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Design of a cavity-backed spiral antenna using frequency-dependent impedance of a stepped-width arm for low frequency gain enhancement

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ABSTRACT

This paper proposes a stepped-width spiral antenna for gain enhancement at a low operating frequency. The frequency-dependent characteristic of the stepped-width transmission line is applied to the spiral arm to enhance the gain at the low end of the operating frequency, and a cavity-backed ground is added to the bottom side of the antenna to further improve the gain at the bore-sight direction. To verify the gain enhancement at the low operating frequency and impedance matching characteristic, we observe the antenna performances such as bore-sight gains and reflection coefficients according to the shape of the spiral arm. The results confirm that the proposed stepped-width structure can enhance the gain at the low operating frequency by improving the impedance matching characteristic.

KEYWORDS

Spiral antenna; Stepped-with arm; Single arm; Cavity-backed structure

Introduction

Spiral antennas have been widely utilized in a variety of commercial and military applications such as mobile communications, Global Positioning Systems (GPSs), and electronic warfare (EW) due to their broadband nature of impedance matching and circularly polarized patterns (Buck and Filipovic 2018; Guinvarc'h and Haupt 2010; Saenz et al. 2014). One of the recent research topics regarding the spiral antenna is to derive the required array characteristics by using a large number of antennas in a given space; consequently, the miniaturization of the spiral antenna is a key technology for implementing such systems (Nakano, Sataki, and Yamauchi 2010), (Nakano et al. 2009). However, since the lowest operating frequency is determined theoretically by the outer radius of the spiral arm, the gain in performance at the low operating frequency is degraded when the antenna configuration is miniaturized (Fu et al. 2010), (Ghassemi et al. 2011). Therefore, a significant amount of effort has been made to enhance the low-frequency gain while increasing the antenna bandwidth. Numerous studies, particularly on improving the bandwidth of the spiral antennas, have already focused on optimizing the shape and number of spiral arms. For example, techniques such as adjusting the turn number, width and rotation angle of the spiral arms (Nakano et al. 2008), tapering the edge shape of the arm (Chen and Huff 2011), varying the center position of the arm that is connected to the feed (Nakano et al. 2011), and inserting additional lumped elements in the arm (Lee et al. 2011), have been reported so far.

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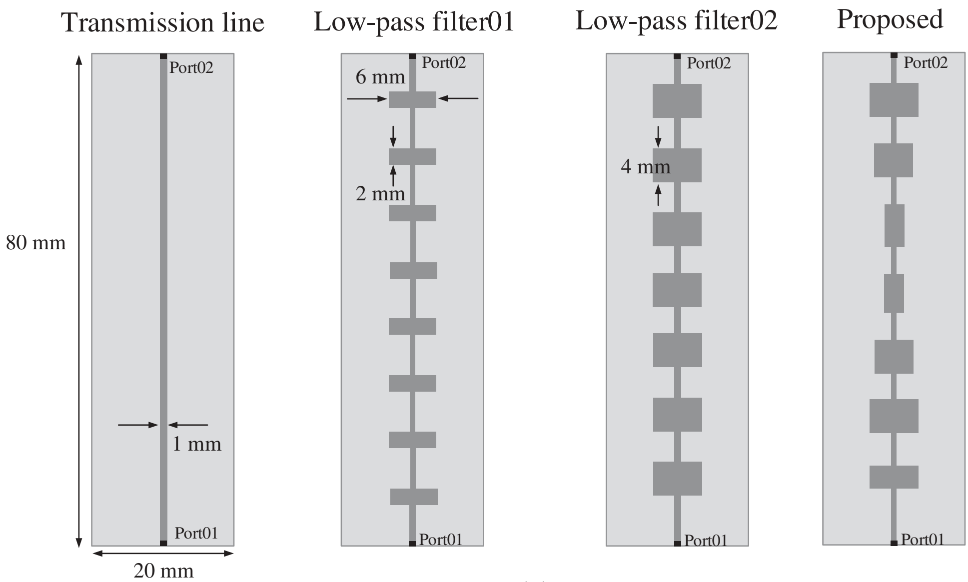

