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A Center-Fed Beam-Steerable Series Antenna Array With a Wide Matching Bandwidth

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ABSTRACT In this paper, a center-fed beam-steerable series antenna array is presented that has both a wide matching bandwidth and easy control. The proposed matched feeding network for the series array is composed of impedance transformers and voltage-controlled phase shifters, and has a fractional bandwidth of 74%. The phase shifters are designed in a reflection-type configuration to minimize loss and reduce size. The 3-way power divider used in the proposed center-fed series array enable beam steering with only two control voltages for phase shifters. To demonstrate the beam-scanning capabilities of the proposed antenna array, the proposed feeding network was combined with angled-dipole antennas. The proposed antenna array has a scan angle of $\pm 60^\circ$ at 3.5 GHz, with a gain varying from 8.9 to 10.4 dBi. It also has a broadband matching bandwidth of 20% and a low beam-squint of $\pm 2^\circ$ in the 0.2 GHz band centered at 3.5 GHz.

INDEX TERMS Series array antenna, center-fed array, broadband matching, beam steering, 3-way power divider, reflection type phase shifters, angled-dipole antenna.

I. INTRODUCTION

BEAM-STEERABLE phased array antennas are widely used in various applications such as mobile communication, satellite links, and radar systems. The feeding network is a crucial component of these systems, and it is typically implemented using either a corporate feed or series feed [1], [2]. Corporate feeding is preferred for its simplicity, but it suffers from high loss when used with large arrays due to the long feeding line [3], [4], [5], [6]. Series feeding, on the other hand, has a shorter length and lower loss but requires high impedance transformers, which limits the matching bandwidth. Therefore, there is a need for a series feeding network that provides both low loss and wide bandwidth.

Various series feeding networks with phase shifters for beam-steerable phased arrays have been presented in several papers [7], [8], [9], [10], [11], [12], [13]. While some networks used traveling-wave antenna with switch devices to lower costs [7], [8], [9], [10], they have a narrow matching bandwidth. The networks [11], [12], [13] utilized phase shifters with various impedances or impedance transformers to widen the matching bandwidth, but they require designing multiple phase shifters and complex bias control for the phase shifters. This paper proposes a beam-steerable series antenna array with a wide matching bandwidth and easy control using an identical phase shifter.

Although a beam-steerable series antenna array may be designed with a wide matching bandwidth, its bandwidth decreases as the array size increases. To address this issue, a center-fed array design is employed. Conventional center-fed arrays use 2-way power dividers [14], [15], [16], but these increase the spacing between antenna elements, making it challenging to maintain consistent spacing or use identical phase shifters between them. This paper proposes a 3-way power divider suitable for a beam-steerable antenna array that maintains the same spacing and uses identical phase shifters between antenna elements, resulting in easy control.

In Section II, a proposed matched feeding network was compared with previously studied networks for beam-steerable series arrays. Additionally, this paper includes a 3-way power divider for a center-fed series array and a reflection-type phase shifter. In Sections III and IV, the

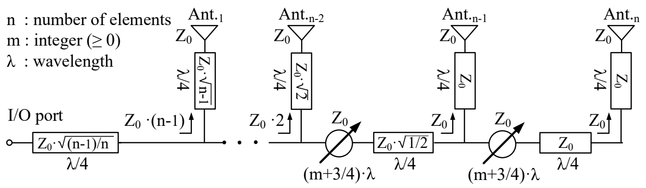

FIGURE 1. Proposed matched feeding network for the beam-steerable series array with n antenna elements.

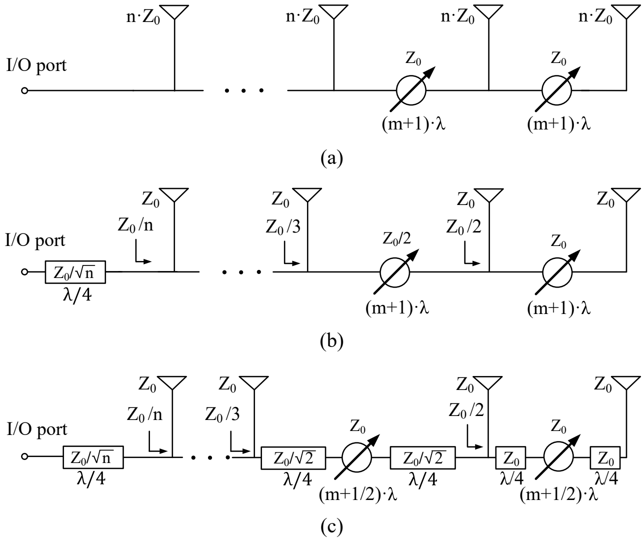

FIGURE 2. Conventional matched feeding networks for the beam-steerable series array with n antenna elements used in (a) [7], [8], [9], [10], (b) [11], [12] and (c) [13]. ($m \geq 0$, is an integer).

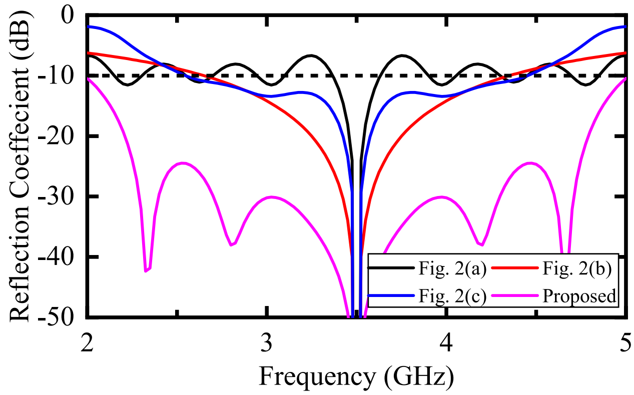

FIGURE 3. Simulated reflection coefficient of various series-feeding networks in a lossless environment (n=5, m=0).

