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Design of spiral antenna using a Vivaldi-shaped balun

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ABSTRACT
This paper proposes a design of a spiral antenna using a Vivaldi-shaped balun for broadband matching characteristic with high tolerance to fabrication error and low geometrical complexity. The proposed antenna consists of spiral arms, a Vivaldi-shaped balun, and a ground with a cavity-backed structure. The Vivaldi-shaped balun is connected to the spiral two arms to obtain broad matching characteristics, and the cavity-backed structure is employed to achieve a high directivity. To verify proposed antenna performance, such as reflection coefficients, bore-sight gains, and radiation patterns, the antenna is measured in a full anechoic chamber. The results confirm that the proposed antenna is suitable for broadband spiral antennas with high tolerance to fabrication error and low design complexity.

KEYWORDS
Spiral antennas; Vivaldi-shaped balun; Hybrid antenna

Introduction

Spiral antennas have been used for various applications, such as commercial and military wireless systems. The wide impedance bandwidth and circular-polarized (CP) pattern of spiral antennas allow for their use in various communication services such as satellite digital audio radio service (SDARS), personal communication service (PCS), and global positioning system (GPS) (Stutzke and Filipovic 2005). A two-arm Archimedean spiral antenna that has a constant input impedance with a CP radiation pattern over a wide bandwidth was proposed by Kaiser in 1960 (Kaiser 1960). To achieve the impedance-matching characteristic over a wide range of frequencies, the radiating spiral arms should be connected to a broadband balun that transforms the unbalanced coaxial mode into a balanced two-wire transmission line mode. The balun provides impedance transformation from 50 Ω of the coaxial line to the impedance of the spiral antenna. Extensive efforts have been made to obtain broadband matching for the spiral antennas using baluns, for example adopting the Dyson balun (Dyson and Mayes 1961; Filipovic, Bhobe, and Cencich 2005; Mruk et al. 2010), a printed circuit balun (Chen and Huff 2011; Yang and Rahmat-Samii 2003), and a lumped-element balun (Balanis 1997; Hertel and Smith 2002; Liu, Yang, and Wang 2013). However, this previous research has been limited by a complicated geometrical structure and tight tolerance to fabrication error. Although the design complexity of balun can be reduced by applying the tapered balun for broadband operation, this approach should insert the additional structure, such as lumped resistors

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and reflector, to decrease the reflected current (Nam and Seo 2018; Wang, Wang, and Zeng 2010; Zhong et al. 2017).

In this paper, we propose a novel design of a spiral antenna using a Vivaldi-shaped balun for broadband matching characteristics. In order to achieve the low design complexity without inserting the additional structure, the proposed antenna adopts a balun with a Vivaldi shape that is well-known for its broadband characteristics even at a small size. This proposed Vivaldi-shaped balun is connected to two spiral arms to provides impedance transformation from 50 Ω of the coaxial line to the impedance of the spiral antenna over a broad bandwidth, and the cavity-backed structure has been employed to guide the radiation pattern in the forward direction. To demonstrate the antenna characteristics, such as reflection coefficient, bore-sight gain, and patterns, the proposed antenna are measured in a full anechoic chamber. To further verify the tolerance of the proposed antenna to the fabrication error, we observe the degradation of the impedance matching when slight fabrication errors are introduced to the design parameters of the balun. In addition, the bore-sight gains depending on the presence of some key structures, such as spiral arms and cavity-back are investigated to better understand the operating principle of the proposed antenna. The results demonstrate that the proposed antenna is suitable for broadband spiral antenna in various communication systems where requires a high tolerance to fabrication error and low design complexity.

