Progress In Electromagnetics Research C, Vol. 41, 1–12, 2013

DESIGN OF A PRINTABLE, COMPACT PARASITIC ARRAY WITH DUAL NOTCHES

Jay J. Yu[1] and Sungkyun Lim[2, *]

[1]SPAWAR Systems Center Pacific, Pearl City, HI 96782, USA

[2]Department of Electrical Engineering, Georgia Southern University, Statesboro, GA 30460, USA

Abstract—A compact, parasitic array antenna printed on both sides of the substrate to generate dual notches is introduced. The antenna is composed of one driver and two directors. Both directors are discretely segmented and are twisted with each other to minimize the radiation interference from one director to the other at each resonance. The antenna is optimized for realized gains in the director direction at the two resonant frequencies. The optimized antenna has been fabricated and measured to verify the simulated results. At both resonances, the measured realized gains in the director direction are greater than 8.5 dBi, and the front-to-back ratios are more than 10 dB.

1. INTRODUCTION

A printable antenna has advantages of light weight, easy fabrication, and low cost, all of which open up the possibility of mass production in many wireless-communication applications, such as mobile phones, satellites, sensors, and RFID systems. Parasitic array antennas are commonly used in long-distance radio communications because of their combination of high-gain characteristics and simple structures. Previous research has developed a compact-sized, printable parasitic array (or Yagi-Uda) antenna [1]. The antenna is composed of a folded driver and a director. The folded driver boosts the radiation resistance [2] and achieves a close spacing of 0.044λ between a driven element and a parasitic element, which normally require spacing of $0.15\lambda - 0.4\lambda$ [3, 4]. A printed parasitic array antenna with multiple directors was also investigated in [5]. The number of directors varies from one to nine, and each set of antenna designs is optimized using the

Received 2 May 2013, Accepted 3 June 2013, Scheduled 10 June 2013

* Corresponding author: Sungkyun Lim (sklim@georgiasouthern.edu).

Invasive Weed Optimization (IWO) method [5, 6] for low VSWR and high gain at a single frequency band. Typically, the main radiation of a parasitic array antenna occurs in one fixed direction that is toward to the director's direction as shown in [3–5]. In [7–9], the methods to switch the radiation pattern of parasitic array antennas using varactor diodes or p-i-n diodes were also introduced.

A dual- or multi-band antenna is useful in overcoming the multipath fading caused by buildings and other obstructions in modern wireless-communication systems [10]. Recently, parasitic array antennas have been designed with multi-band capability [11]. Unlike in a traditional parasitic array, directors are twisted in helical shapes with different radii along the common helical center. More than 8.6 dBi in realized gains in the direction of the directors and front-to-back ratios higher than 9 dB are achieved at all generated resonances.

In this paper, a printable, compact parasitic array antenna with dual notches is introduced. The antenna consists of a driver and two directors. As in [4], the driver is folded to reduce the spacing between the driver and directors. The concept of twisted directors [11] is applied in the printed version. Two directors are printed on the front and back sides of a substrate, Rodgers Duroid 5880 (thickness = 3.2 mm and $\varepsilon_r = 2.2$), while maintaining twisted helical shapes. The antenna dimensions are optimized using the Genetic Algorithm (GA) [12, 13] in conjunction with IE3D [14] to maximize realized gains in the direction of the directors at dual notches. A monopole form is chosen to avoid balun issues. The realized gain is thus about 3 dB higher than that of the dipole form. The total volume of the proposed antenna without ground plane is $0.214\lambda \times 0.096\lambda \times 0.013\lambda$. Copper strips with a width of 2 mm are used for overall antenna geometry. The simulated results are verified with measurements after construction of a prototype of the optimized antenna.

2. ANTENNA DESIGN CHARACTERISTICS

To achieve dual-notch operation, two directors are constructed as follows. First, the stretched lengths of both directors are different, which leads to different resonances for the two directors. Second, the directors are digitized on the substrate to generate twisted helical shapes. Using twisted helical directors in a planar design prevents radiation disturbance from one director to the other at the corresponding resonance. The employment of these two design methods makes the antenna perform as a typical two-element (a driver and a director) parasitic array at both frequency notches.

