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# Design of Dual-Band Series-Fed Dipole Pair Antenna Using Proximity-Coupled Strip and Split-Ring Resonator Directors

**Junho Yeo[1] and Jong-Ig Lee[2, *]**

**Abstract**—In this paper, a design of a dual-band series-fed dipole pair (SDP) antenna using proximity-coupled strip and split-ring resonator (SRR) directors is presented. Two different types of directors are placed close to the top element of the SDP antenna. First, a thick strip director is used to enhance the bandwidth and gain characteristics of the SDP antenna. Next, a pair of SRR directors is appended to both sides of the strip director to create a new resonance for dual-band operation. The performance of three different SDP antenna structures (with a strip director, with a pair of SRRs, and with both directors) are compared with the conventional SDP antenna without directors. When the strip and SRR directors are used together, the mutual coupling might affect the impedance matching of the original frequency band of the SDP antenna and the distance between the two directors is an importance parameter to decide the performance of the antenna. The effects of the distance between the strip and the SRR directors on the input voltage standing wave ratio (VSWR) and realized gain characteristics are studied. A prototype of the proposed dual-band SDP antenna operating in the global positioning system L1 (1.563–1.587 GHz) and 1.7–2.8 GHz bands is designed and fabricated on an FR4 substrate. The experiment results show that the antenna has dual-band characteristics in the 1.56–1.63 GHz and 1.68–2.87 GHz frequency bands for a VSWR $< 2$. Measured gain is 5.9–7.5 dBi in the former frequency band, whereas it ranges from 6.2 dBi to 7.3 dBi in the latter.

## 1. INTRODUCTION

Antennas with broad bandwidth, stable gain, and unidirectional radiation patterns have been widely developed because of the increasing demand for high data rate wireless services [1]. Among various broadband antennas, the planar quasi-Yagi (QY) antenna and the series-fed dipole pair (SDP) antenna have been widely used in many mobile communications applications, such as base-station antennas or wideband phased-array antennas, because of their broad bandwidth, stable and moderate gain, and simple structure [2, 3]. The SDP antenna consists of two dipoles having different lengths and a truncated ground plane, which are serially connected with a transmission line. In the SDP antenna, the lengths of the long and short dipoles control the lower and upper operating frequencies, respectively, and the distance between the two dipoles as well as the distance between the first dipole and truncated ground plane control the input reflection coefficient level between the two main resonances. Therefore, the degree of freedom for the design of the SDP antenna is much increased, and it can achieve relatively broad bandwidth and stable gain easily without using directors compared to QY antennas.

To increase the bandwidth of the QY and SDP antennas, a thick parasitic strip director was appended to the top of the antennas. A broadband three-element QY antenna with a rectangular patch type director placed close to the driver dipole was proposed [4]. An impedance bandwidth of 2.4 : 1 (1.56–3.74 GHz, 82.3%) for a voltage standing wave ratio (VSWR) $< 2$ with a realized gain of more than 4 dBi was achieved. A parasitic strip director was also employed at a location close to the top

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* Corresponding author: Jong-Ig Lee (leeji@dongseo.ac.kr).
[1] School of Computer and Communication Engineering, Daegu University, Jillyang, Gyeongsan, Gyeongbuk 712-714, Korea.
[2] Department of Electronics Engineering, Dongseo University, San 69-1, Jurye-2 dong, Sasang-gu, Busan 617-716, Korea.

dipole element of the SDP antenna, and a bandwidth of 57.95% (1.63–2.96 GHz) for a VSWR < 2 with a gain of more than 5 dBi was obtained [5].

Recently, split-ring resonator (SRR) structures consisting of metallic concentric split rings have attracted a great deal of attention in the antenna field, because their resonance characteristics can be used to create multi-band operation. A monopole loaded with two identical SRRs was proposed for triple-band applications covering the universal 802.11 standard (2.4–2.5 GHz and 4.9–5.875 GHz) and the lower band of the 802.15 standard (3.244–4.742 GHz) [6]. A method of designing a multi-frequency square microstrip patch antenna using SRRs loaded along the non-radiating edges was introduced. Two or more working frequencies arbitrarily chosen can be achieved, depending on the number of SRRs coupled to the patch antenna [7]. An SRR type of director consisting of two rectangular SRRs was applied to a QY antenna instead of a conventional strip type director to yield dual-band characteristics in the 3.45 GHz worldwide interoperability for microwave access, inc. (WiMAX) and 5 GHz wireless local area network bands [8]. A dual-band SDP antenna with SRR directors operating in the global positioning system (GPS) L1 (1.563–1.587 GHz) and 1.7–2.7 GHz bands was proposed, and the effects of the geometric parameters of the SRR directors on the input reflection coefficient and realized gain of the SDP antenna were investigated [9].