Proposed antenna design

Figure 1(a) shows the proposed spiral antenna using a Vivaldi-shaped balun, which is used to obtain broadband matching characteristics without inserting the additional structure, such as reflectors and resistors. Figure 1(b) presents the two-arm spiral with inner radius r_0 and outer radius r_{out}, printed on the FR4 substrate ($\varepsilon_r = 4.5$, $\tan\delta = 0.02$) with a thickness of 1 mm, and the spiral arms are connected to the Vivaldi-shaped balun at feed A and B point to achieve broadband operation. The cavity-backed structure with a height h_1 and a width c_d is employed to achieve high directivity of the antenna, and the two-arm spiral with balun is connected to cavity-backed structure to improve the antenna robustness as shown in Figure 1(c). The Vivaldi-shaped balun shown in Figure 1(d) and (e) is divided into two parts: coupled feed structure and flares with tapered slot. The length and width of tapered flares printed on the substrate are indicated by h_1 and w_2. The coupled feed structure designed using the stepped microstrip lines is specified as hb_1, hb_2, hb_3, and hb_4, and is printed on the other side of the tapered flares. The stepped microstrip line of the feeder is connected to a coaxial cable, and then the tapered flares are electromagnetically coupled to the feeder. The Vivaldi-shaped balun transforms the impedance of the coaxial line (50 Ω) to that of the spiral antenna. Therefore, by appropriately determining those key design parameters for the cavity and the balun, we can achieve a high gain radiation over a broad bandwidth. Detailed design parameters are optimized by a genetic algorithm (GA) (Kim et al. 2018) in conjunction with the FEKO EM simulator (Feko 2018), and the optimized values are listed in Table 1.

Measurement and analysis

To demonstrate the antenna performance, we fabricated the proposed antenna, as shown in Figure 2, and its antenna characteristics are measured in a full anechoic chamber. Figure 3