In order to achieve the helical shape, each director is separated into lower and upper components. As illustrated in Figure 1, the lower component of director 1, which is printed on the front side of the substrate, begins with a vertical segment (a in Figure 1) at the junction of the ground plane. At the top of this vertical segment, one end of a horizontal segment is printed on the same (front) side of the substrate. Next, another vertical segment starts at the other end of the horizontal segment to complete the lower part of director 1. The upper component is constructed in the same way but is printed on the back side of the substrate. Finally, the lower and upper components are connected using a horizontal segment that penetrates the substrate at the height b in Figure 1. Director 2 is designed in a similar fashion, but the lower component is printed on the backside of the substrate, and the upper component is printed on the front.

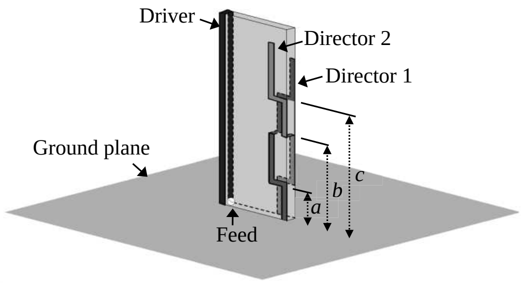

Figure 1. Initial design of a printable, compact parasitic array antenna.

The antenna dimensions are optimized using the GA to maximize the realized gains in the direction of the directors at 1.2 GHz and 1.3 GHz. The operating frequencies and frequency difference of 0.1 GHz between the two frequencies are chosen randomly where the frequency difference was found within the adjustable range between 0.04 GHz and 0.12 GHz, which was determined using simulations in which the lengths of the two directors was altered. If the frequency difference is below 0.04 GHz, both frequency notches are merged. If it is over 0.12 GHz, poor impedance matching occurs because the driver cannot cover both notches. In optimization, a total of eight parameters are taken into account, including the height of the driver, the heights of the two directors, the heights of three turning points (a, b, and c in Figure 1) in the directors, the lengths of the horizontal segments in the directors that are printed on the surfaces of the substrate, and the spacing between the driver and directors. The lengths of all horizontal segments on both surfaces of the substrate are kept the same to reduce the number of variables in the GA optimization, following confirmation through another simulation that the role of these horizontal segments is insignificant and that shorter lengths are better because the main radiation of the antenna occurs from the vertical components. The horizontal segments that pass through the substrate at the height b in Figure 1, however, are determined by the thickness of the substrate (3.2 mm). The number of turns in the helical directors is also fixed at one, because more turns do not give any advantage in antenna performance, including in S_{11} or gain. The effect of the number of turns is further discussed in Section 4.1.

The cost function of the GA optimization is defined as

$$cost\ function = \sqrt{(Goal - RG_1)^2 + (Goal - RG_2)^2} \tag{1}$$

Two realized gains in the direction of the directors, RG_1 at 1.2 GHz and RG_2 at 1.3 GHz, are set in the objective function. Based on the previous finding that the maximum realized gain cannot exceed 10 dBi from the parasitic array antennas using one driver and one director [1], the goal of 10 dBi in Equation (1) is chosen.

3. SIMULATION AND EXPERIMENTAL RESULTS

The overall configuration of the optimized design and the detailed dimensions are shown in Figure 2. To simplify the antenna design, an infinite ground plane is used in the simulation. Interestingly, the heights of the turning points of the directors are relatively low. The directors are twisted at the lower location because it is believed to effectively reduce the radiation interference that occurs between two directors, since the main radiation occurs where strong currents are located (right above the ground plane). By contrast, if the directors were twisted at the higher location, strong radiation interference would remain at the lower location, and the twist at the weak current position (the higher location) would not help to reduce the radiation interference. Another simulation placing restrictions on the turning height is performed for further confirmation and is discussed in Section 4.2.

Figure 3 shows the current distributions of the antenna at 1.2 GHz and 1.3 GHz. At 1.2 GHz (Figure 3(a)), current magnitudes in the lower part of director 2 are stronger than those in the lower part of director 1. It is also confirmed that the phase difference between the driver and the bottom of director 2 is nearly anti-phase (180°). As a result, director 2 becomes the only operating director. At 1.3 GHz (Figure 3(b)), likewise, director 1 becomes the operating mode for similar reasons.