In this paper, a design method for a dual-band SDP antenna using proximity-coupled strip and SRR directors is presented. The effects of the strip and SRR directors on the performance of the SDP antenna were investigated separately in [5, 9], but they have never used together in the literature. The strip director can be employed to enhance the bandwidth and gain characteristics of the original frequency band of the SDP antenna, whereas the SRR directors can be used for dual-band operation. The distance between the strip and the SRR directors are important to decide the antenna performance, and its effects on the input VSWR and realized gain characteristics are analyzed. To validate the proposed design method, a prototype of a dual-band SDP antenna operating in the GPS L1 (1.563–1.587 GHz) and 1.7–2.8 GHz bands is designed and fabricated on an FR4 substrate. The results in this work were obtained using a commercial electromagnetic simulator, CST Microwave Studio (MWS), 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 SDP antenna with proximity-coupled strip and SRR directors. A conventional SDP antenna consists of two strip dipole elements, dipole 1 ($D_1$) and dipole 2

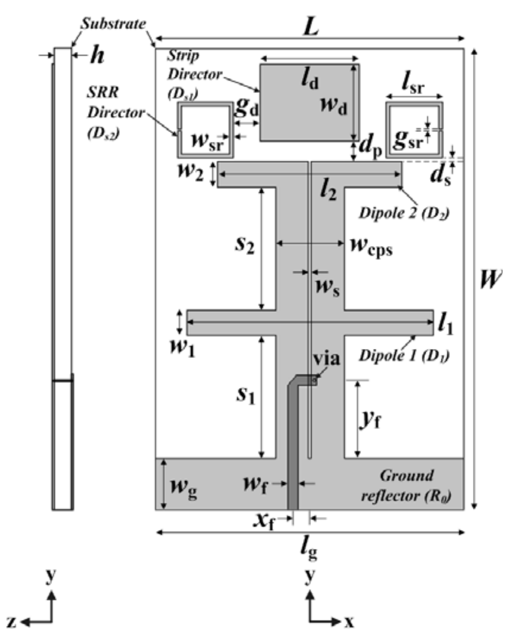



**Figure 1.** Geometry of proposed dual-band SDP antenna.

($D_2$), having different lengths, and a ground reflector ($R_0$). The length and width of $D_1$ are $l_1$ and $w_1$, respectively, and those of $D_2$ are $l_2$ and $w_2$, respectively. The length and width of $R_0$ are $l_g$ and $w_g$, respectively. The distance between $R_0$ and $D_1$ is $s_1$, and that between $D_1$ and $D_2$ is $s_2$. The elements of the SDP antenna are serially connected with a coplanar strip (CPS) line. An integrated balun between the microstrip (MS) and CPS lines is implemented on the CPS line to match the input impedance of the antenna with the $50\,\Omega$ feed line, and the end of the MS line is shorted with a shorting pin at the feed point. 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 $x_f$.

In the proposed antenna, two different types of directors are appended to $D_2$ of the conventional SDP antenna. First, a rectangular-patch-shaped strip director ($D_{s1}$) is placed at distance $d_p$ from $D_2$ to enhance the bandwidth and gain characteristics of the SDP antenna. The length and width of $D_{s1}$ are $l_d$ and $w_d$, respectively. Next a pair of single square-ring SRR directors ($D_{s2}$) is appended to both sides of $D_{s1}$ for dual-band operation. It creates another frequency band below the operating frequency band of the SDP antenna. The distance between $D_{s1}$ and $D_{s2}$ is $g_d$, whereas that between $D_2$ and $D_{s2}$ is $d_s$. The SRR pair mirror each other along the center line of the CPS, and the gap in the SRR is oriented outside for optimum performance [9], as shown in Figure 1. The length and width of each square-ring SRR are $l_{sr}$ and $w_{sr}$, respectively, and the gap in the SRR is $g_{sr}$. The antenna is printed on an FR4 substrate having a dielectric constant of 4.4 (loss tangent = 0.025), and the thickness $h = 1.6$ mm. The length and width of the substrate are $L$ and $W$, respectively. Table 1 summarizes the optimized design

**Table 1.** Optimized design parameters of proposed antenna.

| Parameter | Value [mm] | Parameter | Value [mm] |
|---|---|---|---|
| $L$ | 90 | $w_s$ | 0.7 |
| $W$ | 135 | $x_f$ | 3 |
| $l_1$ | 72 | $y_f$ | 23 |
| $w_1$ | 7.5 | $h$ | 1.6 |
| $s_1$ | 36 | $l_d$ | 28.8 |
| $l_2$ | 50.4 | $w_d$ | 22.5 |
| $w_2$ | 7.5 | $d_p$ | 6 |
| $s_2$ | 36 | $g_d$ | 8 |
| $l_g$ | 90 | $l_{sr}$ | 16.33 |
| $w_g$ | 15 | $w_{sr}$ | 1 |
| $w_{cps}$ | 20 | $g_{sr}$ | 0.5 |
| $w_f$ | 3 | $d_s$ | 1 |

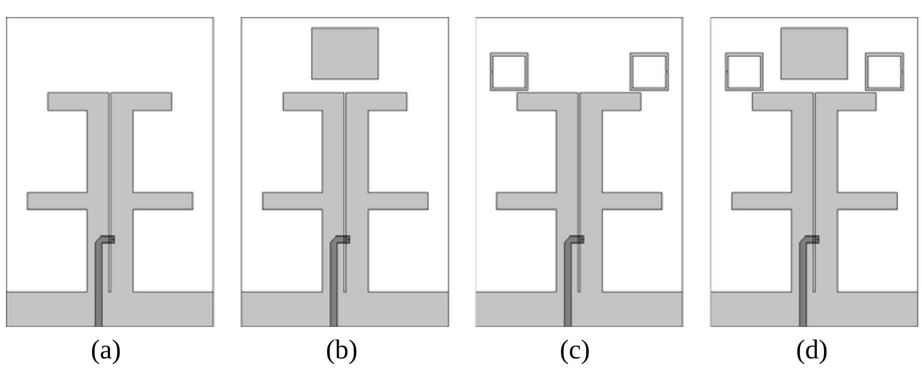



**Figure 2.** Four antenna structures for comparison: (a) conventional SDP antenna without directors, (b) SDP antenna with strip director, (c) SDP antenna with SRR director, and (d) SDP antenna with both strip and SRR directors.