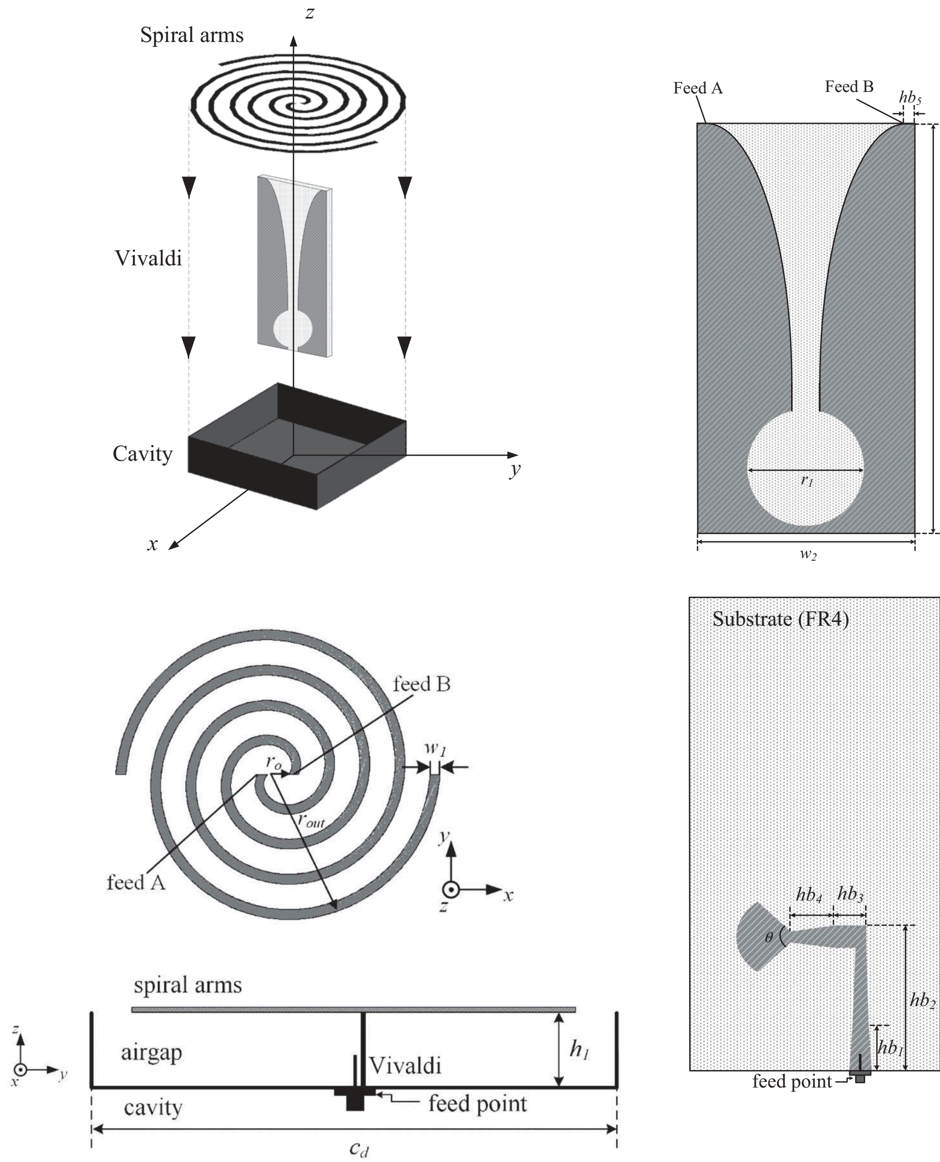

Figure 1. Geometry of the proposed antenna: (a) perspective view, (b) spiral arms, (c) side view, (d) top view of the Vivaldi, and (e) bottom view of the Vivaldi.

represents a comparison of the measured and simulated reflection coefficients, which are represented by solid and dashed lines, respectively. The measured average reflection coefficient is – 9.2 dB, which has a good agreement with the simulated value of – 8.1 dB.

Figure 4 shows the bore-sight gain of the proposed antenna, and the measured data are specified by the solid line with circular makers. The measured and simulated right-hand circular (RHC) polarized average gains are 7.03 dBic and 7.02 dBic (from 1 GHz to 4 GHz), and the measured cross-polarization level is 16.6 dB, which agrees well with the simulated result of 15.1 dB.

Table 1. Optimized values of the proposed antenna.

Parameters	Values
r_0	8 mm
r_{out}	73 mm
r_1	4.2 mm
w_1	1 mm
w_2	16 mm
hb_1	4 mm
hb_2	9.4 mm
hb_3	2.7 mm
hb_4	6.7 mm
hb_5	1 mm
c_d	180 mm
h_1	30 mm
θ	80°
substrate	$\varepsilon_r = 4.4$, $\tan\delta = 0.018$

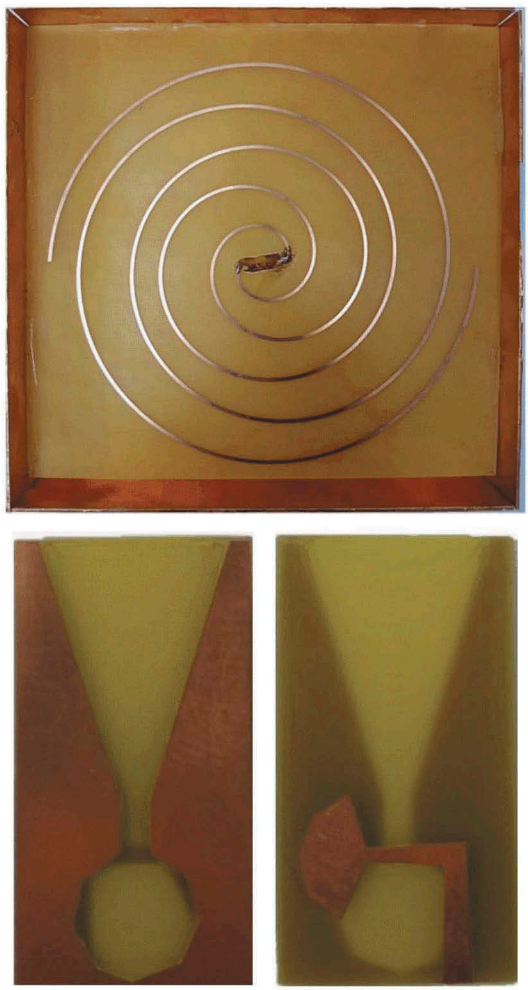

Figure 2. Photograph of the fabricated antenna: (a) top view of the spiral, (b) top view of the Vivaldi, and (c) bottom view of the Vivaldi.

