Progress In Electromagnetics Research C, Vol. 65, 1–9, 2016

Broadband Flat Gain Enhancement of Planar Double-Dipole Quasi-Yagi Antenna Using Multiple Directors

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Abstract—In this article, a method of broadband flat gain enhancement for a planar double-dipole quasi-Yagi antenna using multiple directors is proposed. The proposed antenna consists of two dipole drivers with different lengths, a truncated ground plane, and three parasitic strip directors. First, the length ratio of the two dipoles is adjusted to increase the gain in the low-frequency region. Next, three parasitic strip directors are employed to increase the impedance bandwidth and improve the gain of the antenna in the middle- and high-frequency regions. A detailed design procedure for the proposed antenna, covering a frequency band of 1.70–2.70 GHz with a gain > 8 dBi, is explained, along with a step-by-step analysis of the effects of placing each director on input impedance, voltage standing wave ratio (VSWR), and gain characteristics. Experiment results show that the proposed antenna has the desired impedance characteristics with a frequency band of 1.66–2.88 GHz (53.7%) for a VSWR < 2, and a stable flat gain of 8.0–8.4 dBi in the 1.70–2.70 GHz frequency range. Moreover, a measured front-to-back ratio > 11 dB within the band is achieved.

1. INTRODUCTION

In recent years, various types of planar quasi-Yagi antennas (QYAs) have been widely used as high performance broadband unidirectional antennas because of their advantageous properties: simple structure, broad bandwidth, moderate gain, high front-to-back ratio, low cross-polarization level, and ease of fabrication [1].

To increase the gain of a planar QYA, many different techniques have been developed. A planar microstrip Yagi array antenna with two rows of a patch-shaped director pair was proposed, and an impedance bandwidth of 10% at around 5.2 GHz with a gain > 10 dBi was achieved [2]. Six rows of a strip-shaped director pair were employed in a wideband microstrip-fed QYA, and a bandwidth of 85.5% (1.84–4.59 GHz) with a gain of about 4.5–9.3 dBi was obtained [3]. A reconfigurable printed QYA consisting of a driver dipole and four strip directors with varactor diodes was introduced for the 478–741 MHz UHF TV band. A 46% continuous frequency tuning bandwidth with a gain of 8–12 dBi was achieved [4]. However, the gain in the low-frequency region of these antennas is always 2–4 dBi lower than in the high frequency region, and therefore, a design method to achieve a stable and flat gain in the whole operating frequency band needs to be investigated.

Several approaches have attempted to achieve a flat and enhanced gain characteristic for different types of antennas. A radome consisting of a pair of parallel strips printed on the bottom of a dielectric material was proposed to increase the boresight gain of a microstrip patch antenna [5]. An impedance bandwidth of 9.2% (2.39–2.62 GHz) and a flat gain of 6–7 dBi were obtained by placing the radome above the patch antenna with some air spacing. A compact double-dipole QYA (DDQYA) consisting of two dipoles having different lengths, a truncated ground plane, and an integrated balun was introduced to

Received 21 April 2016, Accepted 21 May 2016, Scheduled 9 June 2016
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achieve an impedance bandwidth of about 49% with a flat gain of 5–6 dBi in the band [6]. An elliptically tapered slot antenna with high and relatively-flat gain of 9.3–11.5 dBi operating in the frequency range of 2.65–12.90 GHz was proposed for ultra-wideband applications [7]. A printed frequency beam-scanning antenna with flat gain and low sidelobe levels operating in the frequency range of 8.9–10.6 GHz was reported [8]. It consists of a low-loss slow-wave printed meander line based on the even-mode bilateral broadside-coupled suspended microstrip line, and exhibits flat gain of more than 13 dBi in the band. An ultra-wideband qusi-planar antenna composed of a CPW-fed printed semi-circular disc monopole antenna and a short horn mounted on the surface of the monopole with nearly constant gain of 5.5 dBi±0.7 dB operating in the frequency range of 2–15 GHz was proposed [9].

In this paper, a method of broadband flat gain enhancement for a planar DDQYA using multiple directors is proposed. The DDQYA consists of two dipoles with different lengths and a truncated ground plane, which are serially connected through a transmission line. A broadband or a dual-band frequency characteristic can be achieved by adjusting the lengths of the two dipoles and the distance between them. In addition, the impedance bandwidth and the gain in the high frequency region of the DDQYA can be enhanced by appending directors. Therefore, the design degree of freedom of the DDQYA is much higher than that of the QYA. The proposed antenna consists of two dipole drivers with different lengths, a truncated ground plane, and three parasitic strip directors. The two dipoles and the ground plane are serially connected through a coplanar strip (CPS) line, and a simple integrated balun consisting of a microstrip (MS) line and a CPS line is used to match the input impedance of the antenna to the 50 Ω feed line with compact ground size. Three parasitic strip directors are employed to increase the impedance bandwidth and to improve the gain of the antenna in the high-frequency region.

