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SFCFOS Uniform and Chebyshev Amplitude Distribution Linear Array Antenna for K-Band Applications

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Abstract

In this study, a compact series-fed center-fed open-stub (SFCFOS) linear array antenna for K-band applications is presented. The antenna is composed of a single-line 10-element linear array. A symmetrical Chebyshev amplitude distribution (CAD) is used to obtain a low sidelobe characteristic against a uniform amplitude distribution (UAD). The amplitude is controlled by varying the width of the microstrip patch elements, and open-ended stubs are arranged next to the last antenna element to use the energy of the radiating signal more effectively. We insert a series-fed stub between two patches and obtain a low mutual coupling for a 4.28-mm center-to-center spacing (0.7λ at 21 GHz). A prototype of the antenna is fabricated and tested. The overall size of the uniform linear array is $7.04 \times 1.05 \times 0.0563\ \lambda_g^3$ and that of the Chebyshev linear array is $9.92 \times 1.48 \times 0.0793\ \lambda_g^3$. The UAD array yields a $|S_{11}| < -10$ dB bandwidth of 1.33% (20.912–21.192 GHz) and 1.45% (20.89–21.196 GHz) for the CAD. The uniform array design gives a –23 dB return loss, and the Chebyshev array achieves a –30.68 dB return loss at the center frequency with gains of 15.3 dBi and 17 dBi, respectively. The simulated and measured results are in good agreement.

Key Words: Chebyshev Amplitude Distribution (CAD), Linear Array, Microstrip, Series-Fed Center-Fed Open-Stub (SFCFOS), Uniform Amplitude Distribution (UAD).

I. INTRODUCTION

Series-fed patch array antennas have been known for many years [1] and have also been examined in the context of traveling wave and resonator antennas [2]. For the standard resonator array antenna, each half-wavelength patch is separated by a uniform $\lambda/2$- transmission line. This important characteristic will lead to a uniform aperture distribution with a broadside radiation pattern if all patches have the same width. In a uniform series antenna circuit model, all radiation resistances of the same value are generally in parallel.

Owing to the half-wavelength patch and line length, these types of antennas provide only a single-frequency operation. Microstrip patch array antennas are widely applied in radar systems [3–6] and wireless communications systems [7–10], which have a high gain, a light weight, a low cost, and a low profile and can accurately control radiation patterns. Resonant and traveling-wave feeds are commonly used in a series-fed structure. The bandwidth of a traveling-wave feed is wider than that of a resonant feed [8, 9]. However, the main beam angle changes in accordance with the change in operating frequency, which is caused by the change in the relative phase difference between two adjacent elements along the series-fed lines.

Several designs have recently been made to suppress the sidelobe level (SLL) in the printed antenna arrays [10–18]. A new aperture is proposed in [10] microstrip antenna array. The an-

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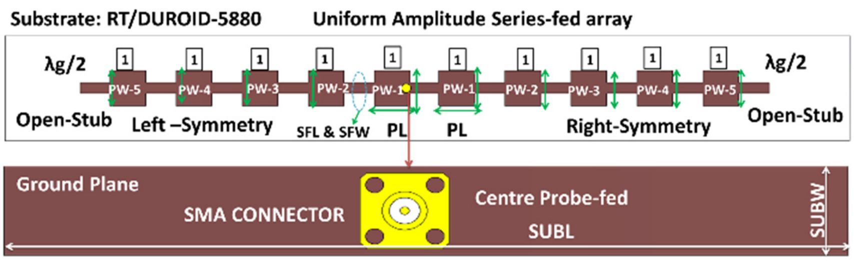
tenna consists of 100 × 50 planar array microstrip elements with an inter-element spacing of 0.51λ, and a –20.9 dB SLL is obtained. In [11], the authors presents a SLL suppression method for an X-band antenna array by designing a novel feeding network with a Chebyshev distribution. The array operates at 9.3 GHz and can give a –19.4 dB SLL, and the gain is only 12.3 dBi. A linear series-fed six-element antenna array is presented in [12]. A 6.5% wideband is obtained, but the SLL and the acquired gain remain poor at –20 dB and 14.2 dBi, respectively. Lower SLLs are dealt with and obtained in [13, 14]. The optimized distribution coefficients through the differential evolution algorithm have been used to achieve a wideband and a lower SLL in the slot antenna with a series-fed network in [13]. The antenna has 10 elements arranged in a series feeding system. The SLL and the half-power beamwidth (HPBW) are –25.3 dB and 8.4°, respectively. However, the gain is only 14.5 dBi. In addition, Nikkhah et al. [14] propose a low SLL and wideband series-fed antenna for the dielectric resonator (DRA). The proposed antenna can achieve a very low –30 dB SLL and a high 19 dBi gain. A 22 × 1 linear array results in a large size and fabrication complexity. Similarly, two other DRA arrays are introduced in [15, 16]. The array in [15] works at 60 GHz and that in [16] operates at 7.4 GHz. The SLLs are –27.7 dB and –23 dB, respectively. In [17, 18], two linear series-fed Yagi-like array samples are presented. The arrays have 22 similar Yagi line elements, which can provide a gain of 15.3 dBi and an SLL of about –27 dB. A literature comparison is presented in [13–16, 19–21] for both uniform and Chebyshev amplitude distributions (CAD).