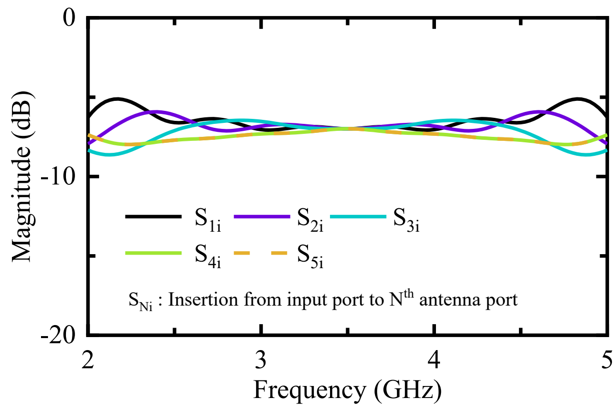

FIGURE 4. Simulated insertion loss of the proposed series-feeding network in a lossless environment (n=5, m=0).

proposed series feeding network and beam-steerable series antenna array were measured.

II. FEEDING NETWORK DESIGN

A. BROADBAND FEEDING NETWORK

The proposed matched feeding network for a wide beam-steerable array of n antennas, depicted in Fig. 1, consists of identical phase shifters and quarter-wave impedance transformers. The phase shifters transmit in-phase signals to each antenna with Z_0 and $(3/4 + m)\lambda$ electrical length (m being an integer). The impedance transformers near the phase shifters adjust the impedance to Z_0, and the ones near the antennas ensure equal power distribution by transforming the input impedance of the antennas. The proposed feeding network becomes wideband through gradual impedance changes as a stepped impedance matching network.

Fig. 2 shows conventional matched feeding networks for a beam-steerable series array of n antennas. These networks transmit signals with equal phase and power. Fig. 2(a) features identical phase shifters and has a simple design but narrow matching bandwidth [7], [8], [9], [10]. Fig. 2(b) uses various impedance phase shifters to enhance matching bandwidth [11], [12], but at the cost of complexity. Fig. 2(c) implements identical antennas, phase shifters, and quarter-wave transformers for impedance matching, resulting in a wider matching bandwidth [13]. The proposed network, with identical phase shifters and antennas, offers wider matching bandwidth than previous designs.

Fig. 3 shows the simulated reflection coefficient of the 5-antenna beam-steerable series feeding networks in a lossless environment with a center frequency of 3.5 GHz, as shown in Figs. 1 and 2. Fig. 2(a) has a narrow 7% fractional bandwidth (under 10-dB return loss) due to mismatches between the antennas and phase shifters. Figs. 2(b) and 2(c) exhibit a wider bandwidth by reducing the impedance differences between components, with fractional bandwidths of 49% and 54%, respectively. The proposed network in Fig. 1 has the widest 86% fractional bandwidth, achieved by using quarter-wave impedance transformers to minimize differences between impedance. The principle behind the wide matching bandwidth of the proposed structure is the same as the impedance matching method using tapered lines. It is a method that minimises the difference in impedance in each section of the feeding network while making a match at the input port. Fig. 4 illustrates the simulated insertion loss of the proposed series feeding network in a lossless environment. This network can transmit equal power to each antenna across a wide frequency range. Figs. 3 and 4 are assumed to be composed of components without losses.

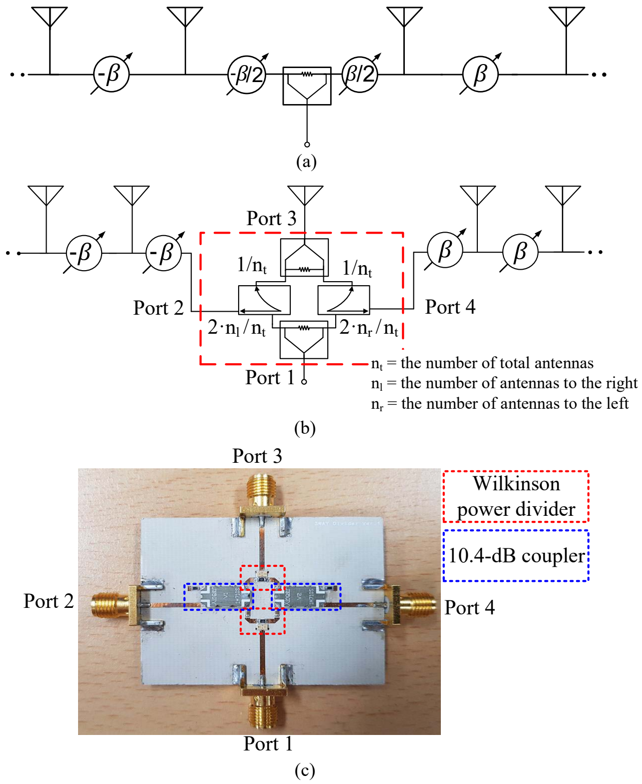

FIGURE 5. Conventional (a) and proposed (b) power divider for center-fed series array, and (c) photo of the proposed 3-way power divider.