A detailed design procedure for the DDQYA with multiple directors, covering a frequency band ranging from 1.70 GHz to 2.70 GHz with a gain > 8 dBi is explained. A step-by-step analysis of the effects of placing each director on input impedance, voltage standing wave ratio (VSWR), and gain characteristics is also provided. The results in this work were obtained using a commercial electromagnetic simulator, CST Microwave Studio, and were validated by measurements of input VSWR, gain, and radiation patterns tested in an anechoic chamber.

2. ANTENNA GEOMETRY AND DESIGN

Figure 1 shows the geometry of the proposed DDQYA with multiple directors. It consists of two strip dipole elements, dipole 1 ($\mathbf{D_1}$) and dipole 2 ($\mathbf{D_2}$), with different lengths, a truncated ground plane

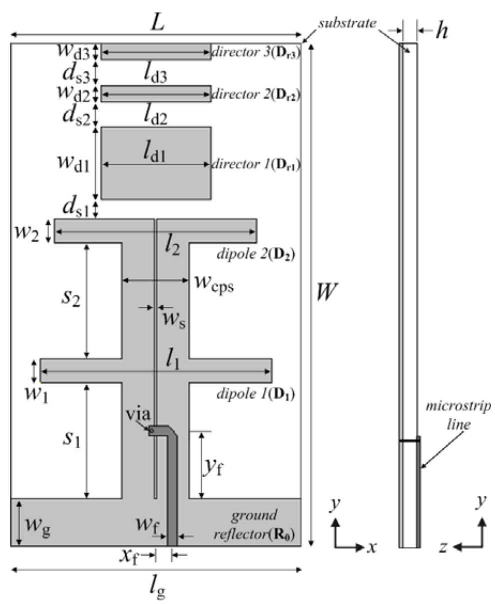


Figure 1. Geometry of the proposed DDQYA with multiple directors.

($\mathbf{R_0}$), and three parasitic strip directors ($\mathbf{D_{r1}}$, $\mathbf{D_{r2}}$, and $\mathbf{D_{r3}}$) appended above $\mathbf{D_2}$. An integrated balun between the MS line and the CPS line is implemented on the CPS line to match the input impedance of the antenna to the 50 Ω feed line, and the end of the MS line is shorted using a shorting pin at the feeding point. The length and width of $\mathbf{D_1}$ are l_1 and w_1, respectively, and those of $\mathbf{D_2}$ are l_2 and w_2, respectively. The length and width of $\mathbf{R_0}$ are l_g and w_g, respectively. The distance between $\mathbf{R_0}$ and $\mathbf{D_1}$ is s_1, and that between $\mathbf{D_1}$ and $\mathbf{D_2}$ is s_2. The widths of the CPS line and slot line are denoted as $w_{cps}$and w_s, respectively. The width of the MS feed line is w_f, and the MS feed is offset from the center at a distance of x_f.

Two different types of directors are appended to $\mathbf{D_2}$ of the DDQYA. First, a rectangular-patch-shaped strip director ($\mathbf{D_{r1}}$) is placed at distance d_{s1} from $\mathbf{D_2}$ to enhance the bandwidth and gain characteristics of the DDQYA. The length and width of $\mathbf{D_{r1}}$ are l_{d1} and w_{d1}, respectively. Next, two thin strip-shaped directors ($\mathbf{D_{r2}}$ and $\mathbf{D_{r3}}$) are placed above $\mathbf{D_{r1}}$. The distance between $\mathbf{D_{r1}}$ and $\mathbf{D_{r2}}$ is d_{s2}, and the distance between $\mathbf{D_{r2}}$ and $\mathbf{D_{r3}}$ is d_{s3}. The length and width of $\mathbf{D_{r2}}$ are l_{d2} and w_{d2}, respectively, and those of $\mathbf{D_{r3}}$ are l_{d3} and w_{d3}, respectively. The antenna is printed on an FR4 substrate with a dielectric constant of 4.4 and a thickness of 1.6 mm (loss tangent = 0.025). The length and width of the substrate are L and W, respectively. The final design parameters of the proposed antenna to achieve a gain > 8 dBi in the frequency range of 1.70–2.70 GHz are obtained based on parametric study, and these are summarized in Table 1.