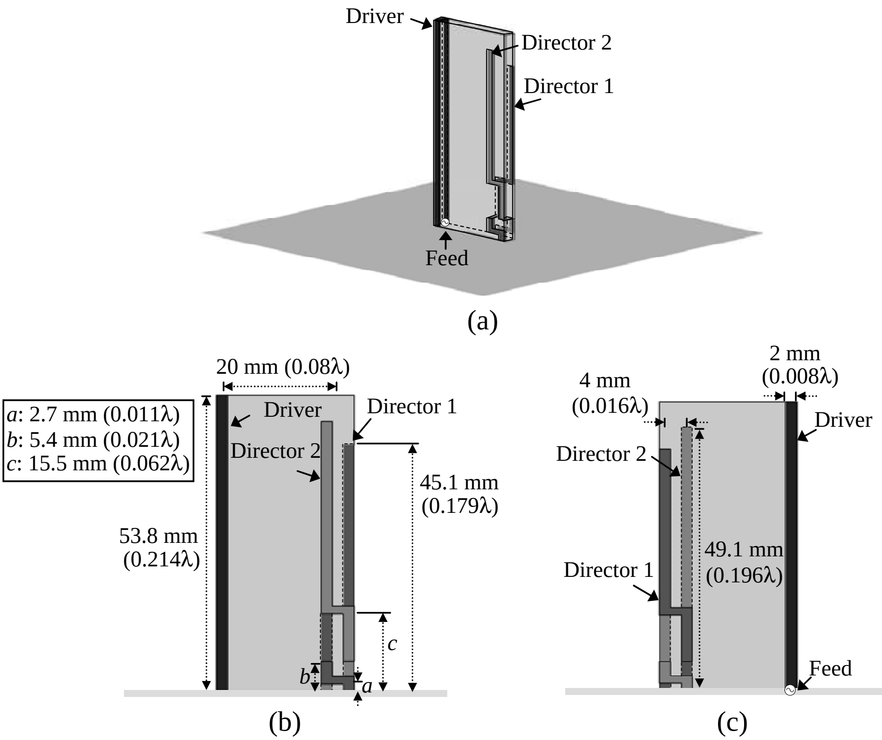

Figure 2. Optimized design of the printable, compact parasitic array antenna. (a) Slanted view. (b) Front view. (c) Rear view.

In the dimensions of the optimized antenna demonstrated in Figure 2, the wavelength, λ, is calculated using the resonant frequency of the only driver (1.19 GHz), which was found by performing a separate simulation without the directors. Since the driver is folded, the spacing between the driver and directors is reduced in comparison with a conventional Yagi antenna. The optimized spacing between the driver and the center of the twisted directors is found to be 20.0 mm (0.08λ) by the GA, as denoted in Figure 2. The length of the driver, including one vertical segment and a half of the horizontal segment on the top, is 55.4 mm (0.22λ). The stretched lengths of the two directors, consisting of horizontal and vertical segments, are 56.3 mm (0.224λ) and 60.3 mm (0.24λ) for director 1 and director 2, respectively. Since the currents in the horizontal segments of one director flow in the opposite direction from those in the other director, and they are closely located, the horizontal currents cancel each other out. By excluding

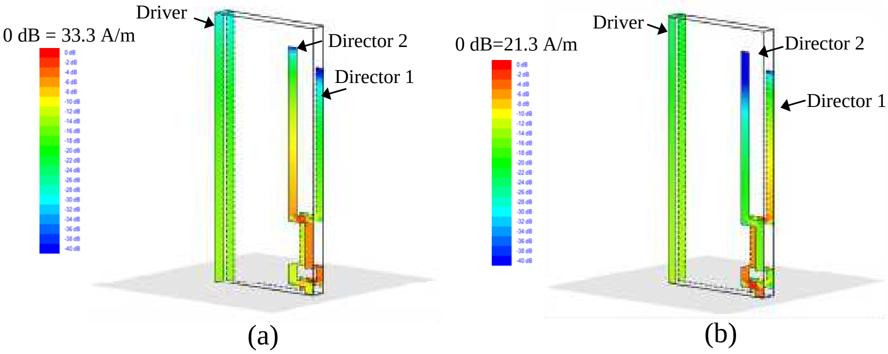

Figure 3. Current distributions of the printable, compact parasitic array antenna. (a) At 1.2 GHz. (b) At 1.3 GHz.

the horizontal segments, therefore, the lengths of directors are slightly shorter than that of the driver.