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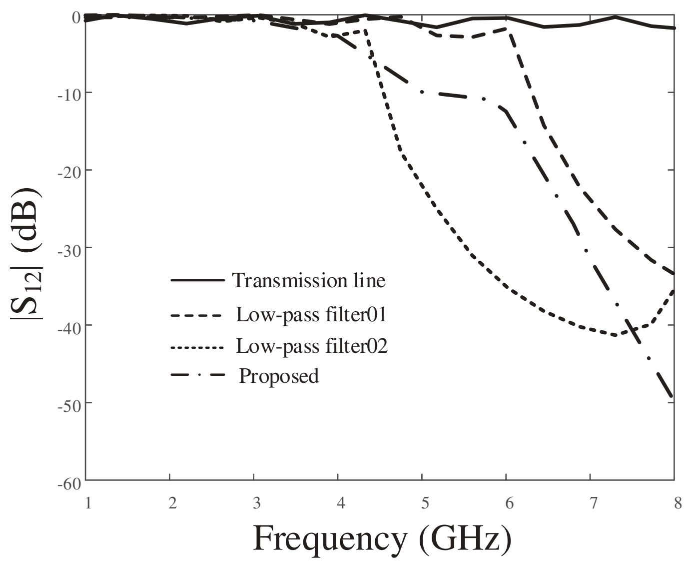


(b)

Figure 1. S-parameter according to the shape of the filter: (a) Geometries, (b) S-parameter.

In this paper, we propose the novel design configuration of the spiral antenna using a stepped-width arm for low-frequency gain enhancement with broad matching bandwidth. For the first time, the frequency-dependent impedance characteristics of the stepped-width transmission lines are applied to the spiral arm to achieve high input resistance at the low end of the operating frequency.

At the low operating frequency band, the stepped-width transmission lines have relatively high resistances; these frequency dependent characteristics are often used in low-pass filters