parameters of the proposed antenna to achieve dual-band operation in the GPS L1 and 1.7–2.8 GHz bands.

Four antenna structures considered for performance comparison are presented in Figure 2. A conventional SDP antenna without directors is shown in Figure 2(a), whereas an SDP antenna with a rectangular-patch-shaped strip director is shown in Figure 2(b). Figure 2(c) shows an SDP antenna with SRR directors, whereas the proposed SDP antenna with both strip and SRR directors is shown in Figure 2(d). We note that the geometric parameters of the antennas for Figures 2(b) and 2(c) are not optimized, but only the SRR directors seen in Figure 2(d) are removed for Figure 2(b). For Figure 2(c), only the strip director is removed. The characteristics of the simulated input impedance, VSWR, realized gain, and total efficiency for the four antenna structures considered are compared in Figure 3.

First, the conventional SDP antenna without directors has a single band for a VSWR $< 2$ in the frequency range of 1.63–2.74 GHz (49.1%), and the gain in the band ranges from 4.4 dBi to 6.8 dBi. The length ratio of $D_2$ to $D_1$ is $l_2/l_1 = 0.75$, and that of $D_1$ to $R_0$ is $l_1/l_g = 0.8$. We note that $l_2/l_1$ is slight

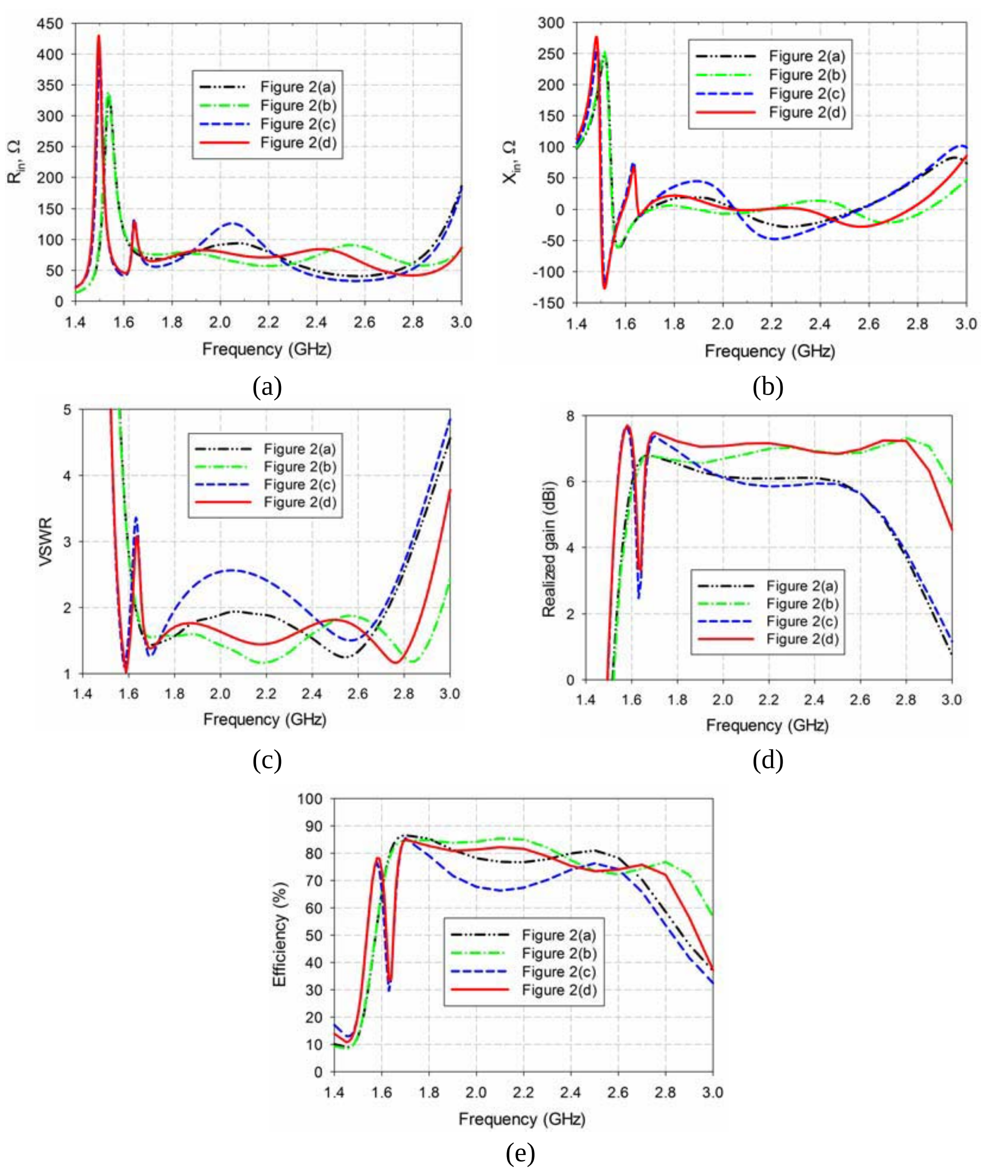



**Figure 3.** Performance comparison of four antenna structures in Figure 2: (a) resistance, (b) reactance, (c) VSWR, (d) realized gain, and (e) total efficiency.