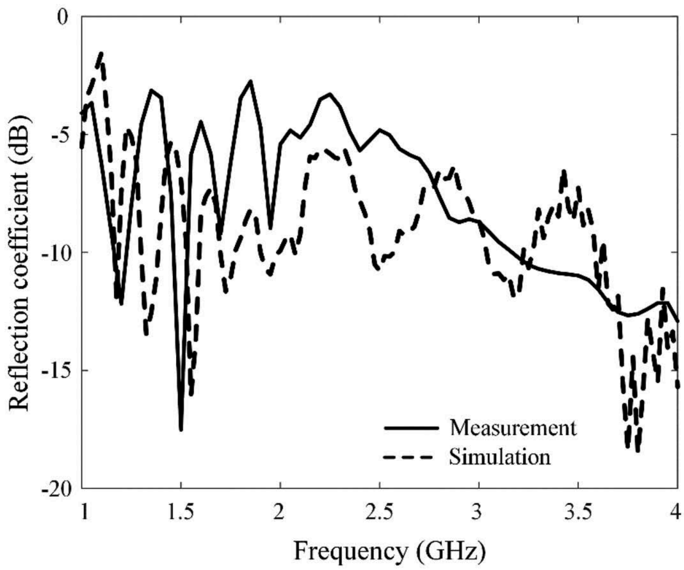

Figure 3. Reflection coefficient of the proposed antenna.

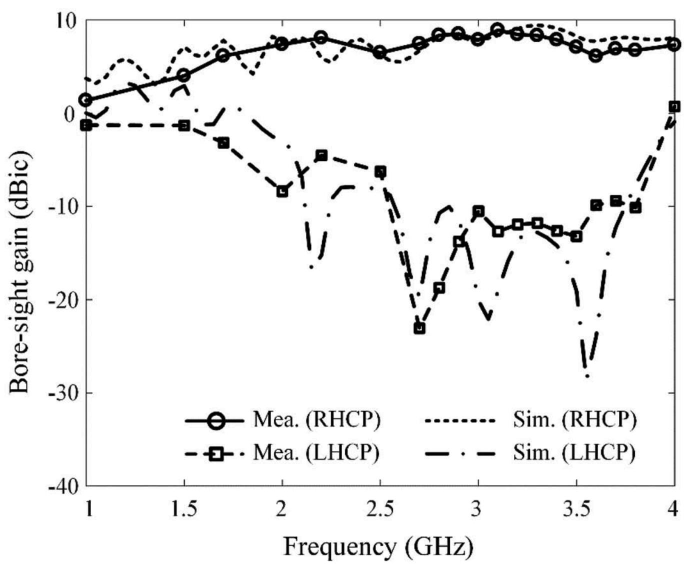

Figure 4. Bore-sight gain of the proposed antenna.

Figure 5 illustrates a comparison of axial ratio (AR) value in the bore-sight direction as a function of frequency. The solid line with circular markers exhibits the measured AR, and the simulation is expressed by the dashed line. The antenna has an average AR value of 2.6 dB (from 2 GHz to 4 GHz), and the simulated average value is 2.2 dB. The result confirm that the proposed antenna has RHC-polarized properties with an AR value lower than 3 dB without a significant degradation of performance.