To validate the simulated results, a prototype of the antenna was fabricated and measured. The photo of the fabricated antenna is shown in Figure 4. To simplify fabrication, copper wire instead of strip was used for the horizontal segments that penetrate the substrate. The radius of the penetrating wire is chosen to be 0.5 mm, which is four times smaller than the strip width [15]. A ground plane with a size of 26.7 cm (1.06λ) $\times$ 26.7 cm (1.06λ) was used for the prototype.

Figure 5 displays the simulated and measured S_{11} results of the proposed antenna design. The lower notch is generated by the longer director (director 2), and the upper notch by the shorter director

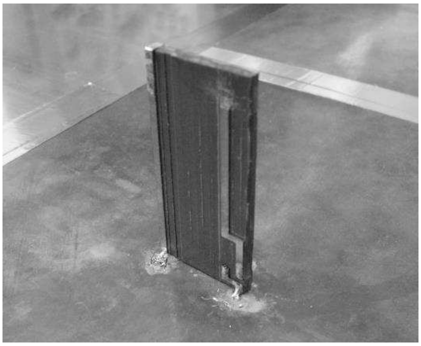

Figure 4. Picture of the fabricated antenna.

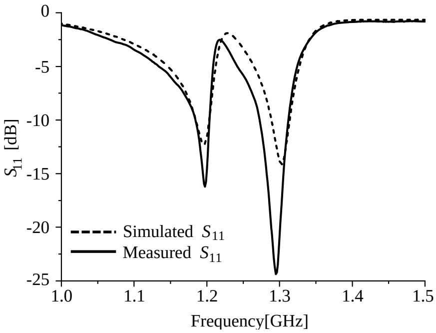

Figure 5. Simulated and measured S_{11} of the printable, compact parasitic array antenna.

(director 1). The minimum S_{11} of the simulated values at 1.2 GHz and 1.3 GHz are −12.3 dB and −14.1 dB, with 10-dB bandwidths of 1.6% and 1.9%, respectively. The measurement of S_{11} was performed using an Anritsu MS4624B network analyzer. After slight trimming (< 1 mm) of the tips of the antenna elements, two resonant frequencies are created at 1.2 GHz and 1.3 GHz with a minimum S_{11} of −16.2 dB and −24.4 dB, respectively, as illustrated in Figure 5. The measured 10-dB bandwidth at 1.2 GHz is 1.6%, and that at 1.3 GHz is 3.0%.

Next, the simulated realized gain patterns in the azimuth plane are obtained from 1.2 GHz and 1.3 GHz, as shown in Figure 6. The realized gains of 8.6 dBi are observed in the director's direction at both frequencies and the front-to-back ratio is 9.7 dB at 1.2 GHz, and 12.6 dB at 1.3 GHz. The measured realized gain patterns in the azimuth plane at 1.2 GHz and 1.3 GHz is also depicted in Figure 6. The maximum measured realized gain in the director's direction is

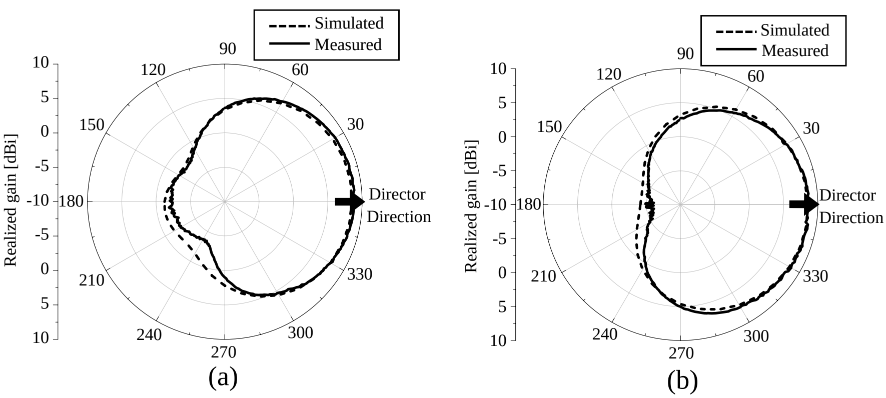

Figure 6. Simulated and measured realized gain patterns in the azimuth plane of the printable, compact parasitic array antenna. (a) At 1.2 GHz. (b) At 1.3 GHz.