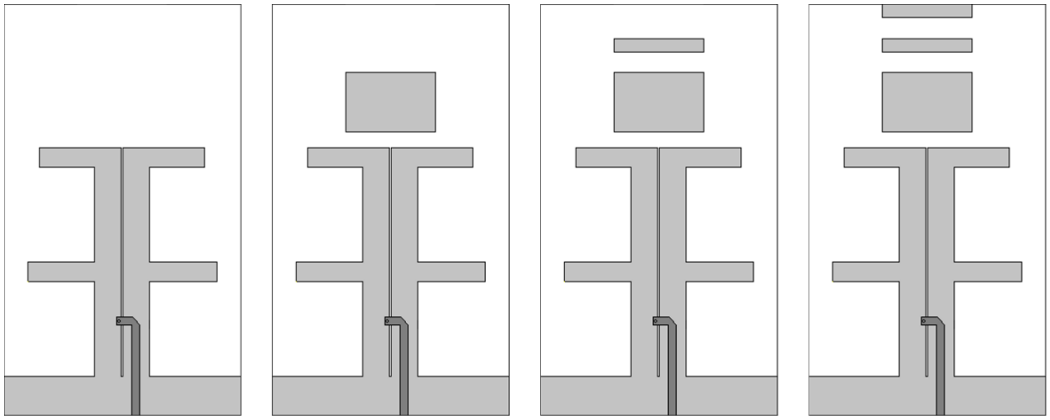
Table 1. Final design parameters of the proposed DDQYA with multiple directors.

Parameter	Value [mm]	Parameter	Value [mm]
L	86.2	x_f	5
W	150	y_f	20.1
l_1	69	l_{d1}	32.6
w_1	7.2	w_{d1}	21.6
s_1	34.5	d_{s1}	5.7
l_2	60	l_{d2}	32.6
w_2	7.2	w_{d2}	4.8
s_2	34.5	d_{s2}	7.7
l_g	86.2	l_{d3}	32.6
w_g	14	w_{d3}	4.8
w_{cps}	20	d_{s3}	7.7
w_f	3	h	1.6
w_s	0.3		

In order to compare the performance of the DDQYA, four antenna structures, depending on the number of directors, are considered in the design procedure, as shown in Figure 2.

Figure 3 shows the corresponding simulated input impedance, VSWR, and realized gain characteristics for the four antenna structures. First, a DDQYA without multiple directors is shown in Figure 2(a). It is well-known that the frequency band moves toward the low frequency, and the gain in the low-frequency region increases, when the length of the second dipole of the DDQYA increases [6]. Based on this knowledge, the length ratio of $\mathbf{D_2}$ to $\mathbf{D_1}$ is set to $r = l_2/l_1 = 0.87$ to enhance the gain in the low-frequency region.

Figure 4 shows the effects of varying the length ratio r from 0.7 to 0.87 on the input VSWR and gain characteristics of the DDQYA without directors. l_1 is fixed at 69 mm, and therefore, l_2 is increased from 48.3 mm to 60.0 mm. Other design parameters are the same as those in Table 1. For instance, when $r = 0.7$, the frequency band for a VSWR < 2 is 1.73–2.64 GHz (41.6%), and the gain is 5.4–6.6 dBi in the band. When r is increased to 0.87, the band decreases to 1.67–1.86 GHz (10.8%), and the gain in the band is 7.2–8.1 dBi. However, the gain in the frequency range of 1.6–1.74 GHz becomes larger than 8 dBi. In this case, the input resistance is in the range of 34–46 Ω, whereas the input reactance is in the range of −33 to 34 Ω in the band.



(a) (b) (c) (d)

Figure 2. Design procedure for the proposed DDQYA: (a) DDQYA without multiple directors, (b) DDQYA with $\mathbf{D_{r1}}$ only, (c) DDQYA with $\mathbf{D_{r1}}$ and $\mathbf{D_{r2}}$, and (d) DDQYA with $\mathbf{D_{r1}}$, $\mathbf{D_{r2}}$, and $\mathbf{D_{r3}}$.