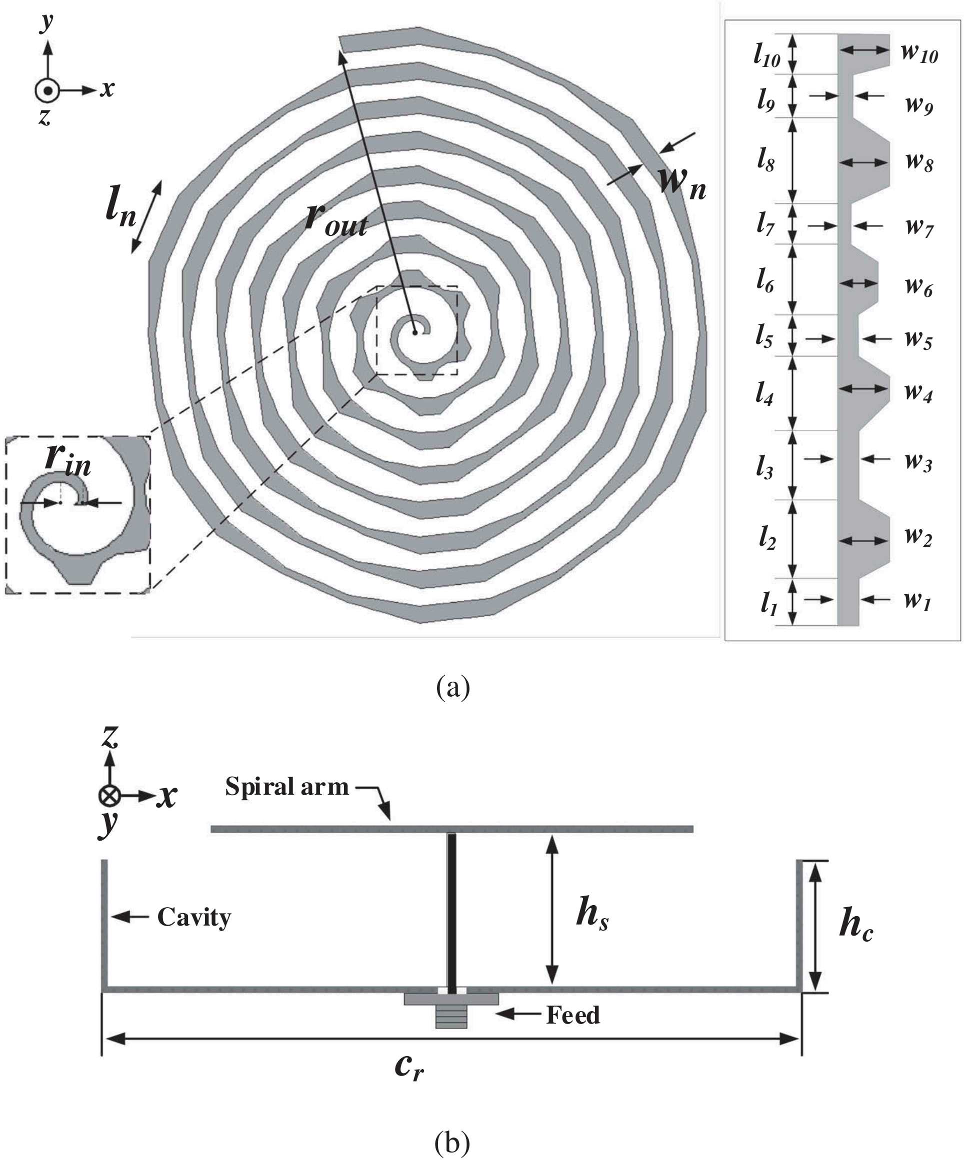


Figure 2. Geometry of the proposed antenna: (a) Top view, (b) Side view.

and are now employed to improve the impedance matching and the gain at the low-frequency band by embedding to the spiral arm. To simplify the antenna structure, the proposed spiral antenna has a single arm configuration that requires a simple feed mechanism connecting directly to the spiral arm without a balun. In addition, to further improve the gain at the bore-sight direction, the cavity-backed ground is added to the bottom side of the spiral antenna. We observe the antenna characteristics according to the shape of the spiral arm to verify the enhancement of the low-frequency gain and the impedance

Table 1. Optimized values of the proposed stepped-width spiral antenna.

Parameter	Value (mm)
w_1	2
w_2	6
w_3	2
w_4	6
w_5	2
w_6	6
w_7	2
w_8	4
w_9	2
w_{10}	4
l_1	10
l_2	5
l_3	2
l_4	10
l_5	2
l_6	6
l_7	2
l_8	7
l_9	5
l_{10}	10
h_s	10
h_c	5
r_{in}	2
r_{out}	52
c_r	140

Figure 3. Photograph of the fabricated antenna.

matching characteristic through the proposed stepped-width spiral arm. The results indicate that the proposed stepped-width arm structure is suitable for achieving gain enhancement at the low-frequency band by improving the impedance matching characteristic.

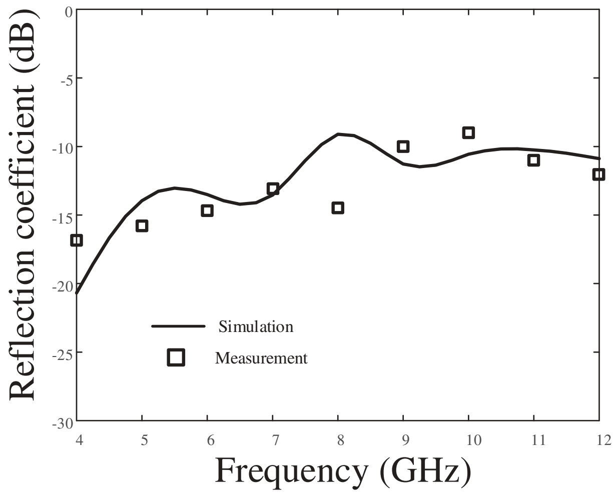


Figure 4. Reflection coefficients of the proposed antenna.