In this study, a series-fed center-fed open-stub (SFCFOS) uniform amplitude distribution (UAD) and Chebyshev amplitude distribution (CAD) linear arrays are designed and applied to achieve a SLL of –25 dB and gain enhancement. Two series-fed linear array antennas with UAD and CAD at the same operating frequency are fabricated, and scattering parameters and radiation characteristics are measured. The amplitude can be controlled by varying the patch width that has been implemented. A $\lambda_g/2$ open-ended stub is introduced at both the ends of the array, so that the energy remaining after the last element is reflected from the open stub and radiates into the space.

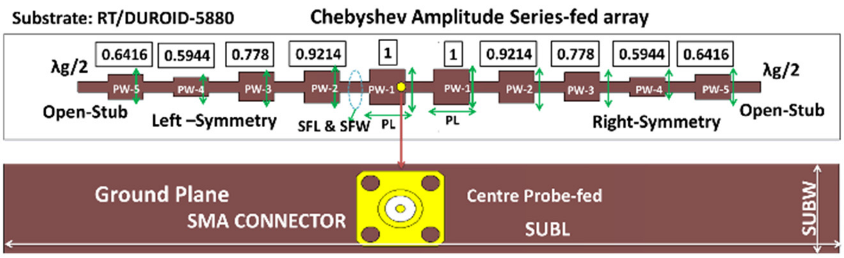
II. Antenna Array Structure and Design

This section introduces a design process of two types of antenna arrays with different configurations. In addition, uniform linear array (ULA) and Chebyshev linear array (CLA) antenna arrays using the corresponding linear polarized—antenna elements are also presented. Here, we define the *xz*-plane as the vertical plane (E-plane or $\phi = 0°$) and *yz*-plane as the horizontal plane (H-plane or $\phi = 90°$). The whole design is analyzed with the aid of the full-wave electromagnetic solver CST Microwave Studio (CST Computer Simulation Technology GmbH, Darmstadt, Germany).

Fig. 1 shows the top and bottom views of the geometry of the UAD and CAD linear array antennas, respectively. The antenna is composed of a microstrip patch array, a series feed, and coaxial probe center-feed structures (substrate and Brass plate). Both arrays are designed with 31 mil with 1 oz., that is, a 0.035 mm-thick copper RT/Duroid-5880 (Rogers Corp., Chandler, AZ, USA) copper cladding substrate with relative permittivity ε_r



(a)



(b)

Fig. 1. Geometry of the configuration with optimized dimensions: (a) 10-element series-fed uniform linear array and (b) 10-element series-fed Chebyshev linear array.

= 2.2, and the loss tangent tanδ = 0.0009 is chosen as the substrate material. After the fabrication of the antenna, we perform gold plating over the patch and the ground copper layer of 1-μ thickness for the ULA and silver plating for the CLA. Then, an antenna mounting plate with brass material of 0.8 mm thickness is mechanically fabricated and used to mount the antenna PCB using M2 (M-Metric Standard) stainless steel screws. The height of the antenna becomes 1.6 mm (electrical dimensions = 0.158λ_g), which corresponds to the center frequency of 21 GHz. The optimized parameters are given in Table 1.

