Shorted Fractal Sierpinski Monopole Antenna

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***Abstract*—This paper describes novel configurations of shorted fractal Sierpinski gasket antenna. The antenna uses half the structure of a conventional Sierpinski gasket antenna and is folded over to be parallel to the ground plane, to form an element similar to that of the inverted L antenna. A quasi log periodic resonance behavior is obtained with a shorting pin placed at the far end of the antenna. Several configurations are shown and a design using two shorting pins which improves the bandwidth at the fundamental band is also demonstrated.**

***Index Terms*—Fractal shaped antenna, inverted L antenna, multiband antenna.**

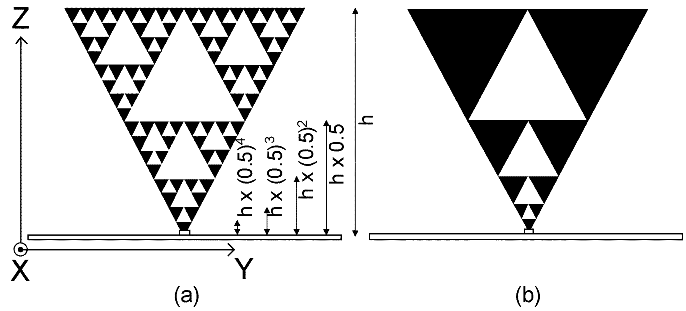

Fig. 1. (a) Fractal Sierpinski gasket monopole and (b) the Parany monopole antenna.

I. Introduction

In recent years, the use of fractal geometries for antenna design has been extensively reported [1]–[15]. Fractal geometries, which are characterized by a series of built-in self-similarities, in which an object, the motif, is being repeated on an ever-diminishing scale, gives the potential for realizing multiband or even broadband antenna behavior. Some of these properties are also applied in designing space filing small antenna [8]. One fractal structure that has aroused particular interest is the Sierpinski gasket which, was first reported by Puente *et al.* [4]. The Sierpinski gasket consists of a series of scaled triangles forming a linear fractal structure, as shown in Fig. 1(a). In the progression of its fractal iteration, the repetitive structural properties translate to a log-periodic allocation of frequency bands as given by (1), where ζ is the scale factor ratio. The Parany monopole antenna as shown in Fig. 1(b), also provides similar electrical properties as the Sierpinski gasket monopole antenna. This antenna was also first reported by Puente [5]. Since these developments, there has been a growing interest in various forms of fractal Sierpinski gasket antennas

$$\zeta = \frac{h_n}{h_{n+1}} = 0.5. \tag{1}$$

It is recognized that perturbation of this geometry is necessary to enhance the performance of these antenna [9]–[14]. One of the major issues is the truncation of these monopole antennas. This results in reflected current, causing the fundamental band to deviate from its log-periodic behavior. Recent researches has also led to planar low-profile fractal Sierpinski patch antennas. However, reflections of currents in the different operating bands cause phase cancellation, causing pattern variations in each band. This is especially true in the second operating band where a null is observed. To correct this defect, shorting pins have been included [15].

The evolution of wire monopole antennas to inverted L and planar inverted F antennas has been a significant importance of the progress in antenna technology. Many different forms of reduce-sized antennas and low profile antennas are all results of this evolution [16], [17]. One of the recent advances combining fractal Sierpinski antenna and the inverted L configuration was first reported in [18]. A shorting pin was used to reduce the size of the Sierpinski monopole, and to remove truncated current. In this paper, we will first present in Section II detailed results of the antenna configuration reported in [18], [19]. We will then describe in Section III two planar antenna configurations using the same concept and also verifying band allocation capability with the Parany monopole antenna. Finally in Section IV, we will propose a new design using dual shorting pins to enhance the bandwidth of the antenna at the lower operating band. This concept will enable design of multiband antenna which covers operation of most cellular bands and also configuring for the 802.11a bands.

II. Vertical Shorted Sierpinski Gasket Antenna

A. Antenna Design

The design of the shorted Sierpinski gasket antenna is similar to that of the inverted L antenna [16], and the shorted loop monopole [20]. The prototype Sierpinski gasket is constructed through a four iteration process. This results to four operating bands from the four-scaled version of the final gasket structure. The four small triangles in the top row resulted from the fourth iteration were however not removed. Using only half of the Sierpinski gasket as shown in Fig. 2, it is then possible to fold the antenna in a similar way to the inverted L antenna, where the symmetry plane is now parallel with the ground plane.