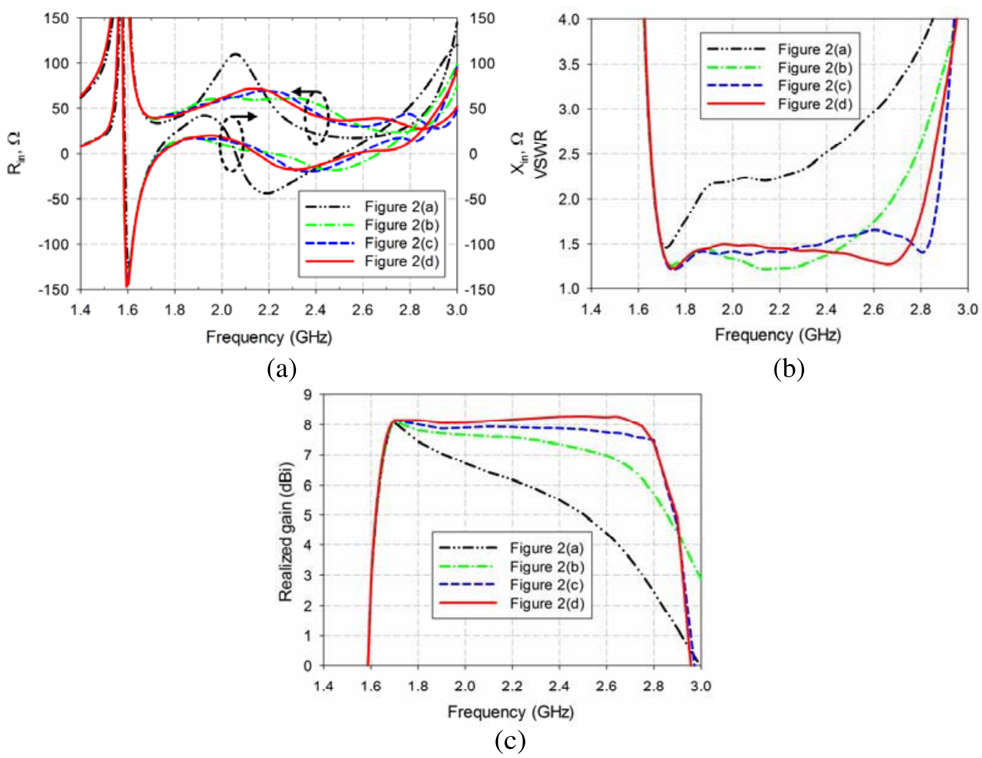
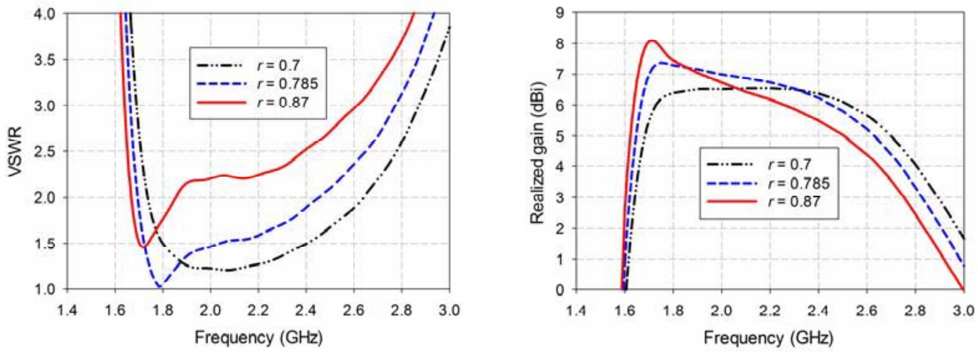


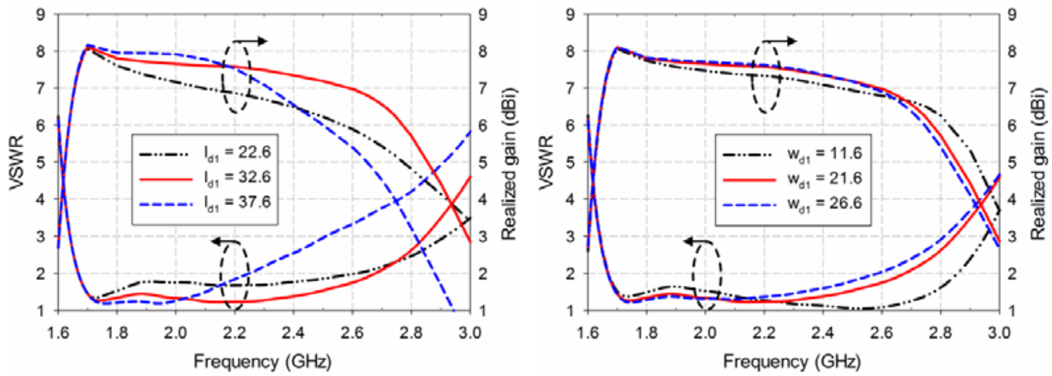
Figure 3. Performance comparison of the four antenna structures shown in Figure 2: (a) input impedance, (b) VSWR, and (c) realized gain.