In the SFCFOS array design, a uniform characteristic with a constant SLL of −13 dB and a Chebyshev characteristic of −25 dB is chosen. To obtain a flat SLL performance, we use amplitude coefficients modified from an ordinary Chebyshev synthesis and introduce a half-wavelength open-ended stub after the last element for an effective utilization of transmitted power. The width of the center patch is 5 mm. The patch width of the other elements is variable, with a ratio of 1, 0.9214, 0.778, 0.5944, and 0.6412 from the array center to the edges. The distance between two adjacent elements is 4.28 mm (0.7λ_0 at 21 GHz). The whole size of the proposed ULA and CLA antenna arrays are 120 mm (*L*) × 15 mm (*W*) × 1.587 mm (*H*) and 100 mm (*L*) × 15 mm (*W*) × 0.787 mm (*H*), respectively. The array factor of the series array for an even number of elements can be written as (1):

$$(AF)_{2M} = \sum_{n=1}^{5} a_n \cos(2n-1)\psi \tag{1}$$

$$\because \psi = kd\cos(\theta)\psi$$

$$\psi = \frac{2\pi}{\lambda} 0.7\lambda\cos(\theta)$$

Let M = 5

$$(AF)_{10} = a_1\cos(\psi) + a_2\cos(3\psi) + a_3\cos(5\psi) + a_4\cos(7\psi) + a_5\cos(9\psi).$$

Table 1. Optimized parameters of a 10-element linear array

Parameter	Value (mm)	λ_0	λ_g
10-element ULA			
PL	5	0.352	0.496
PW-1 to PW-5	5	0.352	0.496
SFL	4.28	0.301	0.424
SFW	1.5	0.105	0.148
10-element CLA			
PL	5	0.352	0.496
PW-1	5	0.352	0.496
PW-2	4.6	0.323	0.456
PW-3	4.15	0.292	0.411
PW-4	2.75	0.193	0.272
PW-5	3.5	0.246	0.347
SFL	4.28	0.301	0.424
SFW	1.5	0.105	0.148

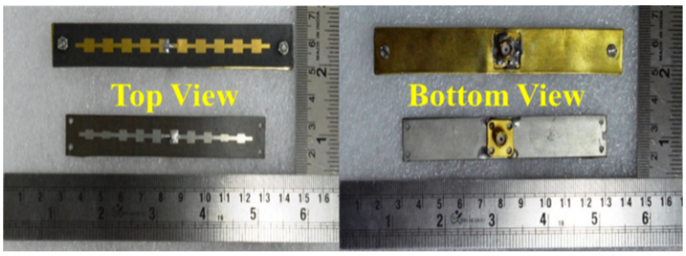
λ_0 = free space wavelength with respect to the velocity of propagation in the air center frequency (21 GHz) (0.0142 m), λ_g = guided wavelength with respect to the velocity of propagation in the substrate material (RT/Duroid-5880) (0.01008 m), PL = length of the patch, PW = width of the patch, SFL = length of the series-fed line, SFW = width of the series-fed line.

III. Fabricated and Measured Results

The proposed ULA and CLA antenna arrays are fabricated and measured. Fig. 2 presents a photograph of the fabricated antenna arrays showing the ULA and CLA antenna arrays assembled with a brass plate and stainless steel screws. The measured return loss of the ULA and CLA antenna arrays is performed with the Agilent N9918A FieldFox microwave analyzer. The radiation patterns and gains of the antenna array are measured using a far-field measurement technique in a microwave anechoic chamber with the Agilent PNA Series Network Analyzer N5230C (10 MHz–40 GHz).