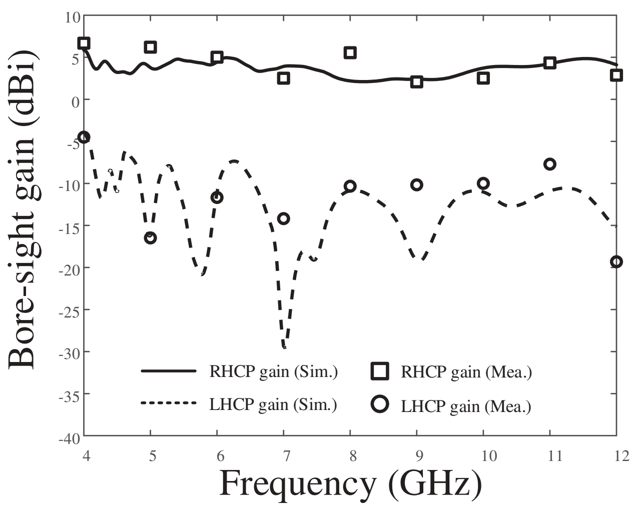


Figure 5. Bore-sight gain of the proposed antenna.

Proposed antenna design and measurement

To verify the direct relationship between the low-pass filter and the proposed stepped arm, we analyzed the insertion loss according to the shape of the filter as shown in figure 1. As can be seen, the proposed stepped structure also clearly shows similar characteristics to the low-pass with gradual cut-off between 4 GHz and 6 GHz, and this frequency-dependent characteristic is now employed to improve the impedance matching and the gain at the low-frequency band by embedding to the spiral arm. Figure 2 shows the geometry of the proposed stepped-width arm spiral antenna. The proposed spiral antenna consists of a single stepped-width arm with an inner and outer radius of r_{in} and r_{out}, and a cavity-backed structure with dimensions of h_c and c_r. We embedded the stepped-width shape of low-pass filter to the spiral arm to enhance

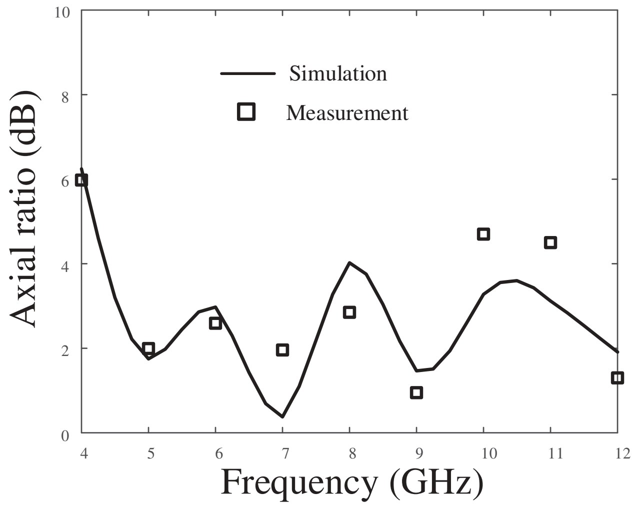


Figure 6. Axial ratio of the proposed antenna.

the matching characteristic at the low operating frequency. This stepped-width arm shape which has a frequency-dependent characteristic can enhance the gain at the low end of the operating frequency by increasing the resistance. The step width ratio is optimized to derive the high impedance at the low operating frequency band. The proposed spiral arm consists of eight turns, and each turn is divided into 10 steps (w_1, …, w_{10} and l_1, …, l_{10}). These ten-step width and length ratios are optimized using the genetic algorithm (GA) in conjunction with the FEKO EM simulator to efficiently find the optimal structure to improve the antenna performance. We embedded the cost function in the GA optimization process, which is determined by the average RHCP gain at low operating frequency band from 4 GHz to 6 GHz. Repeating the GA optimization more than 50 times, the optimal cost value converges to about 0.23, while the shape of the spiral arm also approaches to the proposed design. Since the proposed antenna has a single arm that requires a simple feed structure, the 50-Ω coaxial line is connected directly to the spiral arm without a balun circuit. Further, the cavity-backed structure is inserted to the bottom side of the spiral antenna for additional improvement of the gain at the bore-sight direction. The detailed design parameters are optimized by a genetic algorithm (Rahmat-Samii and Michielssen 1999) and listed in Table 1.