Next, a rectangular-patch-shaped strip director ($\mathbf{D_{r1}}$) is appended to the DDQYA, as shown in Figure 2(b). The length and width of $\mathbf{D_{r1}}$ and the distance between $\mathbf{D_2}$ and $\mathbf{D_{r1}}$ are adjusted to increase the impedance bandwidth and the gain in the middle- and high-frequency regions of the DDQYA. The effects of varying l_{d1} and w_{d1} on the input VSWR and realized gain characteristics are shown in Figure 5. In Figure 5(a), l_{d1} varies from 22.6 mm to 37.6 mm, and other design parameters are the same as those in Table 1. When $l_{d1} = 22.6$ mm, the frequency band for a VSWR < 2 is 1.67–2.62 GHz, and gain ranges from 5.4 dBi to 8.1 dBi in the 1.70–2.70 GHz band. When l_{d1} is increased to 32.6 mm, the frequency band for a VSWR < 2 is 1.67–2.68 GHz, and gain ranges from 6.6 dBi to 8.1 dBi. When l_{d1} is further increased to 37.6 mm, the frequency band for a VSWR < 2 is reduced to 1.67–2.25 GHz, and gain varies from



(a) (b)

Figure 4. Effects of varying length ratio r on the performance of the DDQYA without directors: (a) input VSWR and (b) realized gain.



(a) (b)

Figure 5. Effects of varying l_{d1} and w_{d1} on the performance of the DDQYA shown in Figure 2(b): (a) l_{d1} and (b) w_{d1}.

4.5 dBi to 8.2 dBi in the 1.70–2.70 GHz band. Hence, $l_{d1} = 32.6$ mm is chosen for impedance matching and stable gain over the 1.70–2.70 GHz band. In Figure 5(b), w_{d1} varies from 11.6 mm to 26.6 mm, and other design parameters are the same as those in Table 1. When $w_{d1} = 11.6$ mm, the frequency band for a VSWR < 2 is 1.67–2.86 GHz, and gain ranges from 6.6 dBi to 8.1 dBi in the 1.70–2.70 GHz band. When l_{d1} is increased to 21.6 mm, the frequency band for a VSWR < 2 is 1.67–2.68 GHz, and gain ranges from 6.6 dBi to 8.1 dBi. When l_{d1} is further increased to 26.6 mm, the frequency band for a VSWR < 2 is reduced to 1.67–2.59 GHz, and gain varies from 6.4 dBi to 8.1 dBi in the 1.70–2.70 GHz band. Hence, $w_{d1} = 21.6$ mm is chosen for large average gain over the 1.70–2.70 GHz band. The final geometric parameters related to $\mathbf{D_{r1}}$ are as follows: $d_{s1} = 5.7$ mm, $l_{d1} = 32.6$ mm, and $w_{d1} = 21.6$ mm. In this case, the frequency band for a VSWR < 2 is 1.67–2.68 GHz (46.4%), and the gain is 6.6–8.1 dBi in the 1.70–2.70 GHz band. The input resistance is in the range of 25 to 62 Ω, whereas the input reactance is in the range of -34 to 18 Ω in the band.

Thirdly, the second thin strip director ($\mathbf{D_{r2}}$) is employed, as shown in Figure 2(c), because the impedance bandwidth cannot cover the desired frequency band of 1.70–2.70 GHz, and the gain is less than 8 dBi except 1.69–1.74 GHz. The geometric parameters related to $\mathbf{D_{r2}}$ are as follows: $d_{s2} = 7.7$ mm, $l_{d2} = 32.6$ mm, and $w_{d2} = 4.8$ mm. We note that these parameters are obtained through parametric study to increase the impedance bandwidth and the gain in the middle- and high-frequency regions. When $\mathbf{D_{r2}}$ is added to the antenna, the frequency band for a VSWR < 2 is extended to 1.67–2.87 GHz (52.9%), and the gain ranges from 5.5 dBi to 8.2 dBi in the band. The input resistance is in the range of 30 to 69 Ω, whereas the input reactance is in the range of -35 to 20 Ω in the band. Although the frequency band for a gain > 8 dBi is extended to 1.69–1.80 GHz, its value is still less than 8 dBi in the frequency range of 1.80–2.70 GHz.