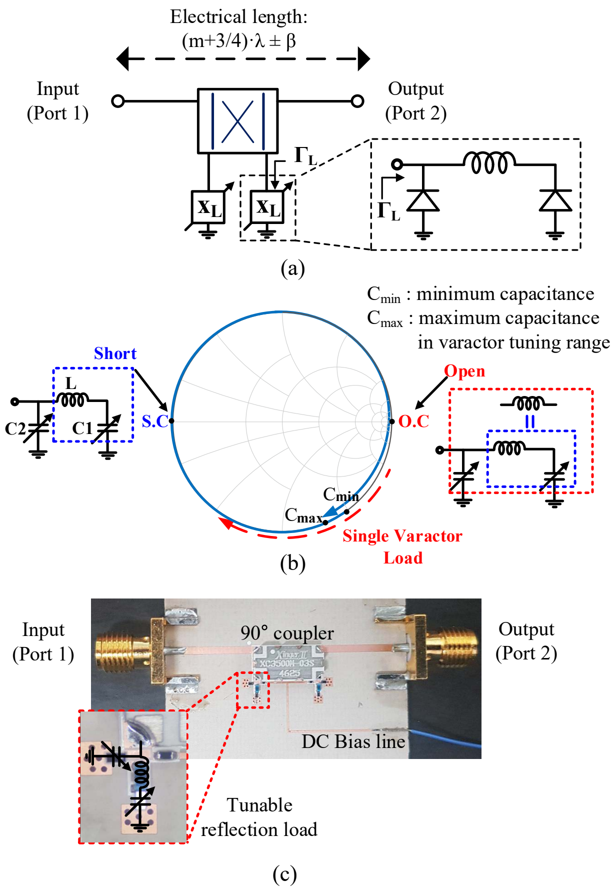

FIGURE 6. (a) Proposed reflection type phase shifter using π-type reflection loads, (b) the smith chart diagram for tuning operations of the single varactor load and the π-type reflection load at 3.5 GHz, and (c) photograph of the RTPS.

Therefore, in an actual network with losses, the antenna port that is farther from the input/output port will experience greater loss.

B. THREE-WAY POWER DIVIDER FOR CENTER-FED ARRAY

As the size of a series array increases, the length of the delay line must also become longer, leading to a reduction in the array's bandwidth. Furthermore, the more antennas in the array, the higher the impedance value of the required transformer. If the required impedance of the transformer is too high, manufacturing with a general PCB process may be impossible. To overcome these difficulties, a center-fed series feed array has been proposed as a viable solution. A center-fed series array with n antennas is equivalent to combining two edge-fed series arrays with n/2 antennas. Compared to a single series array with the same number of antennas, the center-fed series array has a wider matching bandwidth and requires lower impedance values of impedance transformers [14].

Fig. 5 depicts two types of center-fed series arrays. As shown in Fig. 5(a), a conventional center-fed series array using a 2-way divider requires the relative phase between adjacent antennas to be in one of four states: $-\beta$, $-\beta/2$, $\beta/2$, and β. This structure is inefficient due to the need for complex bias control and two different phase shifters for equal spacing between antennas. Fig. 5(b) depicts the proposed center-fed series array using a 3-way power divider.

The proposed 3-way power divider is composed of four 2-way dividers. The power ratios at ports 2, 3, and 4 are n_l:1:n_r, where n_l and n_r represent the numbers of antennas in the left and right sub-arrays respectively. This configuration results in an equal power distribution to all antennas with equal spacing between them. Fig. 5(c) is a photograph of a proposed 3-way divider with a power dividing ratio of 5:1:5. The divider consists of two Wilkinson power dividers and two 10-dB couplers. The proposed series array utilizes identical phase shifters and only two bias controls for β and $-\beta$, making it a more efficient solution.

C. REFLECTION TYPE PHASE SHIFTER

The proposed beam-steerable series feeding network utilizes a reflection type phase shifter (RTPS) due to its compact size and low insertion loss. The RTPS is comprised of a 4-port 90° coupler and two matching tunable reflection loads [17], [18], [19], [20], [21], [22]. The input and output ports of the RTPS are established by using the input and isolation ports of a conventional 90° coupler, while the remaining ports are terminated with the tunable reflection loads. The phase tuning range of the RTPS is equal to that of the reflection

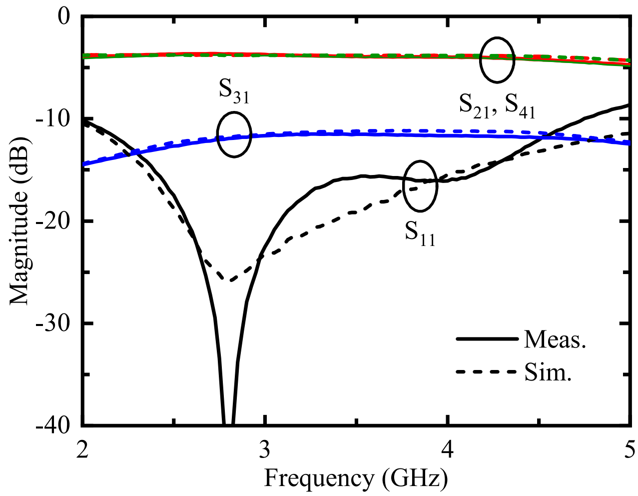

FIGURE 7. Simulated and measured S-parameters of the proposed 3-way power divider.