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An approximated equation to estimate the resonance frequency of the fractal Sierpinski gasket has been given in [5], [7]. In this case, due to the contribution of the feed monopole, an additional term h_m is included. Note that c is the speed of light, n is an integer number and ζ is the scale factor ratio as described in (1). The resonance frequency of the bands can be estimated using (2) as shown below. Comparison with experimental results will be introduced in the next section

$$f \approx c\left\{0.425^x[4.25h\zeta^Y] + h_m\frac{1}{0.5^{0.2^Y}}\right\}^{-1} \tag{2}$$

$$\text{where}\quad \begin{cases} x = 0, & \text{for}\quad \mathrm{n} = 0 \\ x = 1, & \text{for}\quad \mathrm{n} \geq 1 \\ Y = x(n-1). \end{cases}$$

The antenna prototype shown in Fig. 2 has a height h of 40 mm, and ζ of 0.5. It is printed on FR4 substrate with a thickness of 0.5 mm. The ground plane size is 15 × 15 cm and the height of the feed h_m is 0.5 mm.

B. Results and Discussion

The return loss (S_{11}) of the antennas was measured with an HP8720C network analyzer. When fed vertically, the halved Sierpinski gasket still maintains log periodic VSWR resonance behavior. However, radiation pattern shows unbalanced main lobes. This is attributed to the unbalanced nature of the antenna structure, causing pattern degradation in comparison to the conventional Sierpinski gasket monopole antenna [4], [5], [7]. The measured input impedance curve varies more sharply when compared to the unperturbed structure, due to a higher Q, as the antenna now has less area for radiation. In the folded, "inverted L" configuration where the symmetry plane is 0.5 mm above the ground plane, the antenna impedance increases resulting to poor matching characteristic. It is found that the matching improves when the feed monopole height (h_m) is increased to 5 mm, except for the first resonance band. At the upper frequency band, contribution from the feed monopole becomes more significant. These input return loss performances are shown in Fig. 3(a)–(c). The measured resonances are at 1.77, 3.43, 6.73, and 12.2 GHz, giving a frequency ratio of 0.51, 0.51, and 0.55. The slight increase in the third ratio is due to the height of the feed. Using (2), the estimated frequencies for the antenna shown in Fig. 2 are at 1.67, 3.65, 7.17 and 12.93 GHz, giving an error in comparison to experimental results of 5.65, 6.41, 6.53, and 5.98%, respectively.

The poor matching characteristics of the first band and the deviation from log periodic behavior of the Sierpinski gasket antenna can be attributed to the truncation effect. Since currents of the first band are not sufficiently attenuated by radiation, a reflection from the edge of the antenna occurs, forming a standing wave which perturbs the log periodic performance. To remove this edge current, a shorting pin is placed at the far end of the antenna, as shown in Fig. 2. The result is an antenna that is very similar in operation to a shorted loop monopole [20]. From the input return loss observation, it is clear that the matching characteristic of the first band has improved. This is shown as dash

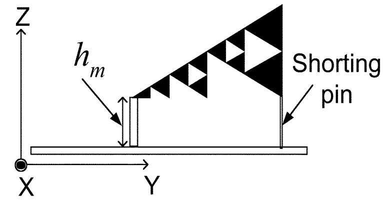

Fig. 2. Folded shorted "inverted L" Sierpinski gasket.

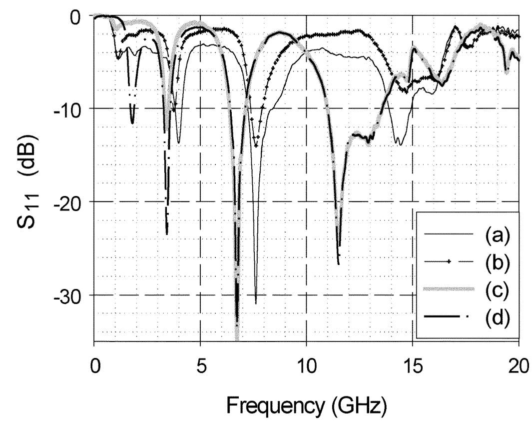

Fig. 3. Measured S_{11} comparison (a) vertically fed Sierpinski gasket shown in Fig. 1(a), (b) vertically fed halved Sierpinski gasket, (c) folded "inverted L" Sierpinski gasket shown in Fig. 2 with $h_m = 5$ mm and shorting pin, (d) shorted folded "inverted L" Sierpinski gasket shown in Fig. 2 with $h_m = 5$ mm.