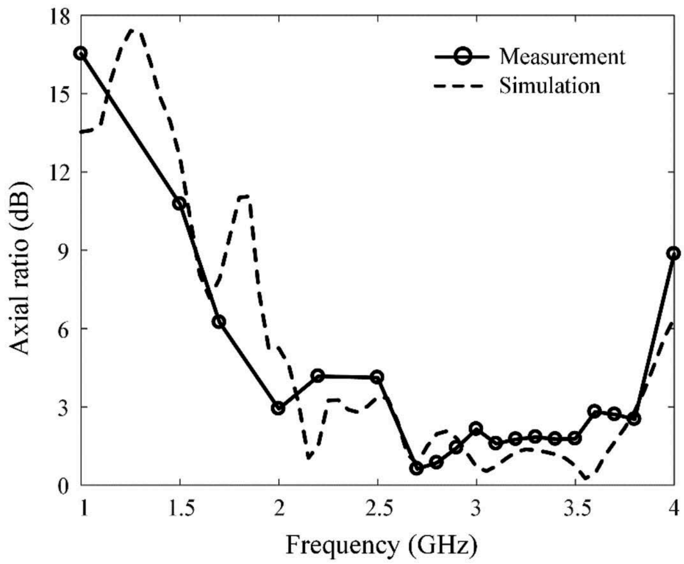

Figure 5. Axial ratio of the proposed antenna.

Figure 6(a) and (b) show the 2D radiation patterns of the proposed antenna in the *zx*- and *zy*-planes at operating frequency. In the *zx*-plane, the half-power beamwidths (HPBWs) are 60.0° (2 GHz), 65.0° (3 GHz), and 70.0° (4 GHz), and the simulated HPBWs are 70.8° (2 GHz), 65.5° (3 GHz), and 67.6° (4 GHz), respectively. The measured HPBWs in the *zy*-

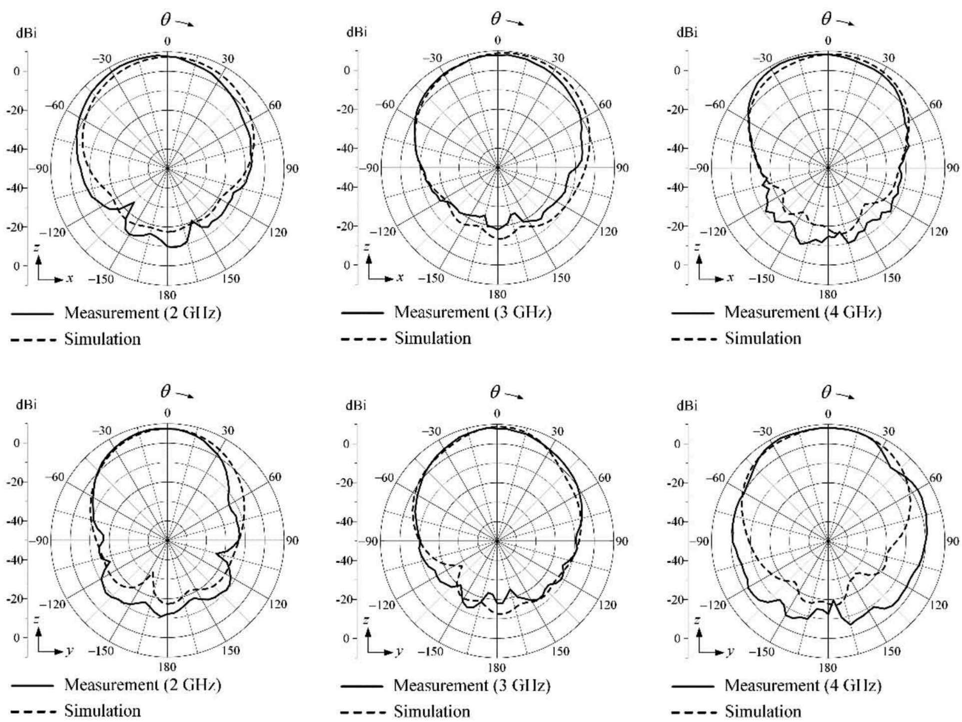

Figure 6. 2D radiation pattern of the proposed antenna: (a) *zx* plane and (b) *zy* plane.