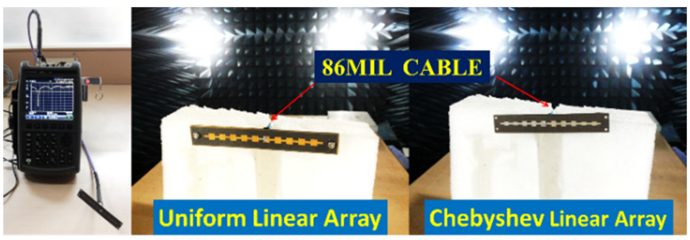
1. *Impedance Bandwidth*

The uniform and Chebyshev 10-element series-fed linear arrays are fabricated and measured to validate the design. Fig. 2 shows the prototype array antenna for K-band applications. The measurement setup for both *S*-parameters and radiation patterns are shown in Fig. 3. The simulated structure using the CST Microwave Studio Simulator shows the electric field distribution illustrated in Fig. 4. The measured return loss $|S_{11}|$ of the proposed K-band 10-element series-fed uniform and Che-



(a) (b)

Fig. 2. Photograph of the fabricated prototypes: (a) Top view of the ULA and CLA and (b) Bottom view of the ULA and CLA.



(a) (b)

Fig. 3. *S*-parameters and radiation pattern measurement setup: (a) ULA and (b) CLA.

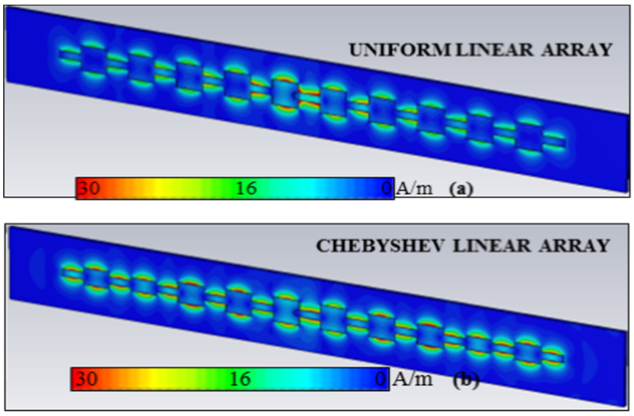


Fig. 4. (a) Uniform amplitude distribution–surface current distribution at 21 GHz and (b) Chebyshev amplitude distribution–surface current distribution at 21 GHz.

byshev linear arrays is presented in Fig. 5. The measured −10 dB impedance bandwidth varies at 20.912–21.192 GHz (1.33%) for the uniform array and at 20.89–21.196 GHZ (1.45%) for the Chebyshev array with a resonant frequency of 21 GHz for each design.

2. Radiation Characteristics

Figs. 6 and 7 show the radiation performance of the simulated and measured results of ULA and CLA, respectively, for the K-band. The radiation is a linear vertical polarization with a

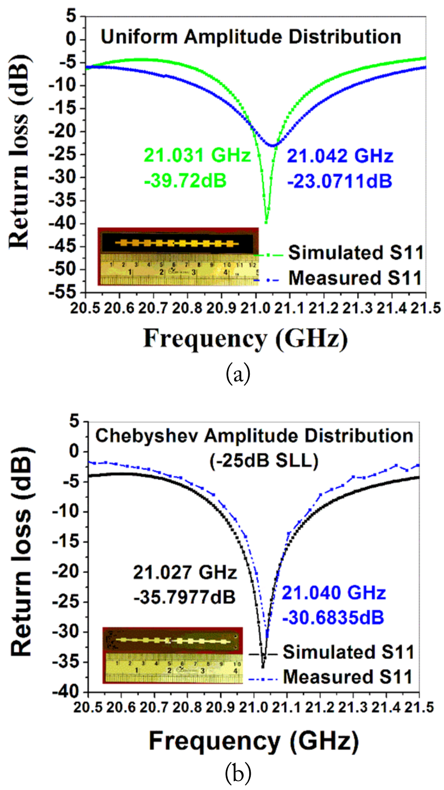


Fig. 5. Simulated and measured reflection coefficients: (a) ULA and (b) CLA.