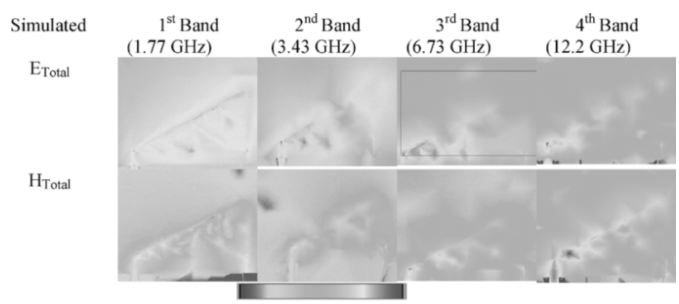

Fig. 4. Simulated field distribution of the four operating bands.

lines in Fig. 3(d). The resonance frequency has also shifted up from 1.05 to 1.77 GHz and the frequency ratio between the first and second band was brought near to about 0.5. Although this seems to indicate log periodic action of the Sierpinski gasket, it is however due to the shorted loop mode. From the input return loss plot, it can also be deduced that the resonance frequency of the third and fourth band are not affected by the shorting pin. These bands can thus be considered due to the Sierpinski gasket.

A full wave electromagnetic simulation software (HP-HFSS) was use to predict the performance of the antenna rather adequately. The simulated field distribution is shown in Fig. 4. For the first band, high E-field strength can be seen on the entire antenna structure and the H-field shows high current density that congregates around the shorting pin. This indicates that at the first resonance, current flows in the closed loop, from the feed to the ground via the shorting pin. In comparison to higher bands, the H-field intensity of the shorting pins are much less, hence its

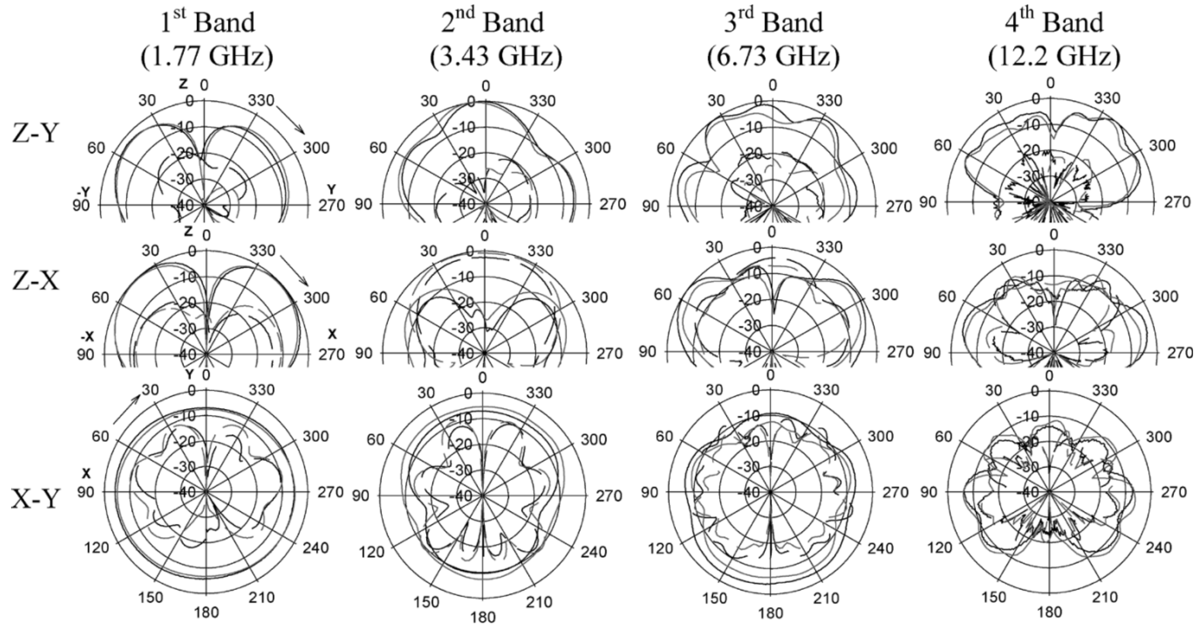

Fig. 5. Measured (black lines) and simulated (red lines) radiation plots of the vertically mounted folded shorted Sierpinski gasket antenna shown in Fig. 2 (——E_θ, - - -E_ϕ).

contribution at that frequency is minimal. As the operating frequency increases, the size of the antenna's "hot" zone also reduces. This further verifies that these resonances are attributed to the fractal Sierpinski gasket modes.