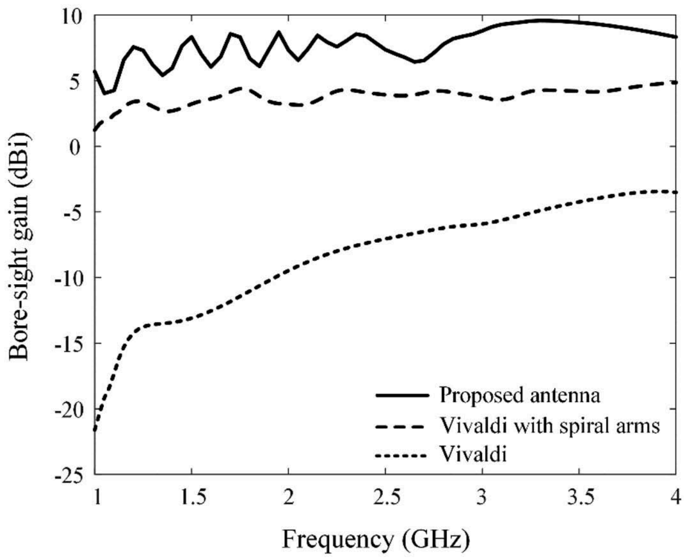

Figure 7. Comparison of the gain properties.

plane are 50.0°, 50.0°, and 70.0°, and these values agree well with the simulated data. As can be seen, the antenna does not exhibit any serious pattern distortion in the upper hemisphere with HPBWs of greater than 50°, which is suitable for use as a spiral antenna.

To verify how the proposed antenna operates, we observe variations in the bore-sight gain depending on the presence of several key structures, such as spiral arms and cavity-back structure as shown in Figure 7. The dotted line shows the gain without both the spiral arms and cavity-back, resulting in an average gain of less than −10 dBic, which indicates that the Vivaldi balun itself does not operate as a radiator. The dashed line indicates the property when only the cavity-back is excluded, and it represents the average gain of 3.8 dBic, which is 4 dB lower than the structure with the cavity-back. It can be seen that in order to improve the directivity of the antenna in the bore-sight direction, the cavity-backed structure should be added. To investigate the tolerance to the fabrication error, we observe variations in impedance characteristics of the proposed antenna when some fabrication errors are introduced into the dimensions of the balun. The parametric study according to the feeder radius (r_1) and the height (h_1) are presented in Figure 8(a) and (b). The value of r_1 varies from 3.1 mm to 4.5 mm at intervals of 0.3 mm, and the real and imaginary parts of the impedance exhibit low impedance deviations of 12.3 and 3.1, respectively. The impedance property is also observed when h_1 is varied from 24 mm to 36 mm at intervals of 2 mm, while other design parameters are fixed, as specified in Table 1, and the results show that the proposed antenna has a high tolerance to fabrication errors while maintaining broadband matching characteristics.

Figure 9 presents the comparison of front-to-back ratio as function of frequency between the proposed antenna and antenna without the cavity-backed structure. The