increased from 0.7 to 0.75 to increase the gain in the low frequency region. The impedance matching in the middle frequency region is a little deteriorated, but VSWR $< 2$ criterion is still satisfied. The input resistance varies in the range of 42–94 ohm, whereas the input reactance varies in the range of $-28$ to 35 ohm in the band. The simulated total efficiency ranges between 66 and 87% in the band.

Next, when a rectangular-patch-shaped strip director is appended to the conventional SDP antenna as shown in Figure 2(b), the frequency band for a VSWR $< 2$ is extended to 1.63–2.97 GHz (58.3%), and the gain in the band ranges from 6.2 dBi to 7.3 dBi. The input resistance varies in the range of 57–91 ohm, whereas the input reactance varies in the range of $-23$ to 37 ohm in the band. The total efficiency ranges between 62 and 86% in the band. It is worthwhile to note that the geometric parameters of the strip director are adjusted to obtain maximum bandwidth with stable gain [5]. In a conventional 3-element QY antennas, the distance between the driver and director is in the range of 0.15–0.35$\lambda$ ($\lambda$ is the free-space wavelength at the center frequency of the frequency band) for effective operation, and the resulting bandwidth usually decreases when a director is appended to the driver [10]. However, a broad bandwidth with an increased gain can be achieved by placing a rectangular-patch-shaped thick strip director close to the second dipole at a distance of $d_p = 0.05\lambda$ [4]. The design parameters related to the strip director are as follows: $l_d = 28.8$ mm, $w_d = 22.5$ mm, and $d_p = 6$ mm. The improvement in the impedance bandwidth, compared to that of the SDP antenna without directors, is 18.7%, and the average peak gain in the band increases from 5.7 dBi to 6.8 dBi.

Third, when only a pair of SRRs is appended to the SDP antenna, as shown in Figure 2(c), a new resonant frequency band appears in the range of 1.56–1.61 GHz for a VSWR $< 2$. The design parameters related to the SRR directors are as follows: $l_{sr} = 16.33$ mm, $w_{sr} = 1$ mm, $g_{sr} = 0.5$ mm, and $d_s = 1$ mm. The SRR directors can be modeled as an LC parallel tank circuit whose equivalent inductance and capacitance are $L_{SRR}$ and $C_{SRR}$, respectively. The LC parallel tank corresponding to the SRRs is coupled to $D_2$ through a mutual inductance which models the magnetic coupling between the elements [9]. The values of $L_{SRR}$ and $C_{SRR}$ are determined by the length and width of the SRR pair ($l_{sr}$ and $w_{sr}$), the gap in the SRR ($g_{sr}$), and the distance between $D_2$ and $D_{s2}$ ($d_s$), and these values determines the new resonant frequency together with the geometric parameters of $D_2$. In the original frequency band of the SDP antenna, the SRR pair acts as a director and it can enhance the gain in the low frequency region, as shown in Figure 3(d). The lower limit of the original frequency band of the SDP antenna increases slightly to 1.66 GHz, and the upper limit decreases to 2.71 GHz; therefore, the bandwidth decreases. Furthermore, the impedance matching deteriorates in the range of 1.81–2.36 GHz. The impedance characteristic might be improved by decreasing $l_2/l_1$ slightly. The gain ranges from 6.0 dBi to 7.7 dBi in the first band, and ranges from 4.9 dBi to 7.4 dBi in the second. The input resistance and reactance vary in the ranges of 41–57 ohm and $-29$ to 36 ohm, respectively, in the first band, whereas their ranges are 39–91 ohm and $-48$ to 45 ohm, respectively, in the second. The total efficiency of the antenna is 55–77% in the first band, and 66–86% in the second.

Finally, when both strip and SRR directors are appended to the conventional SDP antenna, the frequency bands for a VSWR $< 2$ are 1.56–1.62 GHz and 1.66–2.89 GHz, which covers the desired GPS L1 and 1.7–2.8 GHz bands. In this case, the distance between $D_{s1}$ and $D_{s2}$ is the most important parameter to determine the antenna performance, and is chosen to be $g_d = 8$ mm. A detailed parametric study on this will be explained in the next section. Gain ranges from 6.0 dBi to 7.7 dBi in the first band, and ranges from 6.3 dBi to 7.5 dBi in the second. The impedance bandwidth and gain of the first band are similar to the results for Figure 2(c), whereas the impedance and gain bandwidths of the second band decrease slightly, compared to those for Figure 2(b). However, the gain values in the low frequency region increase, and the average peak gain increases slightly from 6.8 dBi to 7.0 dBi. The input resistance and reactance vary in the ranges of 46–62 ohm and $-34$ to 43 ohm, respectively, in the first band, whereas their ranges are 42–91 ohm and $-28$ to 22 ohm, respectively, in the second. The total efficiency of the antenna is 50–78% in the first band, and 60–85% in the second.