Finally, the third thin strip director ($\mathbf{D_{r3}}$) is added to the antenna in order to enhance the gain in the middle- and high-frequency regions, as shown in Figure 2(d). The geometric parameters related to $\mathbf{D_{r3}}$ are as follows: $d_{s3} = 7.7$ mm, $l_{d3} = 32.6$ mm, and $w_{d3} = 4.8$ mm. When $\mathbf{D_{r3}}$ is added to the antenna, the frequency band for a VSWR < 2 is slightly reduced to 1.67–2.82 GHz (51.2%), and the gain is 7.0–8.3 dBi in the band. Note that the gain in the frequency range of 1.70–2.70 GHz is 8.1–8.3 dBi, which satisfies the gain requirement of the DDQYA. The input resistance is in the range of 29 to 72 Ω, whereas the input reactance is in the range of −36 to 20 Ω in the band.

Figure 6 compares the simulated radiation patterns of the four antenna structures in the E-plane (x-y plane) and H-plane (y-z plane) at 1.7 GHz, 2.2 GHz, and 2.7 GHz. At 1.7 GHz, the radiation patterns of the four antenna structures are almost the same with a similar peak gain value of around 8.1 dBi, as shown in Figure 6(a). However, the peak gain value at 2.2 GHz increases to 8.2 dBi for Figure 2(d) from 6.2 dBi for Figure 2(a). When the frequency is increased to 2.7 GHz, the peak gain value further increases to 8.1 dBi for Figure 2(d) from 3.5 dBi for Figure 2(a).

The simulated surface current distributions of the proposed DDQYA at 1.7 GHz and 2.7 GHz are shown in Figure 7. We can observe that the surface currents are strong on $\mathbf{D_1}$ and $\mathbf{D_2}$, and they are weak on the directors at 1.7 GHz. However, the surface currents on the directors are enhanced at 2.7 GHz, which means the three directors are working effectively in the high-frequency region.

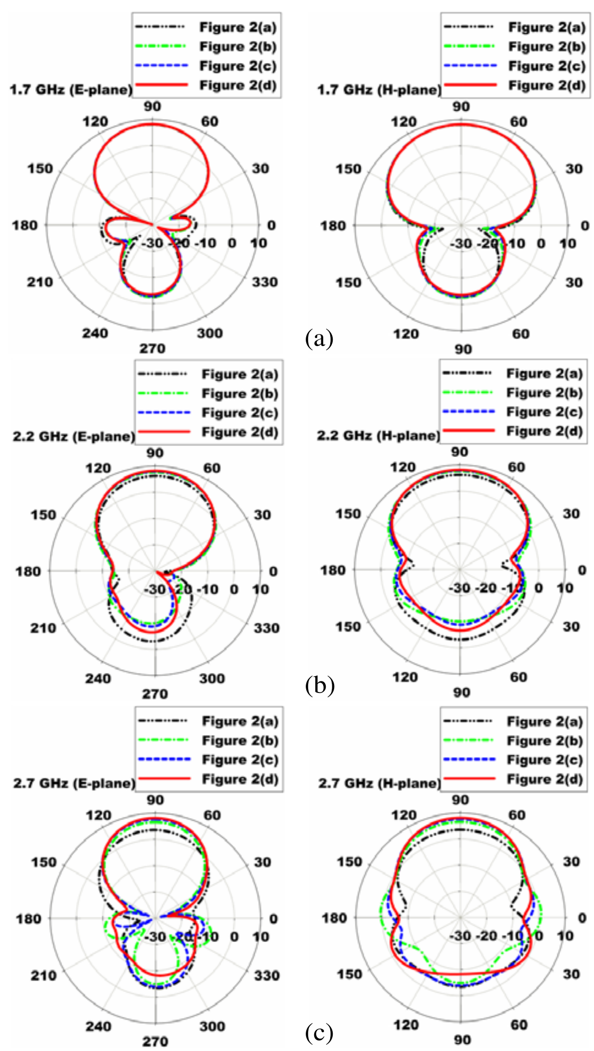


Figure 6. Comparison of radiation patterns of the four antenna structures in the E- and H-planes at (a) 1.7 GHz, (b) 2.2 GHz, and (c) 2.7 GHz.