The measured and simulated radiation patterns of the four bands are shown in Fig. 5. A good agreement between the theoretical and experimental results is achieved. The first band demonstrates a monopolar-liked pattern, while the expected nulls along the Z axis of the second and third band were not present along the $Z-Y$ plane. The $X-Y$ plane also demonstrates asymmetrical omni-directional patterns. This is attributed to the asymmetrical nature of the antenna structure, and field contribution from horizontal and vertical planes in each band. At the fourth band, the $Z-X$ and $Z-Y$ planes show better monopolar patterns. The generated patterns of the first two resonances are clearly shorted loop modes [20], however with higher cross-polar power for the second resonance in the $Z-X$ plane. Although the third and fourth bands are the Sierpinski modes, a slight null is observed for the fourth band and this is due to the greater contribution of the feed monopole.

III. Planar Shorted Antenna Configuration

A. Planar Shorted Sierpinski Gasket Antenna

Using the design concepts demonstrated above, the shorted antenna may also be designed in a planar configuration as shown in Fig. 6. The gasket height, h, is maintained at 40 mm and the antenna is printed on similar FR4 substrate. In this case, the antenna height h_m is raised to 14 mm, so as to improve the matching by reducing the interaction of the ground plane with the antenna. The measured input return loss comparison with simulation, and (d) of Fig. 3, are shown in Fig. 7. Resonances were obtained at 1.52, 3.23, 5.49, and 9 GHz, giving frequency ratios of 0.47, 0.58, and 0.61, respectively. A lower resonance frequency is observed compared to the vertically mounted

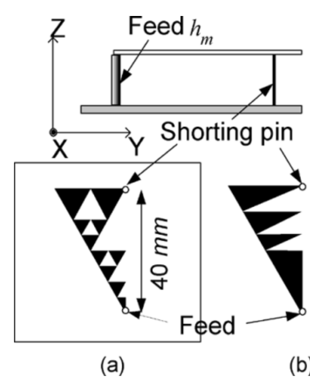

Fig. 6. (a) Configuration of the planar shorted Sierpinski gasket antenna and (b) configuration of the planar shorted Parany antenna.

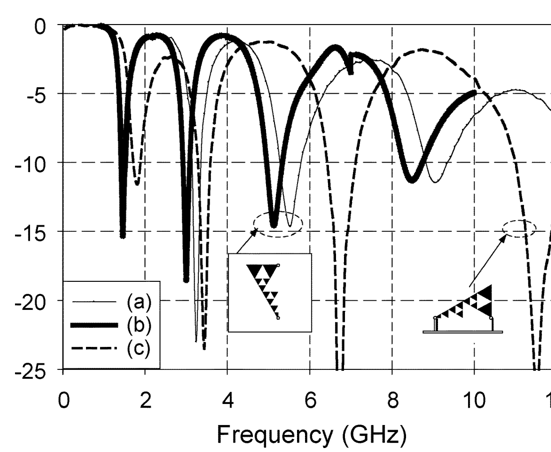

Fig. 7. S_{11} characteristics of the planar shorted Sierpinski gasket antenna: (a) measured, (b) simulated, and (c) vertical type configuration.