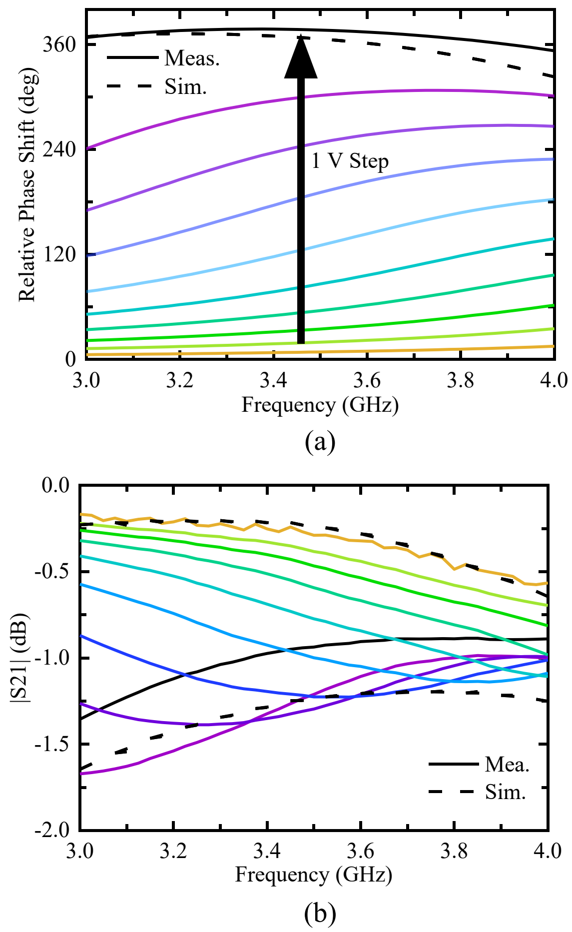

FIGURE 8. Simulated and measured (a) relative phase shift and (b) insertion loss of the proposed RTPS for a control voltage ranging from 0 to 10 V.

loads. Its output phase is defined as θ, which is expressed as:

$$\theta = 270^\circ - \angle\Gamma_L \tag{1}$$

where Γ_L is the reflection coefficient of the reflection load [18]. The reflection load in the RTPS has been designed as a multi-resonance π-type circuit for its wide phase tuning range and simple structure [17]. As depicted in Fig. 6(a), the proposed RTPS employs a π-type reflection load. Fig. 6(b) illustrates the smith chart diagrams for the tuning operations of both a single varactor load and a π-type reflection load. As seen in Fig. 6(b), while the tuning range of the reflection coefficient was limited to less than 180° with a single varactor load, the tuning range exceeded 360° with the π-type reflection load. The operation principle can be explained as follows:

1) When the capacitance C1 increases, C1 and L act as a series resonator and a short circuit.
2) As C1 continues to increase, the series resonator functions as an inductor.
3) When the reactance of the series resonator increases further, the resonator and C2 form a parallel resonator and an open circuit.

Note that, since the RTPS has an inherent phase delay, the RTPS's electrical length was designed to be $(7/4)\lambda \pm \beta$ for m=1, rather than $(3/4)\lambda \pm \beta$ for m=0.

Fig. 6(c) is a photo of the RTPS fabricated. This RTPS consists of a 90° coupler, two inductors, and four varactors, with a single dc bias controlling the four varactors.

III. FEEDING NETWORK MEASUREMENT

A. THREE-WAY POWER DIVIDER FOR ELEVEN ANTENNA SERIES ARRAY

To verify the performance of the proposed series feeding network, we fabricated it with eleven antenna ports. To ensure equal power distribution, the 3-way power divider with a power dividing ratio of 5:1:5 was required. The 3-way power divider was composed of 2-way dividers and 10.4-dB couplers, using 1M710 from Anaren and PD3150J5959S2HF from TTM tech.

Fig. 7 shows the simulated and measured S-parameters. The simulated power dividing ratio was −3.4:−10.4:−3.4 dB, while the measured ratio was −3.9:−11.0:−3.9 dB (the difference due to component loss). The bandwidth with 10-dB return loss was 2.0 to 4.7 GHz.

B. REFLECTION TYPE PHASE SHIFTER

Fig. 8 illustrates the relative phase shift and insertion loss of the proposed RTPS over a control voltage range of 0 to 10 V with a 1-V step. The XC3500M-03S coupler from Anaren was used as a 4-port 90° coupler, while the 0402DC-4N3 from Coilcraft and two MAVR-000120-1141 from MACOM served as tunable reflection loads. Fig. 8 shows that the maximum insertion loss was 1.7 dB and the phase tuning range covered 360° at 3−4 GHz. The relative phase shift of the proposed RTPS ranged from 430° to 800°, which is $(7/4)\lambda \pm \beta$.

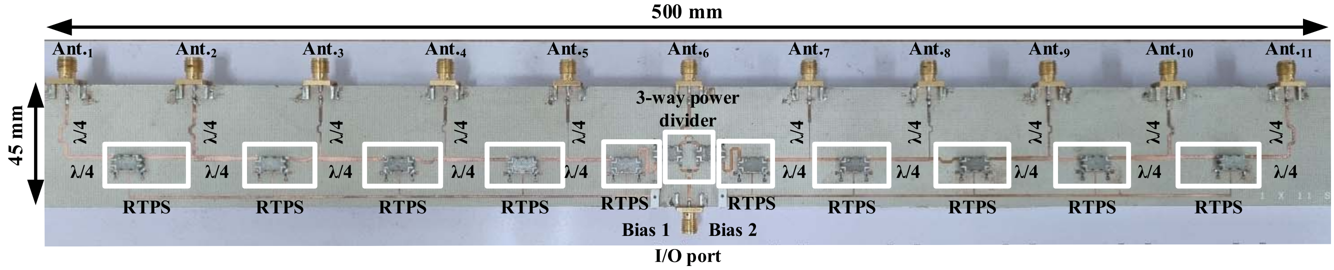

FIGURE 9. A photograph of the proposed feeding network for beam-steerable series array.