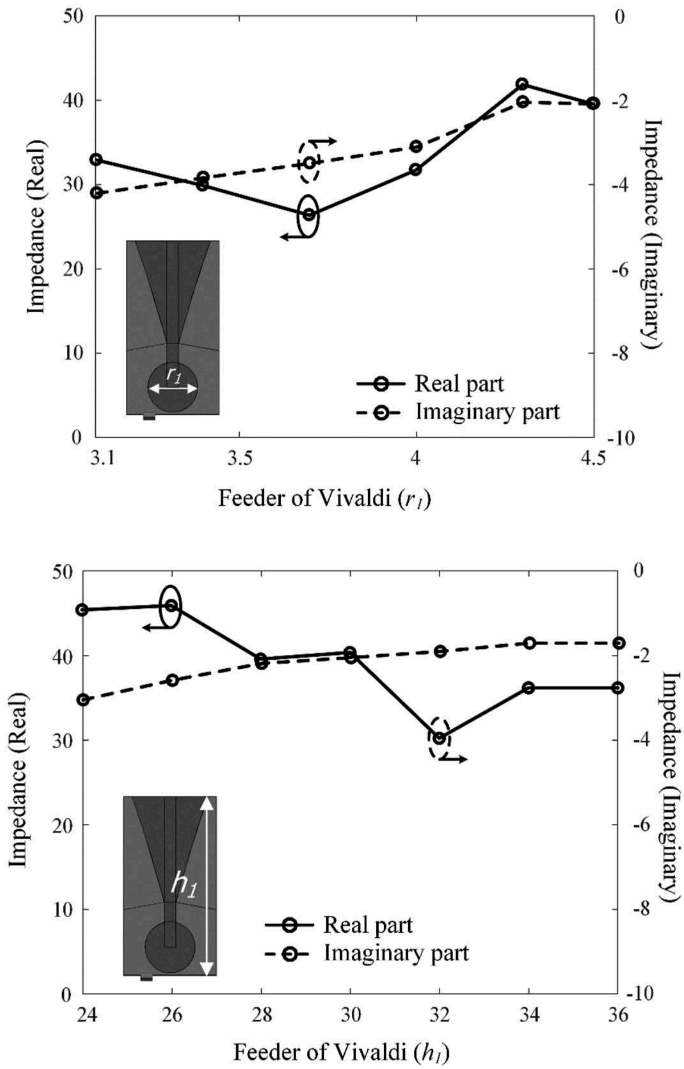

Figure 8. Parametric study of Vivaldi balun: (a) r_1 and (b) h_2.

front-to-back ratio improved by 17.6 dB due to the minimized backward radiation when the cavity-backed structure is employed.

Conclusion

We have proposed the novel design of a spiral antenna using a Vivaldi-shaped balun and cavity-backed structure with high fabrication tolerance and low geometrical complexity. The Vivaldi-shaped balun was inserted to the spiral arms to obtain broad matching characteristics, and the cavity-backed structure was employed to achieve high directivity and front-to-back ratio. To verify the feasibility of the proposed antenna, the antenna

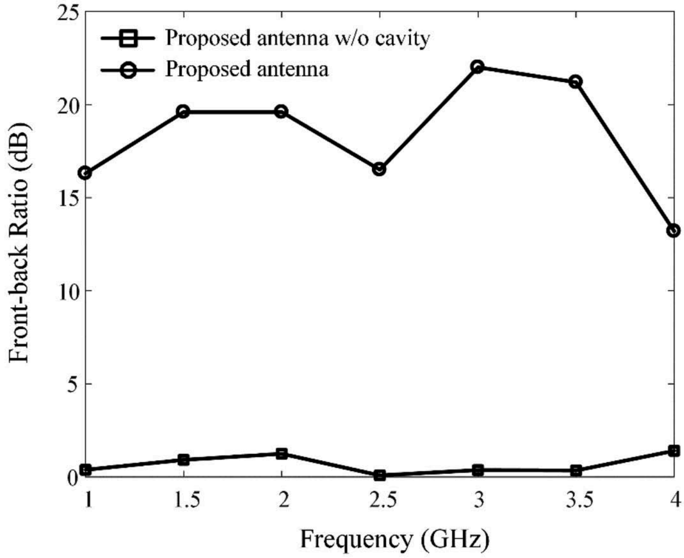

Figure 9. Comparison of front-back ratio.

characteristics were measured in a full anechoic chamber. The measured average boresight gain was 7.03 dBic with an average AR of 2.6 (from 2 GHz to 4 GHz), and the cross-polarization level was 16.6 dB. The results confirmed that the proposed antenna was suitable for broadband spiral antennas in various communication systems with high tolerance to fabrication error and low design complexity.

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