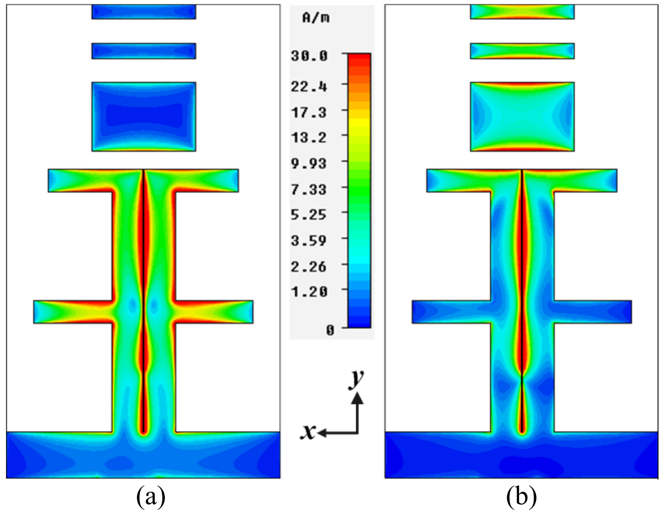


Figure 7. Simulated surface current distributions of the proposed DDQYA with multiple directors at (a) 1.7 GHz and (b) 2.7 GHz.

3. EXPERIMENT RESULTS AND DISCUSSION

A prototype of the proposed DDQYA with multiple directors was fabricated on an FR4 substrate. Figure 8 shows the photographs of the fabricated antenna.

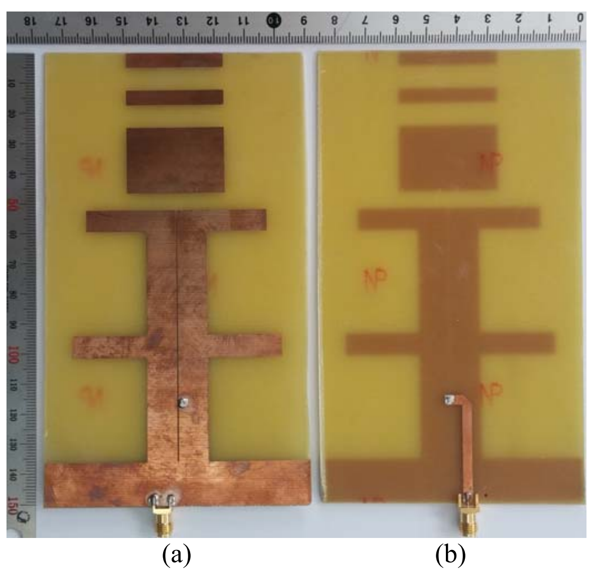
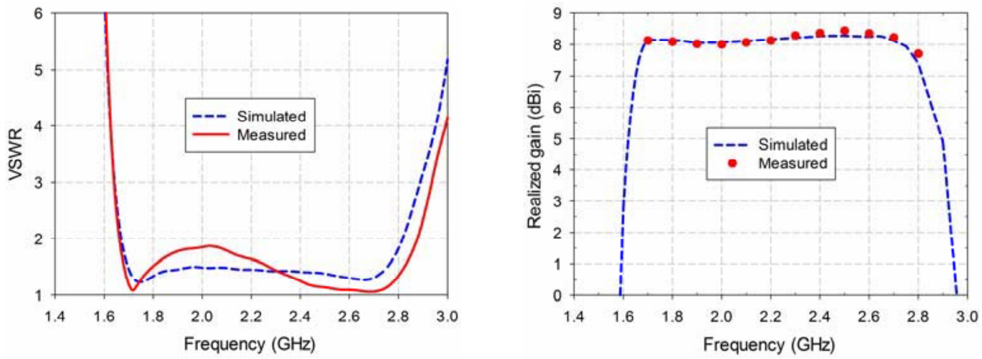


Figure 8. Photographs of the fabricated antenna: (a) front view and (b) back view.