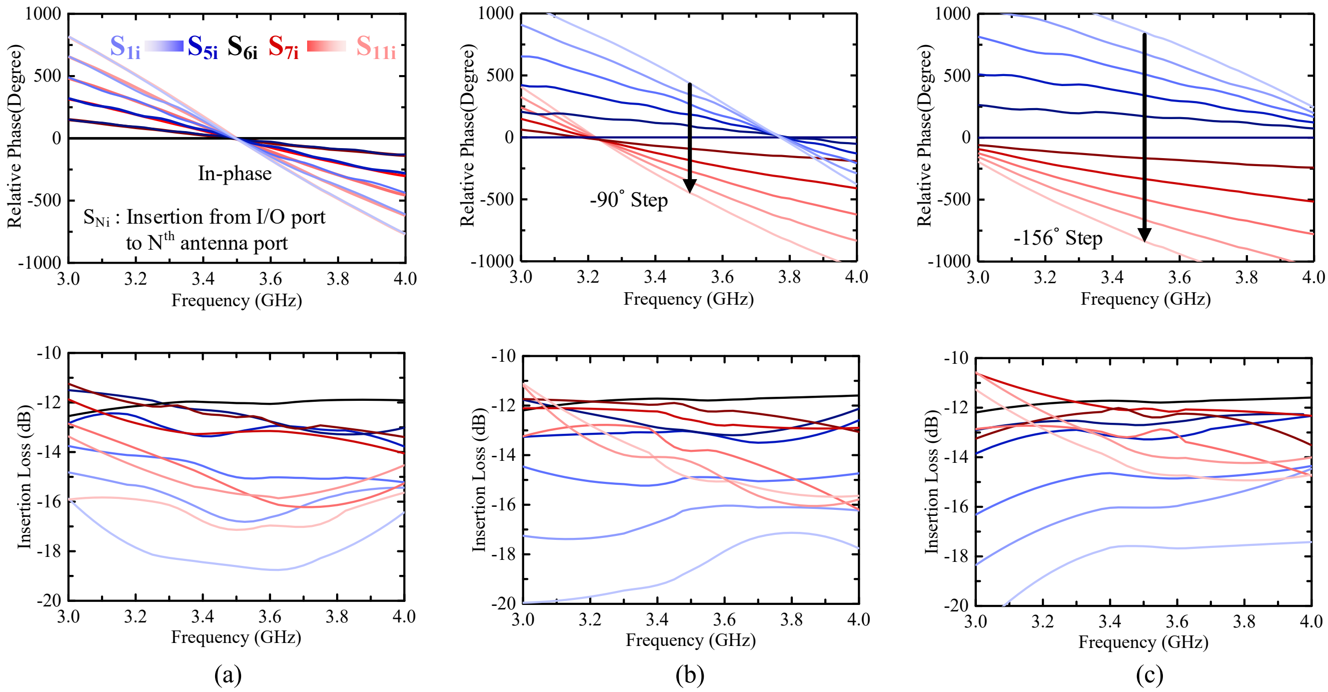

FIGURE 10. Relative phase and insertion loss of all antenna ports normalized to the center antenna (Ant.6) for a scan angle of (a) 0°, (b) 30°, and (c) 60°.

C. PROPOSED SERIES ARRAY

Fig. 9 shows a photograph of the proposed feeding network for a beam-steerable series array. The network consists of quarter-wave impedance transformers, the 3-way power divider, and RTPSs. The quarter-wave impedance transformers are located next to each RTPS and below each antenna port for impedance matching and equal power distribution. The 3-way power divider, with a power dividing ratio of 5:1:5, is connected to the I/O port. The RTPSs are positioned between adjacent antenna ports for 360° phase tuning, and the antennas are spaced by $0.5\lambda_0$ at 3.5 GHz. There are two bias pads near the I/O port, Bias1 for controlling the RTPSs of the left sub-array and Bias2 for controlling the RTPSs of the right sub-array.

Fig. 10 shows the relative phase and insertion loss for all antenna ports at various scan angles. At 3.5 GHz, the relative phase between the antenna ports was 0°, −90°, and −156° for the scan angles of 0°, 30°, and 60°, respectively. The relative phase was normalized with phase of the center antenna port (Ant._6). The insertion loss gradually increased from the center antenna to both ends, which is caused by the loss in the RTPSs. This increase in loss resembles the tapering effect commonly seen in antenna arrays.

Fig. 11 illustrates the simulated and measured reflection coefficient of the proposed network. It can be seen that the bandwidth with a 10-dB return loss ranges from 2.0 to 4.6 GHz. The proposed series feeding network has a fractional bandwidth of 74%, presenting a solution for the narrow impedance bandwidth issue commonly seen in series feeding networks.

IV. ANTENNA ARRAY MEASUREMENT

A. ANGLED-DIPOLE ANTENNA

For verifying a wide matching bandwidth and wide beam-steerable series antenna array using the proposed feeding network, we had to use a wide-matching and wide beam-width antenna. However, there was no planar antenna that satisfied both requirements. The verification of the wide matching bandwidth was replaced by a measurement of the

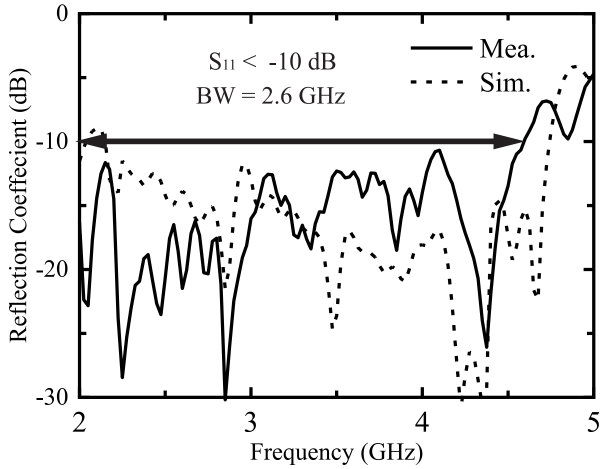

FIGURE 11. Simulated and measured reflection coefficients of the proposed network.