Table 1. Simulated and measured results.

	Operating frequency [GHz]	Minimum S_{11} [dB]	10-dB bandwidth [%]	Realized gain in the director direction [dBi]	Front-to-back ratio [dB]
Simulated results	1.2	−12.3	1.6	8.6	9.7
	1.3	−14.1	1.9	8.6	12.6
Measured results	1.2	−16.2	1.6	8.7	10.9
	1.3	−24.4	3.0	8.5	14.4

8.7 dBi at 1.2 GHz, and 8.5 dBi at 1.3 GHz. The measured front-to-back ratios at both frequencies are greater than 10 dB. The measured results agree fairly well with the simulated ones except for the wider 10-dB bandwidth and the lower realized gain at 1.3 GHz, probably due to ohmic loss from the soldering junction between the printed strips and the copper wires that penetrate the substrate. The simulated and measured results are summarized in Table 1.

4. FURTHER DISCUSSION OF THE ANTENNA DESIGN

4.1. The Effect of the Number of Turns in the Directors

In this section, S_{11} and gain of the antenna are investigated when the number of turns in the directors is increased. Two antenna designs are optimized using conditions similar to those given in the previous design,

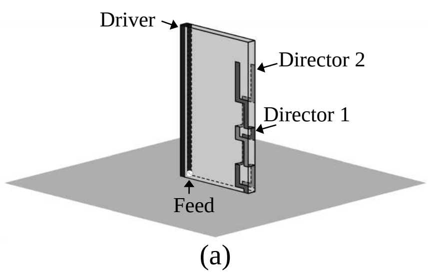

Figure 7. Optimized design of the printable, compact parasitic array antenna, using different numbers of turns. (a) Directors with two turns. (b) Directors with three turns.

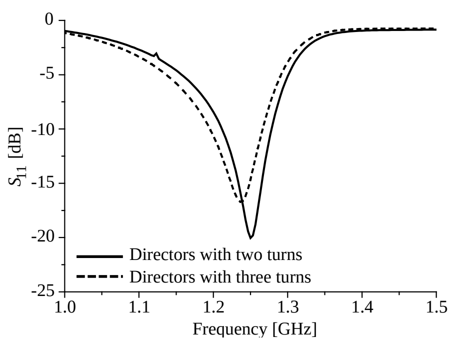

Figure 8. Simulated S_{11} of the printable, compact parasitic array antenna, using different numbers of turns in the directors.

shown in Figure 2, except that the number of turns in the directors is increased to two (Figure 7(a)) or three (Figure 7(b)). Because of the extra turns in the directors, additional variables (the heights of turning points for the additional turns) are added to the optimization.

The simulated results of S_{11} and realized gain patterns are illustrated in Figures 8 and 9, respectively. As shown in Figure 8, a single notch instead of dual notches is generated, and the maximum realized gains in the direction of the directors are reduced at both frequencies (Figure 9) in comparison with those of the single-turn antenna design because of the directors' extra turns, which likely generate distortion of current flows on the over-segmentized strips.