Figure 4 shows the surface current distributions of the proposed antenna at the four resonance frequencies, $f = 1.575$ GHz, 1.69 GHz, 2.18 GHz, and 2.76 GHz. The first resonance at 1.575 GHz is due to the strong currents induced on the SRR pair. The second resonance at 1.69 GHz corresponds to $D_1$, and some currents are induced on the SRR pair to improve the gain. The third resonance at 2.18 GHz corresponds to $D_2$, and the strip director mainly operates to enhance the gain. The fourth resonance at 2.76 GHz is due to a slot in the CPS line, and the induced currents are on both directors.

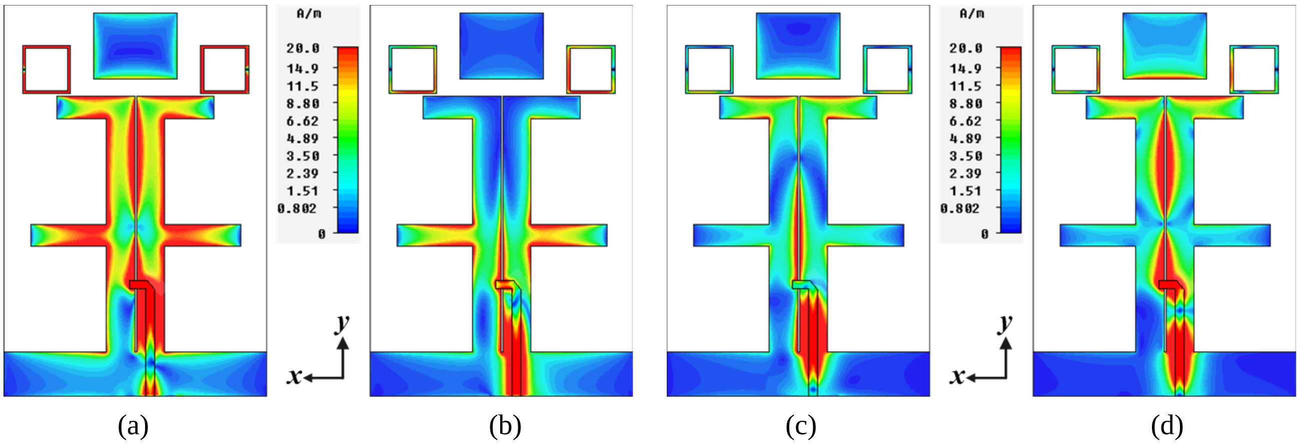



**Figure 4.** Surface current distributions of proposed antenna: (a) 1.575 GHz, (b) 1.69 GHz, (c) 2.18 GHz, and (d) 2.76 GHz.

## 3. PARAMETRIC STUDY

In this section, the effects of some crucial parameters related to the strip and SRR directors on input VSWR and realized gain characteristics of the antenna are investigated. As mentioned before, the most important parameter to the antenna performance is the distance between $D_{s1}$ and $D_{s2}$. The geometric parameters considered for the parametric study are the distance $g_d$ between $D_{s1}$ and $D_{s2}$ and the length $l_{sr}$ of the SRR.

The first parameter to consider is the distance between $D_{s1}$ and $D_{s2}$. Figure 5 shows the effects of $g_d$ on the input VSWR and realized gain characteristics of the proposed antenna. In Figure 5, $g_d$ varies from 2 mm to 14 mm, and other design parameters are the same as those in Table 1. As $g_d$ increases, the first frequency band moves toward a higher frequency, and its bandwidth decreases. At the same time, the lower limit of the second band decreases, and the upper limit increases. Hence, the bandwidth of the second band increases when $g_d$ increases. For instance, when $g_d = 2$ mm, the first frequency band for a VSWR $< 2$ is 1.54–1.60 GHz. However, the second band for a VSWR $< 2$ decreases to 1.68–2.19 GHz because of impedance mismatch above 2.19 GHz caused by the mutual coupling between the two directors. Gain ranges from 6.5 dBi to 7.5 dBi in the first band, and ranges from 6.8 dBi to 7.4 dBi in the second. When $g_d$ is increased to 8 mm, the frequency bands for a VSWR $< 2$ move to 1.56–1.62 GHz and 1.66–2.89 GHz; gain ranges from 6.0 dBi to 7.7 dBi in the first band, and ranges from 6.3 dBi to 7.5 dBi in the second. When $g_d$ is further increased to 14 mm, the boundary between the first and the second bands disappears, and a single wider frequency band is obtained. The frequency band