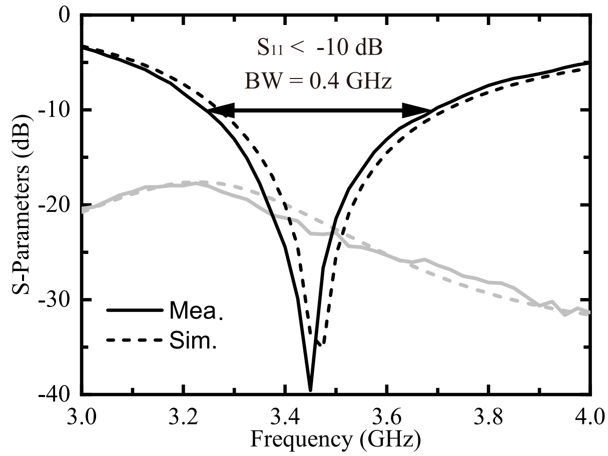

FIGURE 13. Simulated and measured reflection coefficient and mutual coupling of the angled-dipole antenna.

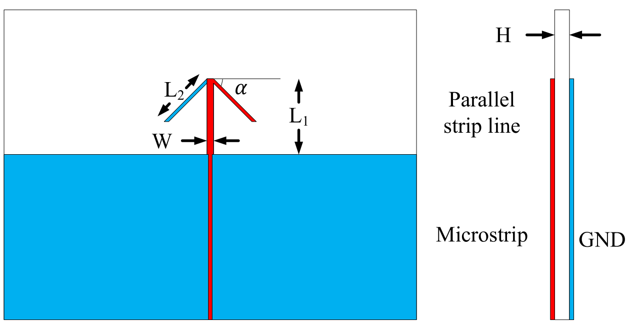

FIGURE 12. Geometry of the angled-dipole antenna.

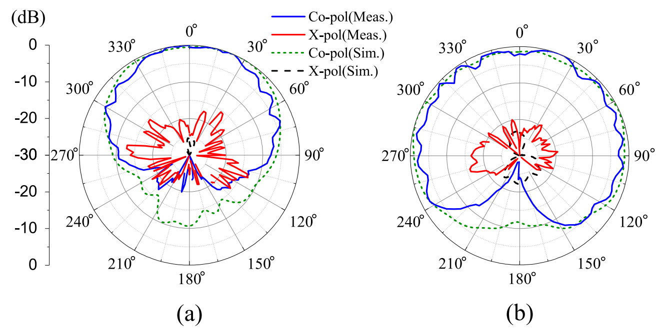

FIGURE 14. Simulated and measured (a) E-plane and (b) H-plane radiation patterns of the angle-dipole antenna at 3.5 GHz.

feeding network (as shown in Fig. 11), and the wide beam-steerable capability of the proposed feeding network was verified using an angled-dipole antenna [23], [24].

Fig. 12 displays the geometry of the angled-dipole antenna. The substrate used is a Taconic 0.51 mm RF35TC (with a dielectric constant of 3.5). The design parameters were as follows: $W = 1.9$ mm, $L_1 = 22.0$ mm, $L_2 = 12.5$ mm, and $\alpha = 45°$. The feeding line was designed as a parallel stripline, with an optimized length and width to ensure that the antenna's input impedance was 50 Ω.

Fig. 13 displays the simulated and measured reflection coefficient and mutual coupling of the angled-dipole antenna. The measured return loss was more than 10 dB at 3.3–3.7 GHz. To confirm the mutual coupling, auxiliary antennas were designed and placed at a distance of $0.5\lambda_0$ at 3.5 GHz. The mutual coupling was found to be low, ranging from −18 to −31 dB at 3.0–4.0 GHz. As depicted in Fig. 14, the measured radiation pattern had a half power beamwidth of 139° and a gain of 2.5 dBi in the E-plane, and a half power beamwidth of 258° and a gain of 2.6 dBi in the H-plane at 3.5 GHz.

B. ANTENNA ARRAY

Fig. 15 displays a photograph of the proposed beam-steerable series antenna array. The array was fabricated on a single-layer board and consisted of the proposed feeding network and eleven angled-dipole antennas, as well as two 50-Ω terminated dummy antennas at both ends. Our research group confirmed its beam-forming capability, return loss, and beam-squinting by controlling only two bias voltages: Bias1, which was used to control the RTPSs of the left sub-array, and Bias2, which was used to control those of the right sub-array.

1) Beam-Forming: Fig. 16 shows the measured co- and cross-polarization gain patterns of the proposed antenna array with scan angles at 3.5 GHz. The scan angle was ±60°. Within this range, the gain ranged from 8.9 to 10.4 dBi, the cross polarization discrimination was from −23 to −28 dB, and the side lobe level (SLL) was from −10 to −20 dB. The gain at 0° is lower than the gain at 60° because the insertion loss of the phase shifter for the 0° scan is greater than the insertion loss for the 60° scan. In Fig. 8, the state for 0° scan is when the relative phase shift is 180°, and the phase state for 60° is when the relative phase shift is 20° or 340° (one sub-array or the other sub-array). As shown in Fig. 8, for a 0° scan, the insertion loss of the phase shifter is about 1.5 dB, but for a 60° scan, the insertion loss of the phase shifter is about 0.3 dB or 1.0 dB. This resulted in the gain of the 0° beam-forming being lower than the gain of the 60°

