to broaden the impedance bandwidth. A maximum gain of 19 dBi is achieved, within an impedance bandwidth of larger than 1000MHz for $|S_{11}|$ less than -10 dB. This proposed linear antenna array behaves enough impedance bandwidth, broadside gain and proper main beam width, indicating a good candidate as a subarray for beam-steering wireless communication systems.

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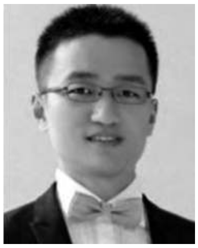

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Dr. Guo was a recipient of the Young Investigator Award 2009 from the National University of Singapore. He has received the 2013 Raj Mittra Travel Grant Senior Researcher Award and the Best Poster Award from the International Conference on Wearable and Implantable Body Sensor Networks (BSN2014), Zurich, Switzerland, in 2014. He was the General Chair of the IEEE MTT-S International Microwave Workshop Series 2013 on RF and Wireless Technologies for Biomedical and Healthcare Applications (IMWS-Bio2013) in Singapore. He has served as a Technical Program Committee (TPC) Co-Chair for the IEEE International Symposium on Radio Frequency Integration Technology (RFIT 2009). He has been a TPC member and the Session Chair of numerous conferences and workshops. He is serving as an Associate Editor for the IEEE Antennas and Wireless Propagation Letters and *IET Microwaves, Antennas and Propagation*.