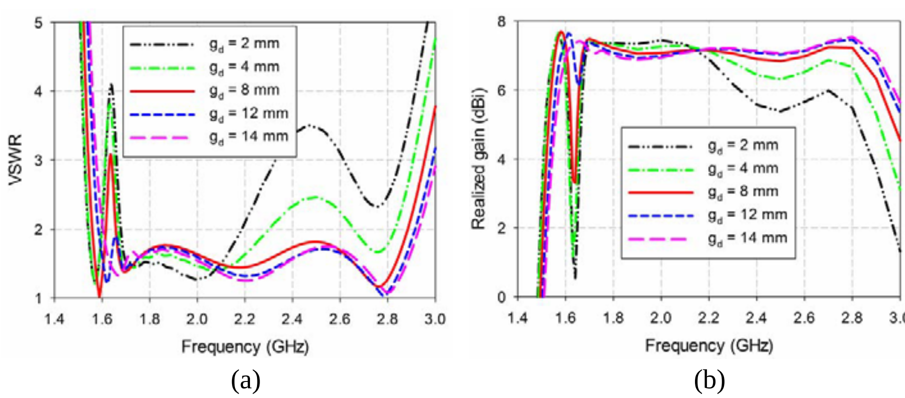
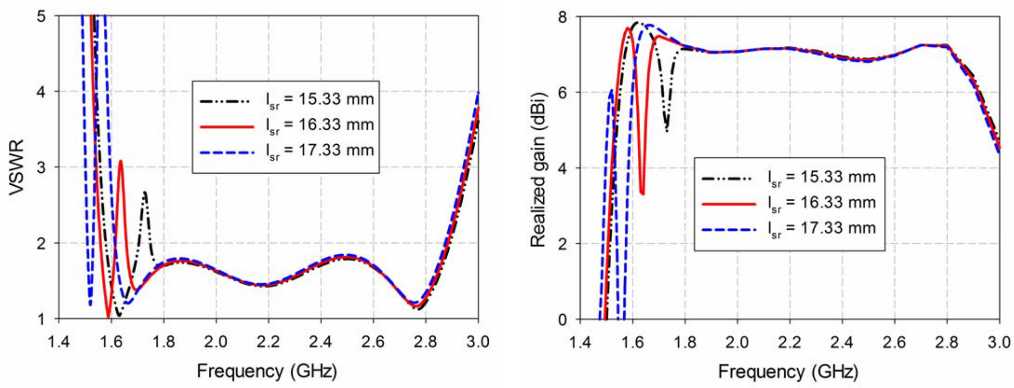
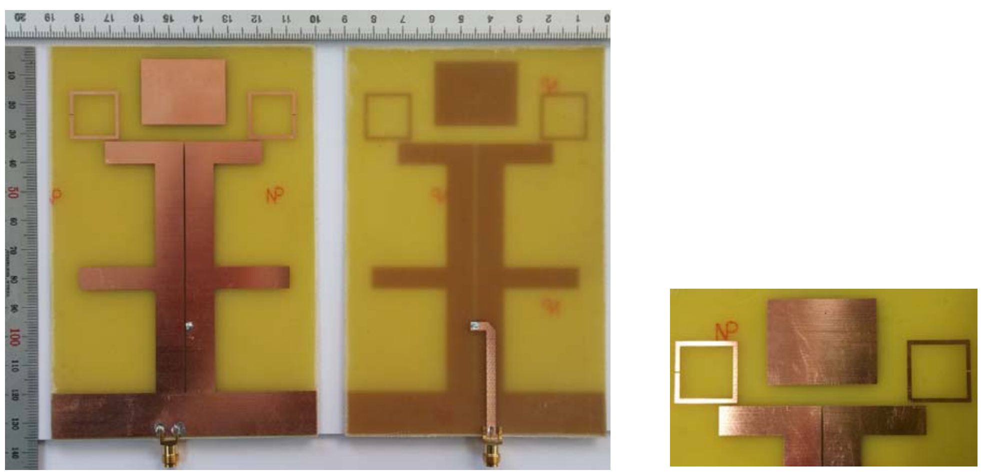



**Figure 5.** Effects of distance $g_d$ on (a) input VSWR and (b) realized gain.



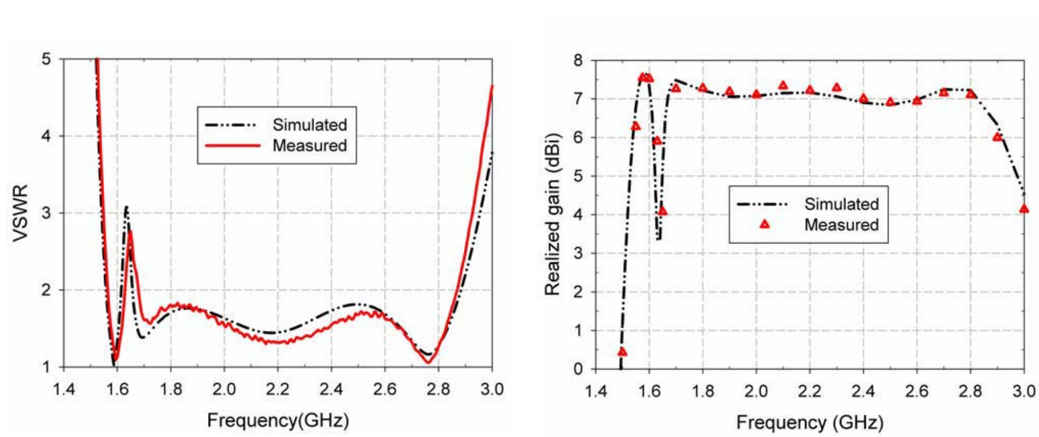

(a) (b)