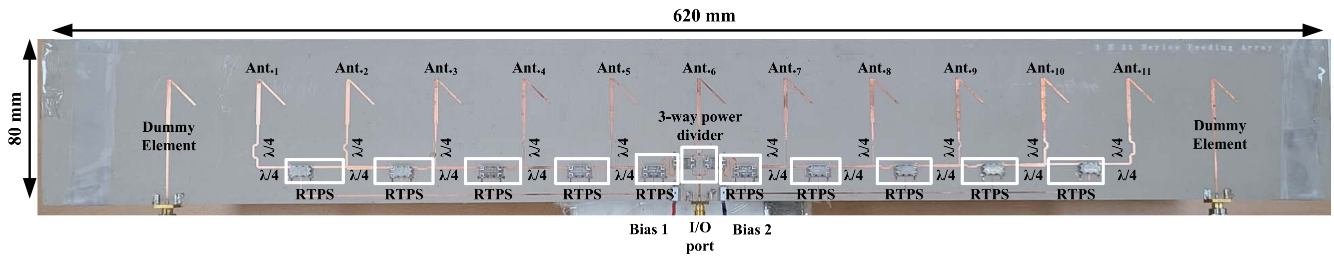

FIGURE 15. A photograph of the proposed beam-steerable series antenna array.

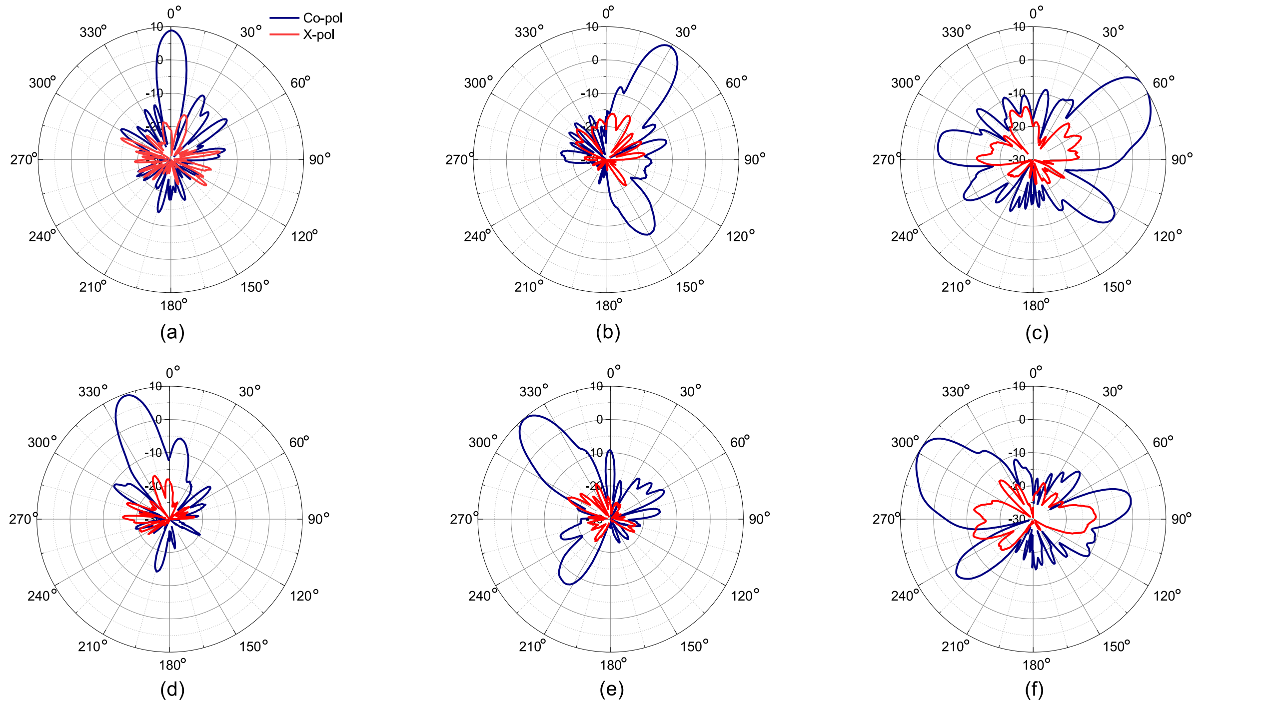

FIGURE 16. Measured co- and cross-polarization gain patterns of the proposed antenna array with scan angles of (a) 0°, (b) 30°, (c) 60°, (d) − 20°, (e) − 40° and (f) − 60°.

beam-forming. The SLL was lower than that of a uniform power divided antenna array due to the power tapering effect of the proposed feeding network, which reduced the SLL. Furthermore, at ±60° degrees, the wide beam-width is a result of using the broad beam-width antenna and an unequal power distribution (Fig. 10 (c)).

2) Return Loss: Fig. 17 shows the measured reflection coefficient of the proposed antenna array with scan angles ranging from 0° to 60° with a 10° step. The proposed antenna array provided a wide matching bandwidth of 20% from 3.1 to 3.8 GHz with a 10-dB return loss. However, due to the limited bandwidth of the antenna, the bandwidth of the proposed antenna array was narrower than that of the proposed feeding network, which was 74%. Therefore, the proposed antenna array has the potential to have a bandwidth wider than 20%.