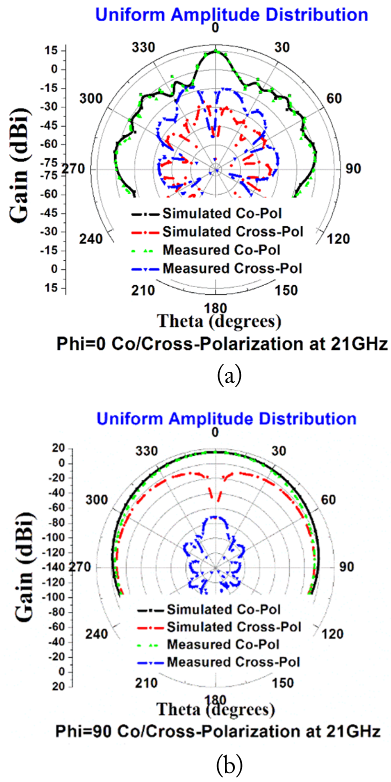


Fig. 6. Simulated and measured radiation patterns for the ULA at 21 GHz: (a) ϕ = 0° E-plane (co-pol and cross-pol) and (b) ϕ = 90° H-plane (co-pol and cross-pol).

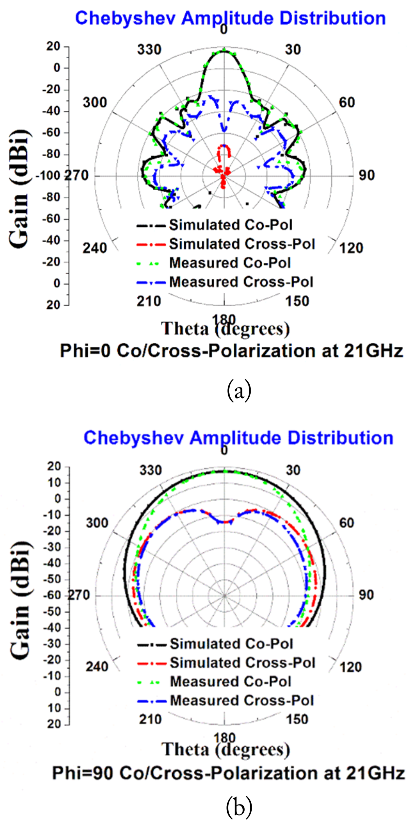
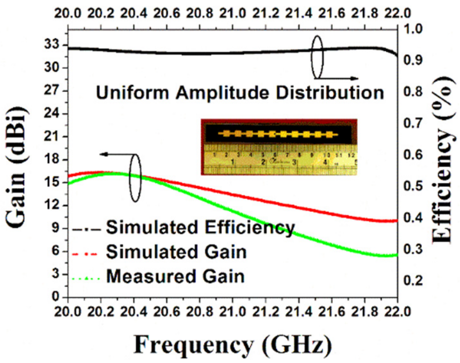


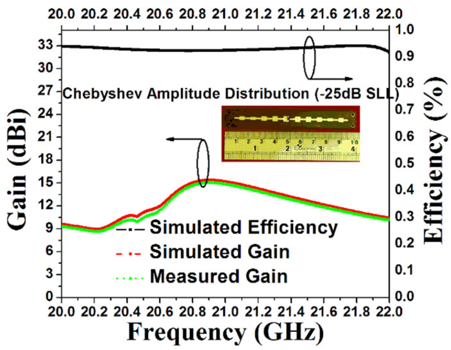
Fig. 7. Simulated and measured radiation patterns for the CLA at 21 GHz: (a) ϕ = 0° E-plane (co-pol and cross-pol) and (b) ϕ = 90° H-plane (co-pol and cross-pol).

high front-to-back ratio and a highly symmetric profile in both the x–z and y–z planes.

For the ULA design, the measured antenna gain is 15.3 dBi with HPBWs of 10.4° and 64.4° for the $\phi = 0°$ (E-plane) and $\phi = 90°$ (H-plane), respectively. The maximum SLLs are –10.4 dB and –26.4 dB for the $\phi = 0°$ (E-plane) and $\phi = 90°$ (H-plane) in the case of ULA. For the CLA design, the measured antenna gain is 17.4 dBi with HPBWs of 9.1° and 64.9° for the E-plane and H-plane, respectively. The maximum SLLs are –26.3 dB and –26.3 dB for the E-plane and H-plane, respectively, in the case of CLA. From the measured results, the SLL reduction of greater than –12 dB and gain enhancement of greater than 2 dBi can be obtained simultaneously. The simulated radiation efficiency and the measured and simulated realized gains are shown in Fig. 8 for both the ULA and CLA arrays. Fig. 9 shows the 3D far-field gain. The results agree well with the simulated and measured antenna parameters. The radiation discrepancies between the simulation and the measurement are attributed to the fabrication errors. UAD and CAD has been compared with literature in Table 2.