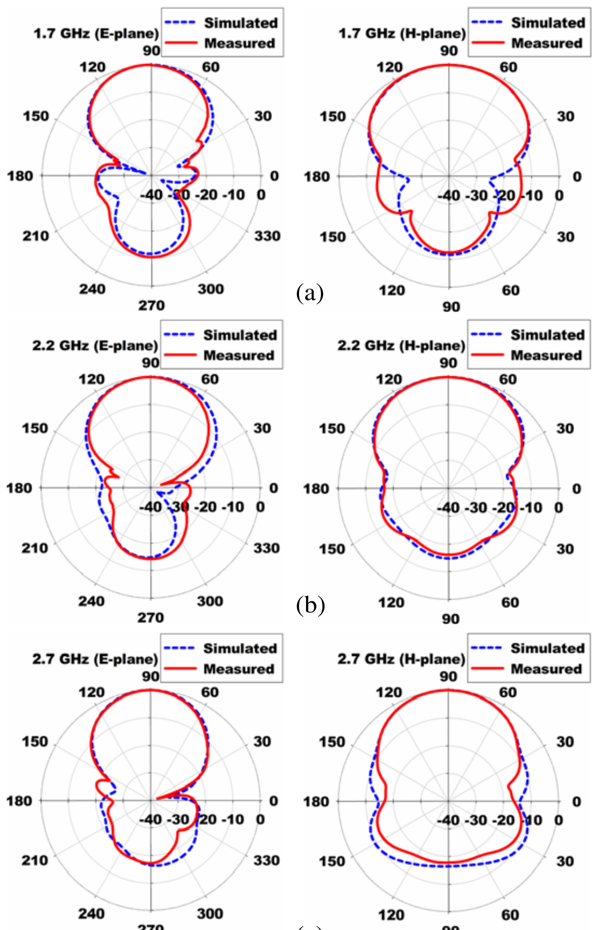
Figure 9 compares the input VSWR and gain characteristics of the fabricated DDQYA with multiple directors. An Agilent N5230A network analyzer was used to measure the input VSWR and gain. The simulated and measured bandwidths of the proposed antenna for a VSWR < 2 are 1.67–2.82 GHz (51.2%) and 1.66–2.88 GHz (53.7%), respectively, as shown in Figure 9(a). The measured impedance bandwidth is slightly increased compared to the simulated one. The simulated gain is 8.1–8.3 dBi in the frequency band of 1.70–2.70 GHz, whereas the measured gain of the proposed antenna ranges from 8.0 dBi to 8.4 dBi, which satisfies the desired requirement of a gain > 8 dBi.

Figure 10 shows the simulated and measured radiation patterns of the proposed DDQYA with



(a) (b)

Figure 9. Measured performance: (a) input VSWR and (b) gain.



(a) (b) (c)

Figure 10. Measured radiation patterns in the E- and H-planes at (a) 1.7 GHz, (b) 2.2 GHz, and (c) 2.7 GHz.

multiple directors in the E-plane (x-y plane) and H-plane (y-z plane) at 1.7 GHz, 2.2 GHz, and 2.7 GHz. Table 2 compares the simulated and measured half-power beamwidths (HPBWs) in the E- and H-planes and the front-to-back ratios (FBRs) at 1.7 GHz, 2.2 GHz, and 2.7 GHz. The simulated and measured patterns agree well with each other, and the proposed antenna has end-fire directional patterns with a measured FBR > 11 dB in the frequency range of 1.70–2.70 GHz.

Table 2. Comparison of simulated and measured HPBWs in E- and H-planes and FBRs at 1.7 GHz, 2.2 GHz, and 2.7 GHz.

Freq. (GHz)	E-plane				H-plane			
	HPBW (degree)		FBR (dB)		HPBW (degree)		FBR (dB)	
	simulated	measured	simulated	measured	simulated	measured	simulated	measured
1.7	58.3	54.4	11.7	11.0	89.9	90.8	11.7	12.5
2.2	61.5	54.2	14.8	14.2	82.5	76.4	14.8	16.1
2.7	52.3	49.2	16.4	17.1	67.5	67.4	16.4	17.8

4. CONCLUSION

A design method for broadband flat gain enhancement in a double-dipole quasi-Yagi antenna using multiple directors has been presented in this paper. The length ratio of the two dipoles is first adjusted to increase the gain in the low-frequency region, and, then, three parasitic strip directors are employed to increase the impedance bandwidth and to improve the gain of the antenna in the middle- and high-frequency regions.

A prototype antenna operating in the frequency range of 1.70–2.70 GHz with a gain $>$ 8 dBi was designed and fabricated on an FR4 substrate to validate the effectiveness of the proposed design method. The fabricated antenna has the desired impedance characteristics with a frequency band of 1.66–2.88 GHz (53.7%) for a VSWR $<$ 2 and a flat gain of 8.0–8.4 dBi in the 1.70–2.70 GHz frequency range. Moreover, a measured FBR $>$ 11 dB within the band is achieved

The proposed antenna can be useful as a broadband flat-gain base-station antenna for covering various mobile communications systems (PCS, IMT-2000, LTE, LTE-A) and wireless services (WiBro, WLAN, Bluetooth, WiMAX). It also can be applicable for an element of wideband high gain phased-array systems.

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