**Figure 6.** Effects of SRR length $l_{sr}$ on (a) input VSWR and (b) realized gain.



(a) (b)

**Figure 7.** Photographs of fabricated antenna: (a) antenna and (b) directors.

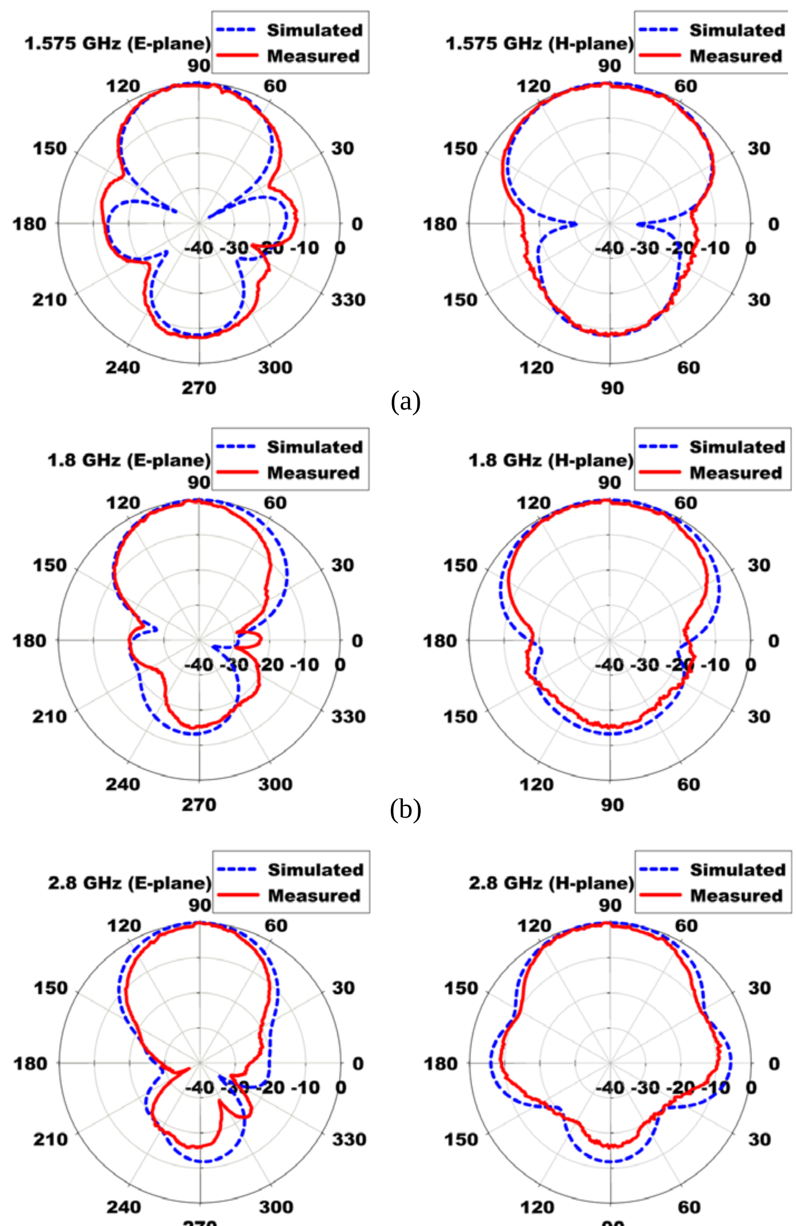



(a) (b)

**Figure 8.** (a) Input VSWR and (b) realized gain of fabricated antenna.

for a VSWR $< 2$ is 1.60–2.93 GHz (58.7%), and gain ranges from 6.6 dBi to 7.6 dBi in the band. The frequency band increases slightly with a shift toward a low frequency, and the average peak gain in the band increases from 6.8 dBi to 7.1 dBi, compared to the SDP antenna with the strip director only, as shown in Figure 2(b).

The second parameter to consider is the length of the SRR, as shown in Figure 6. In this case, $l_{sr}$ varies from 15.33 mm to 17.33 mm, and other design parameters are the same as those in Table 1. We can see from Figure 6 that when $l_{sr}$ increases, the first frequency band moves toward a lower frequency, and its bandwidth decreases. For the second band, both the lower and upper limits decrease, and the bandwidth increases. For example, when $l_{sr} = 15.33$ mm, the frequency bands for a VSWR $< 2$ are 1.58–1.70 GHz and 1.75–2.89 GHz; gain ranges from 6.8 dBi to 7.9 dBi in the first band, and ranges from




(a)

(b)

(c)

**Figure 9.** Measured radiation patterns of fabricated antenna in $E$- and $H$-planes at (a) 1.575 GHz, (b) 1.8 GHz, and (c) 2.8 GHz.

6.5 dBi to 7.2 dBi in the second. When $l_{sr}$ is increased to 17.33 mm, the frequency bands for a VSWR $< 2$ move to 1.51–1.53 GHz and 1.61–2.87 GHz; gain ranges from 4.8 dBi to 6.1 dBi in the first band, and ranges from 6.5 dBi to 7.8 dBi in the second.