3) Beam-Squinting: Fig. 18 displays the measured beam pattern of the proposed series antenna array to confirm its beam-squint performance. The beam-squint was measured in the range of 3.4−3.6 GHz by setting the scan angles to

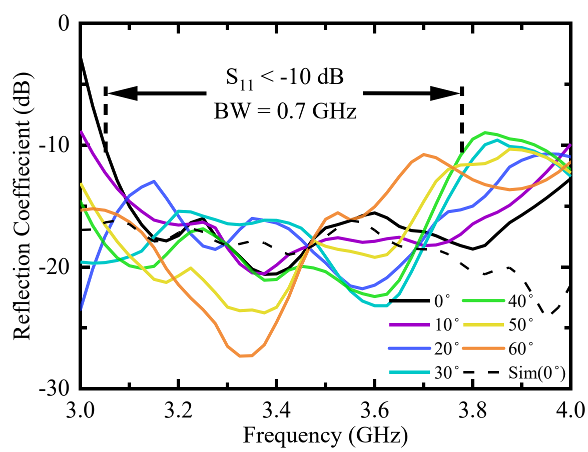

FIGURE 17. Simulated and measured reflection coefficient of the proposed antenna array with the scan angles ranging from 0° to 60°.

0°, 30° and 60° at 3.5 GHz. In this 200 MHz range, the proposed antenna array showed a measured beam-squint of ±2° and a gain variation within 3 dB. The left series-fed

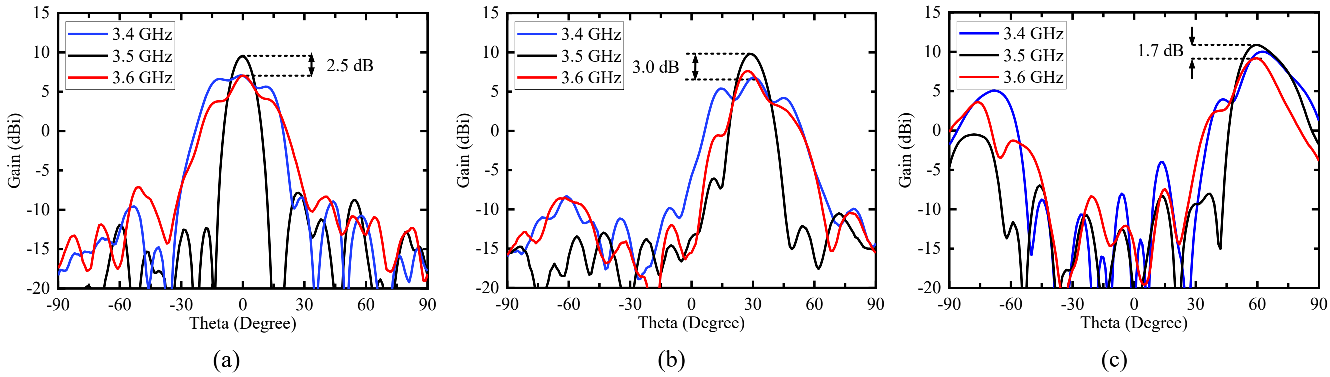

FIGURE 18. Measured beam pattern when the scan angels were 0° (a), 30° (b) and 60° (c) at 3.4, 3.5 and 3.6 GHz.

TABLE 1. Comparison of beam-steerable series antenna arrays.

Specification	This work	[7]	[8]	[9]	[10]	[11]	[13]	[25]
Number of elements	11	10	5	4	600	8	4	10
Center frequency	3.5 GHz	5.8 GHz	77 GHz	2 GHz	5.8 GHz	3.65 GHz	2.5 GHz	28 GHz
$S_{11} \leq$ -10 dB bandwidth	20 %	3 %	1 %	12%†	7%	14 % †	3%	-
Scan angle*	± 60°	± 32°	± 8°	± 45°	± 3°	± 49°	± 24.5°	± 60°
Max. SLL **	-10 dB	-9 dB†	-15 dB	-	-16 dB	-10 dB †	-10 dB †	-6 dB†
Max. gain	10.4 dBi	11.3 dBi	9.6 dBi	6.8 dBi	24.9 dBi	11.8 dBi	8.4 dBi	11.7 dBi
No. of control voltages†	2	1	10	5	4	16	7	4
Single layer PCB	✓	✓	✓	✓	-	✓	-	-

*Scan angle is defined when the SLL is lower than Max. SLL.**

†Estimated from the figure.

sub-array of the proposed network is based on $-\beta$ phase shifters, while the right series-fed sub-array is based on $+\beta$ phase shifters. Consequently, at frequencies higher than the center frequency, the phase difference between elements in the right series-fed sub-array becomes smaller than β, and in the left series-fed sub-array, the phase difference becomes larger than β. As a result, beam-squint occurs in opposite directions for the two sub-arrays, and these effects counteract each other, leading to beam-squint reduction, decrease in gain, and an increase in beam width due to the frequency change.

Table 1 summarizes the performance of the proposed beam-steerable series antenna array compared to others presented. The proposed antenna array boasts the widest matching bandwidth, the widest scan angle, and a low side lobe level (SLL). Additionally, the proposed antenna array is more efficient than others due to its two-bias control and single-layer board fabrication. However, its low gain when considering the number of elements is a result of the loss of wide-matching and wide-scanning components.

V. CONCLUSION

A center-fed beam-steerable series antenna array with a wide matching bandwidth has been proposed in this work. The proposed series feeding network utilized impedance transformers to achieve a matching bandwidth of 74%. To reduce the long line effects of the series array by half and simplify control using only two biases, the proposed feeding network was designed to be center-fed through a 3-way power divider. A reflection-type phase shifter with a π-type reflection load was used to achieve 360° of phase shift with a loss of 1.3 dB. The proposed feeding network was combined with eleven angled-dipole antennas to demonstrate the performance of the proposed beam-steerable series antenna array. The array has a scan angle of ±60° and a side lobe level of -10 dB at 3.5 GHz. Additionally, it has a matching bandwidth with a 10-dB return loss of 20% from 3.1 to 3.8 GHz and a beam-squint of ±2° from 3.4 to 3.6 GHz.

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