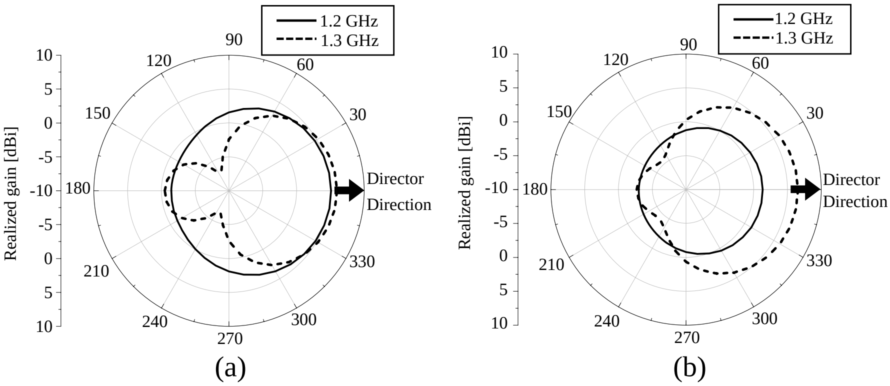

Figure 9. Simulated realized gain patterns in the azimuth plane of the printable, compact parasitic array antenna. (a) Directors with two turns. (b) Directors with three turns.

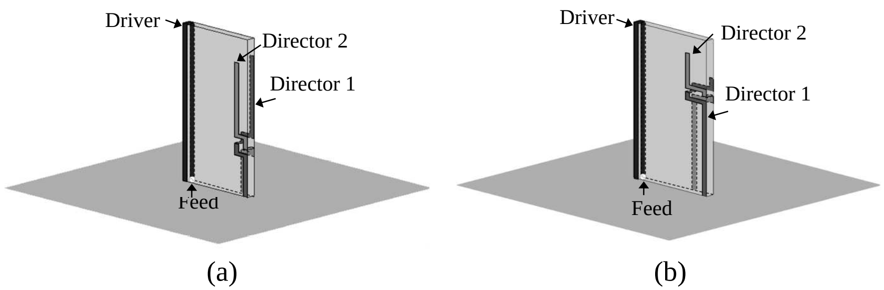

Figure 10. Optimized design of the printable, compact parasitic array antenna with the restricted turning heights. (a) Two directors are twisted at the middle area. (b) Two directors are twisted at the upper area.

4.2. Restriction of the Turning Height in Directors

Next, the height of the turning point in the directors is investigated in the single-turn antenna design. In this study, the range of the turning height in the directors is restricted in two different cases. In case (1), the range of the turning height is limited to the middle portion (1/3–2/3) of the directors, and the restriction in case (2) is to the upper area (1/2–5/6) of the directors. The optimized antenna designs for cases (1) and (2) are shown in Figures 10(a) and (b), respectively, and their simulated results are illustrated in Figures 11 and 12. In both

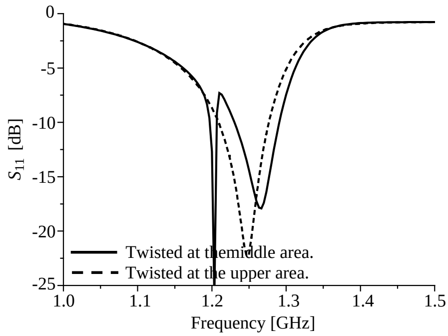

Figure 11. Simulated S_{11} of the printable, compact parasitic array antenna with different turning height in directors.

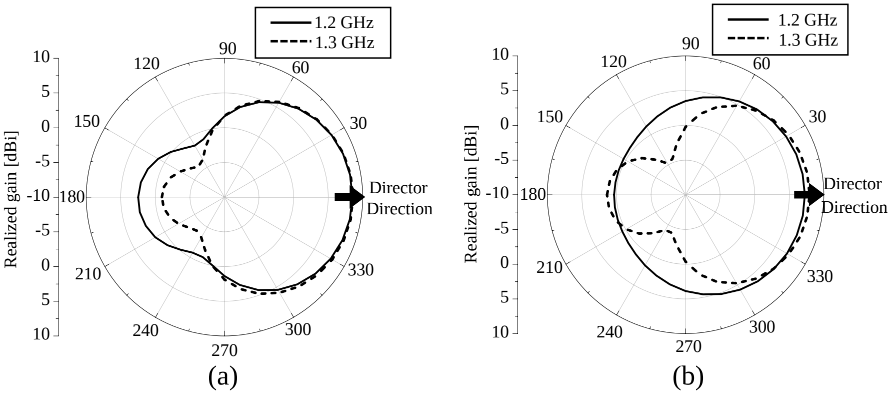

Figure 12. Simulated realized gain patterns in the azimuth plane of the printable, compact parasitic array antenna. (a) Two directors are twisted at the middle area. (b) Two directors are twisted at the upper area.

case (1) and case (2), the two notches tend to be merged into one, and the realized gains in the direction of directors and the front-to-back ratios become degraded. These results support the conclusion that turning the directors at the lower area (where the strong current flows) is ideal for achieving clear dual-notch performance with good realized gain (> 8.5 dBi) and front-to-back ratios at the desired frequencies.