To verify the antenna performance, such as the reflection coefficients, bore-sight gain, axial ratio (AR), and radiation patterns, the optimized stepped-width arm spiral antenna is fabricated on a thin FR4 substrate ($\varepsilon_r = 4.4$ $\tan\delta = 0.018$) as shown in figure 3. The simulated reflection coefficients are shown in comparison with the measurements in figure 4. The measured and simulated reflection coefficients are well matched from 4 GHz to 12 GHz with a value of less than – 9 dB. Due to the stepped-width arm structure, which has a high input resistance at the low operating frequency, the impedance matching at the low-frequency band from 4 to 6 GHz, in particular, is better than thin or thick shape of the spiral antenna. Figure 5 shows the bore-sight gain of the proposed spiral antenna as a function of the frequency. The simulated data presented by the solid line for right-hand circular polarization (RHCP) and the dashed line for left-hand circular polarization (LHCP), are compared with the measured data specified by "□" and "o" symbols. Both results show good agreement, and

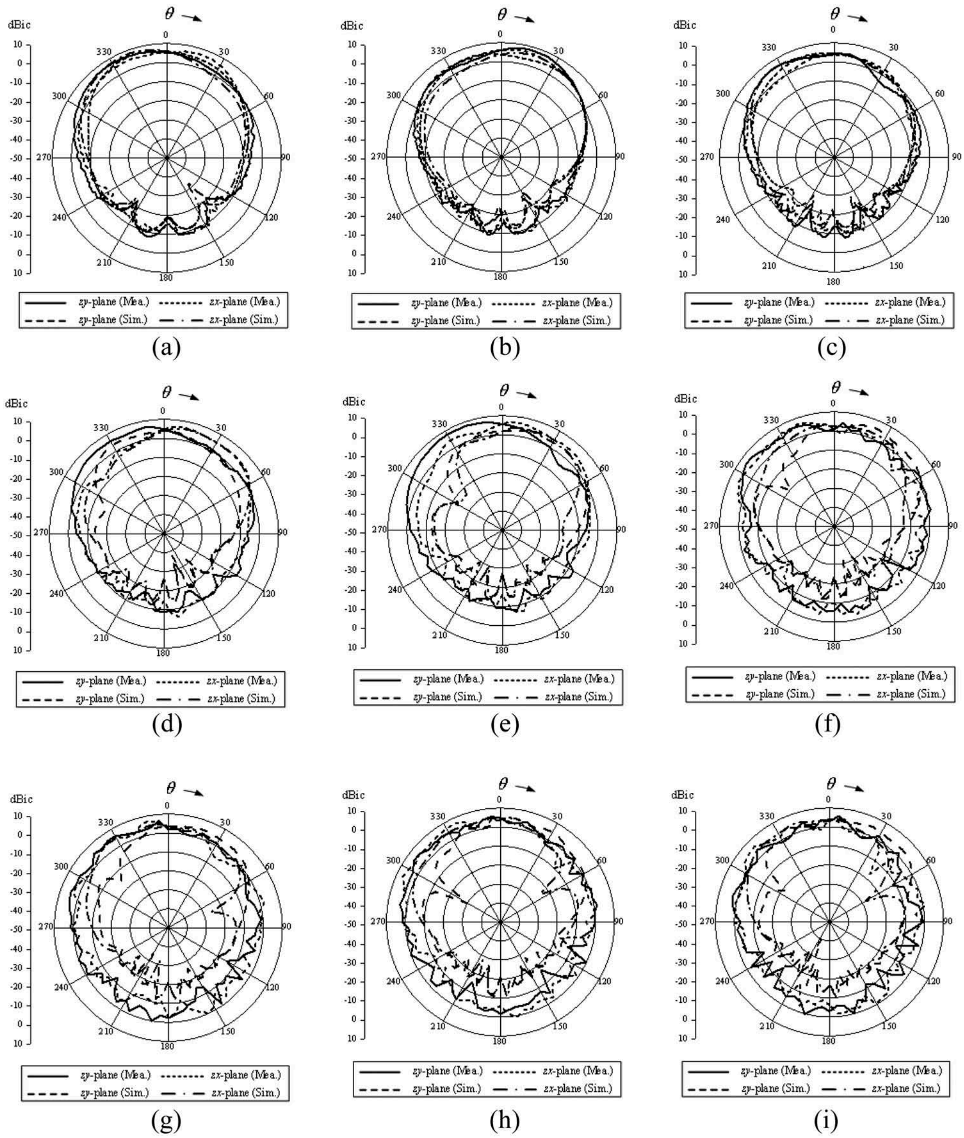
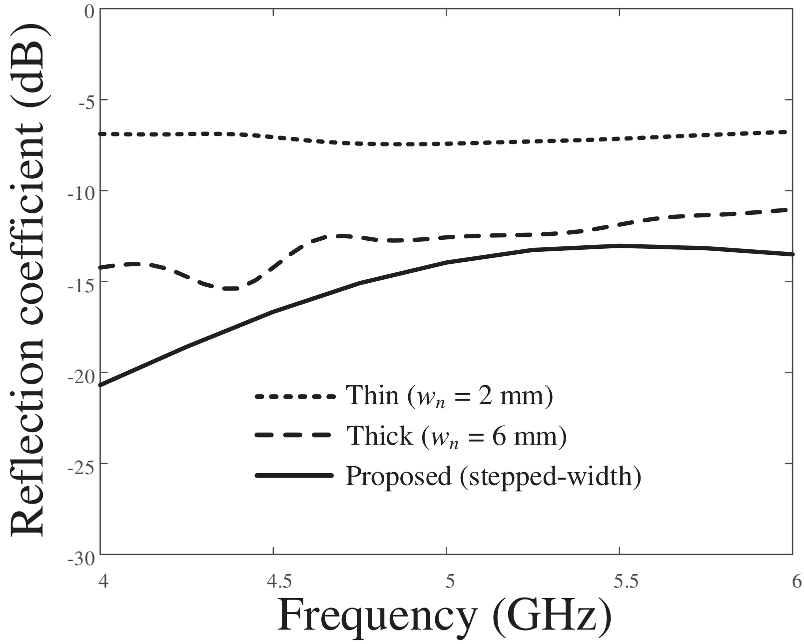
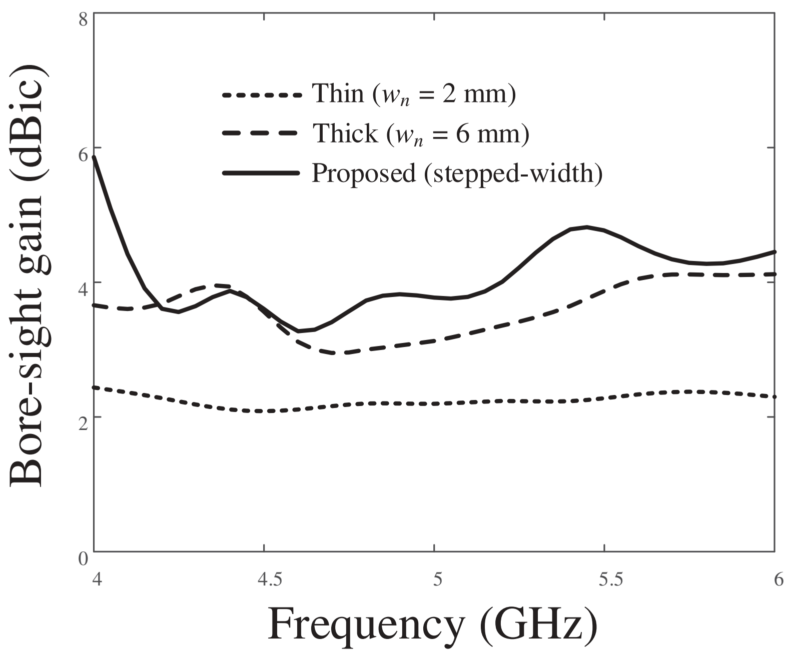