From the results of the parametric study, shown in Figures 5 and 6, the final optimized design parameters of the SRR directors of the proposed antenna to cover the desired GPS L1 and 1.7–2.8 GHz bands are $g_d = 8$ mm and $l_{sr} = 16.33$ mm.

## 4. EXPERIMENT RESULTS AND DISCUSSION

A prototype of the proposed dual-band SDP antenna was fabricated on an FR4 substrate. Figure 7 shows the photographs of the fabricated antenna.

Figure 8 compares the input VSWR and realized gain characteristics of the fabricated antenna. An Agilent N5230A network analyzer was used for measuring the input VSWR and realized gain. As shown in Figure 8(a), the simulated frequency bandwidths for a VSWR $< 2$ are 1.56–1.62 GHz in the first band and 1.66–2.89 GHz in the second, whereas the measured characteristics are 1.56–1.63 GHz in the first band and 1.68–2.87 GHz in the second. The measured results show a small increase in the upper limit of the first band and a slight decrease in the bandwidth of the second, but the desired GPS L1 and 1.7–2.8 GHz bands are successfully covered. Figure 8(b) shows the measured gain ranges of 5.9–7.5 dBi in the first band and 6.2–7.3 dBi in the second, which agrees well with the simulated characteristics.

In Figure 9, the measured radiation patterns of the proposed SDP antenna in the $E$-plane ($x$-$y$ plane) and $H$-plane ($y$-$z$ plane) at 1.575 GHz, 1.8 GHz, and 2.8 GHz are compared with the simulated characteristics. The simulated and measured patterns agree well with each other. The antenna has end-fire directional patterns with a front-to-back ratio (FBR) $> 8$ dB in the first band and an FBR $> 12$ dB in the second.

## 5. CONCLUSION

We have presented a design of a dual-band SDP antenna using two different types of proximity-coupled directors, rectangular-patch-shaped strip and SRR pair directors. A rectangular-patch-shaped strip director is employed to enhance the bandwidth and gain characteristics of the conventional SDP antenna, whereas a pair of SRR directors is appended to both sides of the strip director for dual-band operation. When the two types of directors are placed together, the distance between the two directors is important to the antenna performance, and its effects on the input VSWR and realized gain characteristics are analysed.

A prototype of the dual-band SDP antenna operating in the GPS L1 and 1.7–2.8 GHz bands was designed and fabricated on an FR4 substrate. We demonstrated with experiment results that the antenna has dual-band characteristics in the frequency bands of 1.56–1.63 GHz and 1.68–2.87 GHz for a VSWR $< 2$. Measured gain is 5.9–7.5 dBi in the first band, whereas it ranges from 6.2 dBi to 7.3 dBi in the second.

The proposed antenna is expected to be useful for base-station antennas in multiband wireless communications applications.

## ACKNOWLEDGMENT

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## REFERENCES

1. Waterhouse, R., *Printed Antennas for Wireless Communications*, John Wiley & Sons Ltd., England, 2007.
2. Kaneda, N., W. R. Deal, Y. Qian, R. Waterhouse, and T. Itoh, "A broad-band planar quasi-Yagi antenna," *IEEE Trans. Antennas Propag.*, Vol. 50, No. 8, 1158–1160, Aug. 2002.

3. Tefiku, F. and C. A. Grimes, "Design of broad-band and dual-band antennas comprised of series-fed printed-strip dipole pairs," *IEEE Trans. Antennas Propag.*, Vol. 48, No. 6, 895–900, Jun. 2000.
4. Lee, J.-I. and J. Yeo, "Design of a simple three-element quasi-Yagi antenna with a broad impedance bandwidth up to 2.4 : 1," *Journal of Electromagnetic Waves and Applications*, Vol. 27, No. 17, 2247–2262, 2013.
5. Yeo, J. and J.-I. Lee, "Bandwidth and gain enhancement of a series-fed two-dipole array antenna using nearby parasitic director," *Microwave Opt. Technol. Lett.*, Vol. 55, No. 11, 2782–2787, Nov. 2013.
6. Gemio, J., J. Parron, P. de Paco, G. Junkin, J. Marin, and O. Menendez, "A split-ring-resonator loaded monopole for triple band applications," *Journal of Electromagnetic Waves and Applications*, Vol. 24, Nos. 2–3, 241–250, 2010.
7. Montero-de-Paz, J., E. Ugarte-Munoz, F. J. Herraiz-Martinez, V. Gonzalez-Posadas, L. E. Garcia-Munoz, and D. Segovia-Vargas, "Multifrequency self-diplexed single patch antennas loaded with split ring resonators," *Progress In Electromagnetics Research*, Vol. 113, 47–66, 2011.
8. Kim, D. O. and C. Y. Kim, "Dual-band quasi-Yagi antenna with split ring resonator directors," *Electron. Lett.*, Vol. 48, No. 14, 809–810, Jul. 2012.
9. Yeo, J. and J.-I. Lee, "Design of series-fed dipole pair antenna with split-ring resonator directors for dual-band operation," *Journal of Electromagnetic Waves and Applications*, Vol. 29, No. 2, 154–168, 2015.
10. Balanis, C. A., *Antenna Theory: Analysis and Design*, John Wiley & Sons, Inc., Hoboken, NJ, 2005.