(a)



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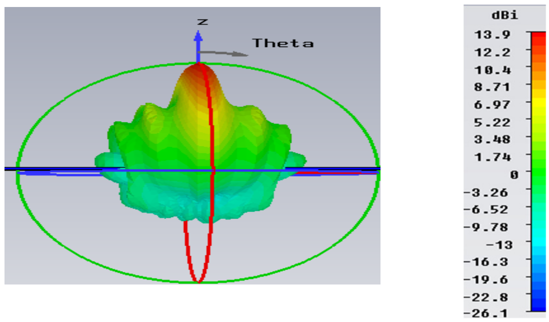
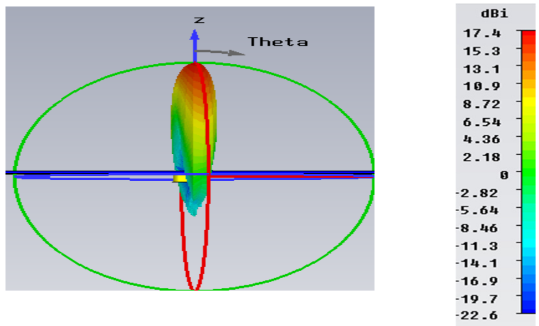
(b)

Fig. 8. Simulated radiation efficiency and measured gain: (a) ULA and (b) CLA.



(a)



(b)

Fig. 9. Simulated 3D far-field gain: (a) $\phi = 0°$ (E-plane) ULA at 21 GHz and (b) $\phi = 0°$ (E-plane) CLA at 21 GHz.

The results of this work are compared with those in the literature in Table 3. The proposed array has a gain of 17.4 dBi with the same number of elements, and it is higher than that in [13] with only 14.5 dBi and in [15] with approximately 15.7 dBi. In this work, the SLL is 1 dBi higher than that in [13] and 3 dB higher than that in [15]. Compared with that in [16], the antenna has better gains and SLL results.

IV. Conclusion

A novel SFCFOS antenna design for K-band radar applications is presented in this letter. The antenna structure shows a high gain performance and a low sidelobe level with a conformal size. The measured results are in good agreement with the simulated ones with gains of 15.3 dBi and 17.4 dBi, respectively.

Table 2. Comparison with the uniform amplitude distribution

Ref.	Year	No. of elements	SLL (dB)	HPBW (°)	Resonant frequency (GHz)	Gain (dBi)	Beam scan range (°)
[19]	2004	1 × 4	–9	25	2	8.7	20
[20]	2007	1 × 5	–10	N/A	5.8	11.3	22
[21]	2010	1 × 8	–10	N/A	2	N/A	25
This work	-	1 × 10	–25	10.4	21	15.3	25

Table 3. Comparison with the Chebyshev amplitude distribution

Ref.	Year	No. of elements	SLL (dB)	HPBW (°)	Resonant frequency (GHz)	Gain (dBi)	Beam scan range (°)
[14]	2013	1 × 22	–30	NA	9.2	19	NA
[15]	2016	1 × 10	–27.5	NA	60	15.7	NA
[16]	2017	1 × 8	–23.1	NA	7.54	15.7	NA
[13]	2017	1 × 10	–25.3	8.3	9	14.5	NA
This work	-	1 × 10	–26.3	9.1	21	17.4	25

The gain enhancement greater than 1.5 dBi can be obtained with an SLL of –25 dB using the CLA with 10 elements in the operating frequency band of 20.9–21.19 GHz. The HPBWs for the CLA/ULA at both E-plane and H-plane are 9.1°/10.4° and 64.4°/64.9°, respectively. With these advantages, the proposed antenna array is a good candidate for use in radar systems.

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