5. CONCLUSION

A printable, compact parasitic array antenna was introduced for dual-notch operation. Two directors with different lengths were discretely segmented and printed continuously on both sides of the substrate in helical shapes to achieve dual notches with high gains. The antenna was optimized using the GA to maximize realized gains in the direction of the directors at the frequencies of 1.2 GHz and 1.3 GHz. At each frequency, only one director is activated, and the resulting realized gain is similar to that of a typical two-element parasitic array antenna. The prototype was constructed and measured. Good agreement was obtained between the simulation and measurements. In the measurements more than 8.5 dBi of realized gains in the director's direction and front-to-back ratios greater than 10 dB were measured at both frequencies.

REFERENCES

1. Lim, S. and H. Ling, "A printable Yagi antenna with closely spaced elements," *Microwave Opt. Technol. Lett.*, Vol. 49, No. 9, 2106–2109, Sep. 2007.
2. Lim, S. and H. Ling, "Comparing electrically small folded conical and spherical helix antennas based on a genetic algorithm optimization," *Journal of Electromagnetic Waves and Applications*, Vol. 23, Nos. 11–12, 1585–1593, 2009.
3. Stutzman, W. L. and G. A. Thiele, *Antenna Theory and Design*, John Wiley & Sons, Inc., 1998.
4. Lim, S. and H. Ling, "Design of a closely spaced, folded Yagi antenna," *IEEE Antenna Wireless Propag. Lett.*, Vol. 5, No. 1, 302–305, 2006.
5. Sedighy, S. H., A. R. Mallahzadeh, M. Soleimani, and J. Rashed-Mohassel, "Optimization of printed Yagi antenna using invasive weed optimization (IWO)," *IEEE Antenna Wireless Propag. Lett.*, Vol. 9, No. 3, 1275–1278, 2010.

6. Mehrabian, A. R. and C. Lucas, "A novel numerical optimization algorithm inspired from weed colonization," *Ecol. Inform.*, Vol. 1, No. 4, 355–366, 2006.
7. Schlub, R., J. Lu, and T. Ohira, "Seven-element ground skirt monopole ESPAR antenna design from a genetic algorithm and the finite element method," *IEEE Trans. Antennas Propagat.*, Vol. 51, No. 11, 3033–3039, Nov. 2003.
8. Islam, M. R., N. H. Chamok, and M. Ali, "Switched parasitic dipole antenna array for high-data-rate body-worn wireless applications," *IEEE Antenna Wireless Propag. Lett.*, Vol. 11, 693–696, 2012.
9. Lim, S., "Design of a multi-directional, high gain, compact Yagi antenna," *IEEE Antennas Wireless Propagat. Lett.*, Vol. 8, 418–420, 2009.
10. Basilio, L. I., R. L. Chen, J. T. Williams, and D. R. Jackson, "A new planar dual-band GPS antenna designed for reduced susceptibility to low-angle multipath," *IEEE Trans. Antennas Propagat.*, Vol. 55, No. 8, 2358–2366, Aug. 2007.
11. Yu, J. J. and S. Lim, "Design of multi-band, compact parasitic array with twisted, helical directors," *IEEE Trans. Antennas Propagat.*, Vol. 61, No. 1, 444–449, 2013.
12. Rahmat-Samii, Y. and E. Michielssen, *Electromagnetic Optimization by Genetic Algorithms*, John Wiley & Sons, Inc., 1999.
13. Sigher, T. S. and A. A. Kishk, "Antenna modeling by infinitesimal dipoles using genetic algorithms," *Progress In Electromagnetics Research*, Vol. 52, 225–254, 2005.
14. IE3D, Mentor Graphics, Inc..
15. Elliott, R. S., *Antenna Theory and Design*, Prentice Hall, 1981.