Figure 7. Radiation patterns of the proposed antenna: (a) 4 GHz, (b) 8 GHz, (c) 12 GHz, (d) 7 GHz, (e) 8 GHz, (f) 9 GHz, (g) 10 GHz, (h) 11 GHz, (i) 12 GHz.

the RHCP gain is higher than 5 dBic from 4 GHz to 6 GHz. This relatively high gain at the low-frequency band is achieved by the proposed stepped-width arm. Figure 6 provides a comparison between the measured and simulated axial ratios (ARs) of the antenna. The AR values are less than 6 dB, from 4 GHz to 12 GHz, and the simulation and measurement have a similar tendency. The radiation patterns of the proposed spiral antenna in the *zx*- and *zy*-planes are shown in figure 7. As can be seen, the simulation and measurement data have similar values, and there is no significant pattern distortion in the upper hemisphere of the proposed antenna.



(a)



(b)

Figure 8. Reflection coefficients and bore-sight gain according to the shape of the spiral arm: (a) Reflection coefficients, (b) Bore-sight gain.

Parametric study and analysis

To confirm the effectiveness of the stepped-width spiral arm, we analyze the reflection coefficients and bore-sight gains according to the shape of the spiral arm at the low operating frequency, from 4 GHz to 6 GHz as shown in figure 8ab. The spiral antenna has a higher resistance when it has a thick straight arm (w_n = 6 mm) compared with a thin straight arm (w_n = 2 mm), and the stepped-width spiral antenna has the highest resistance at the low-frequency band. The reflection coefficients and bore-sight gains are improved as the width of the spiral arm increases. Then, the most improvement at low operating frequency is achieved when the spiral arm has a stepped-width structure, which is indicated by the solid line.

Figure 9 shows the bore-sight gains at 4 GHz, 8 GHz, and 10 GHz, depending on the number of the *Turn* from the center with the stepped-width arm. For example, *Turn* = 0 means that the spiral antenna has a straight arm without the stepped-width structure, and *Turn* = 3 means that the stepped-width structure is applied to first three internal windings of the spiral arm. As the number of *Turn* increases, the part of the stepped-width arm increases from the center of the spiral antenna. The bore-sight gain at the low frequency of 4 GHz is 3.63 dBi when *Turn* is zero; however, the gain is enhanced to 5.37 dBi when *Turn* becomes eight. It can be seen that the stepped-width spiral arm helps to improve the gain at the low frequency while maintaining the gain at the high frequency.

The surface current distributions of the proposed antenna at 4 GHz, 8 GHz, and 12 GHz, are examined as shown in figure 10. The proposed stepped-width arm spiral antenna has a 2 dB higher average surface current density compared to the straight

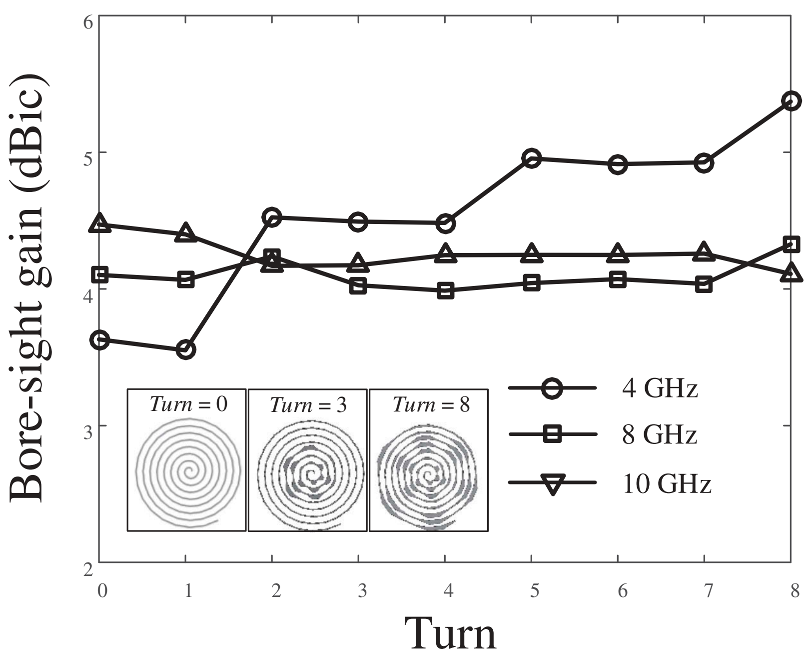


Figure 9. Bore-sight gains depending on the number of the *Turn*.

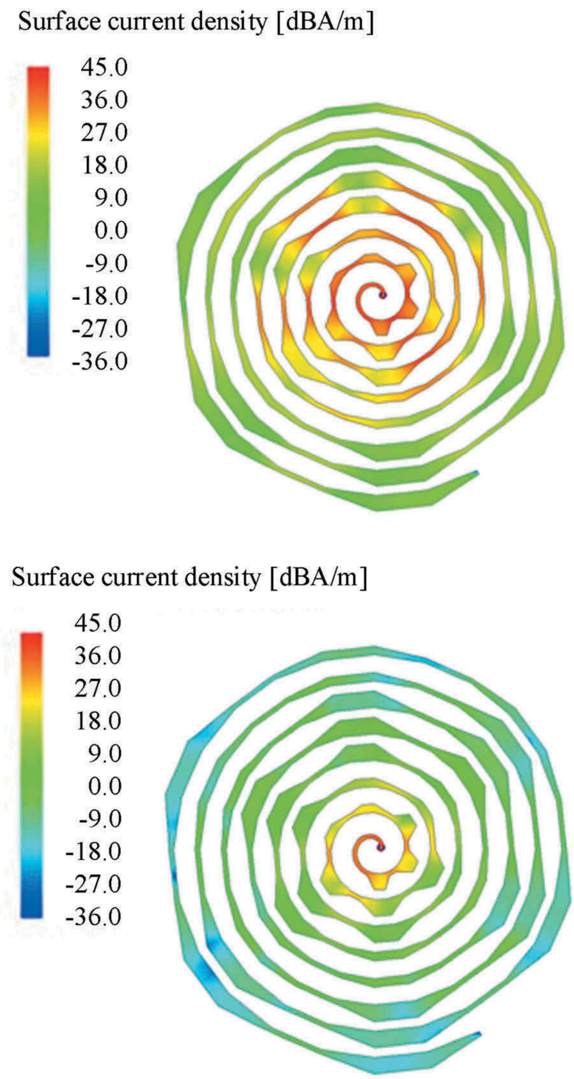


Figure 10. Surface current distributions of the proposed antenna: (a) 4 GHz, (b) 8 GHz, (c) 12 GHz.

thick arm (w_n = 6 mm) at the low end of the operating frequency. These strong current distributions at the low operating frequency again demonstrate the high resistance characteristics of the proposed stepped-width arm. The current distributions extend outside the spiral antenna when the operating frequency is low, while the currents are concentrated inside the spiral antenna as the operating frequency increases. Thus, the operating characteristics at low and high frequency are predominantly determined by the outer and inner parts of the spiral arm, respectively. It also means that the stepped-width structure should be applied to the entire spiral arm in order to increase the gain particularly at the low operating frequency.

Conclusion

The design of a stepped-width arm spiral antenna was proposed to enhance the gain at the low operating frequency. To achieve high resistance at the low end of the operating frequency, which can derive the impedance matching and gain enhancement, we applied the frequency dependent characteristic of the stepped-width transmission line to the spiral arm. The proposed stepped-width arm spiral antenna had a relatively high gain at the low-frequency band, and the RHCP gain is higher than 5 dBic from 4 GHz to 6 GHz. We also confirmed that the proposed antenna had a 2 dB higher average current density compared to the straight arm shape at the low operating frequency, and this strong current strength demonstrated the high resistance characteristic of the proposed structure.

Acknowledgments

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