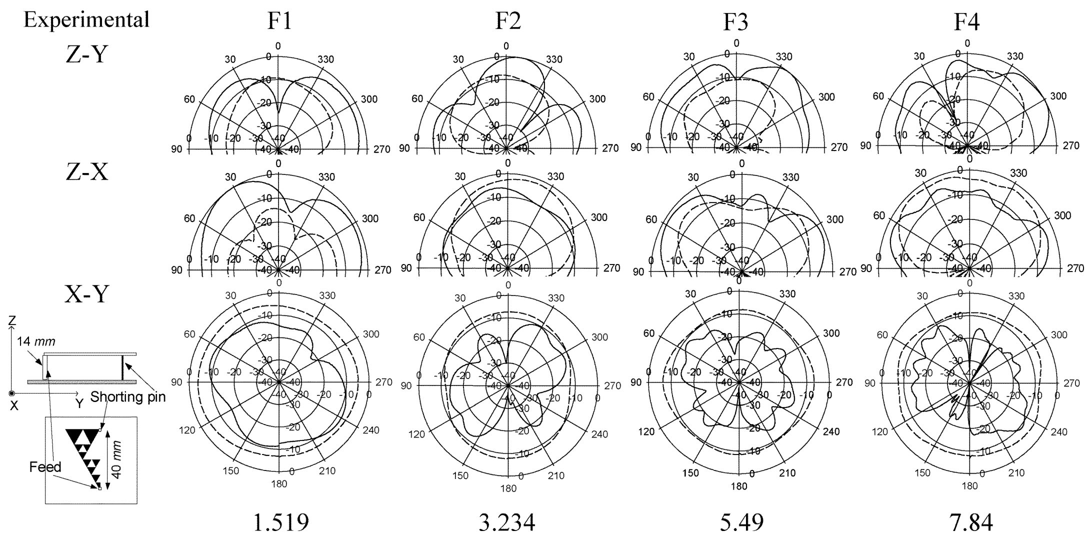

Fig. 8. Measured radiation pattern of the planar shorted Sierpinski gasket antenna shown in Fig. 6(a) (——E_θ, - - -E_ϕ).

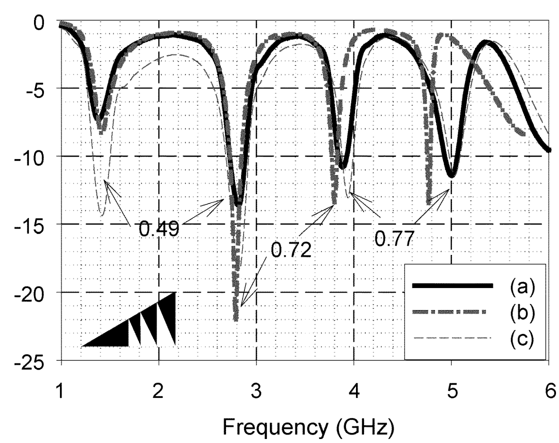

Fig. 9. Measured and simulated S_{11} characteristics of shorted Parany antenna shown in Fig. 6(b) (a) measured planar Parany, (b) simulated planar Parany, and (c) measured vertical Parany.

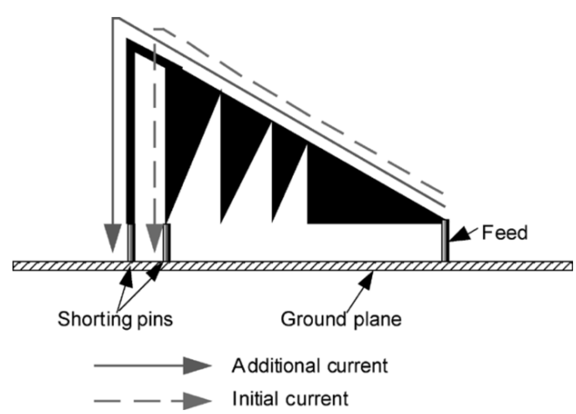

Fig. 10. Parany monopole antenna with dual shorting pins.

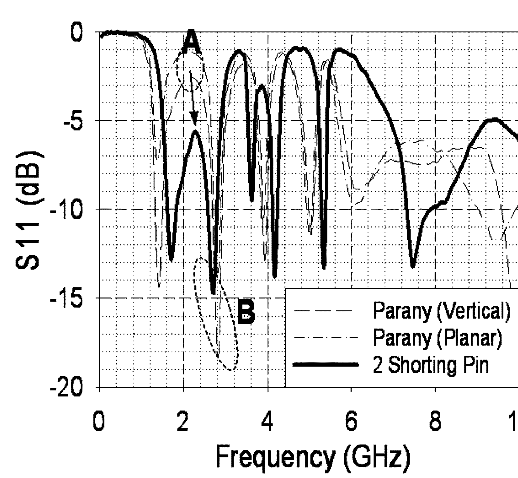

Fig. 11. Improved performance using two shorting pins.

configuration of Fig. 2. This is due to the contribution from the longer feed, hence resulting in a longer current path. The full wave simulation was able to predict quite accurately the generated resonance. The simulated E and H field distribution also shows resonance due to the discontinuity of the Sierpinski gasket, similar to that in Fig. 4. Due to the change from vertical to planar configuration, radiation patterns are also expected to vary as shown in Fig. 8.

B. Planar Shorted Band Allocated Parany Antenna

It is well understood that the allocation of operating bands can be achieved by changing the scale factor ratio of the Sierpinski gasket and Parany monopole antenna [5], [9], [13], [14]. This technique can also be applied to the shorted antenna configuration. The perturbed fourth iterated Parany monopole antenna shown in Fig. 6(b) with $h = 40$ mm and $h_m = 16$ mm is printed on a similar FR4 material in the previous section. The scale factor ratio, ζ of 0.8 was used. The simulated and measured results of the planar fed shorted Parany monopole antenna

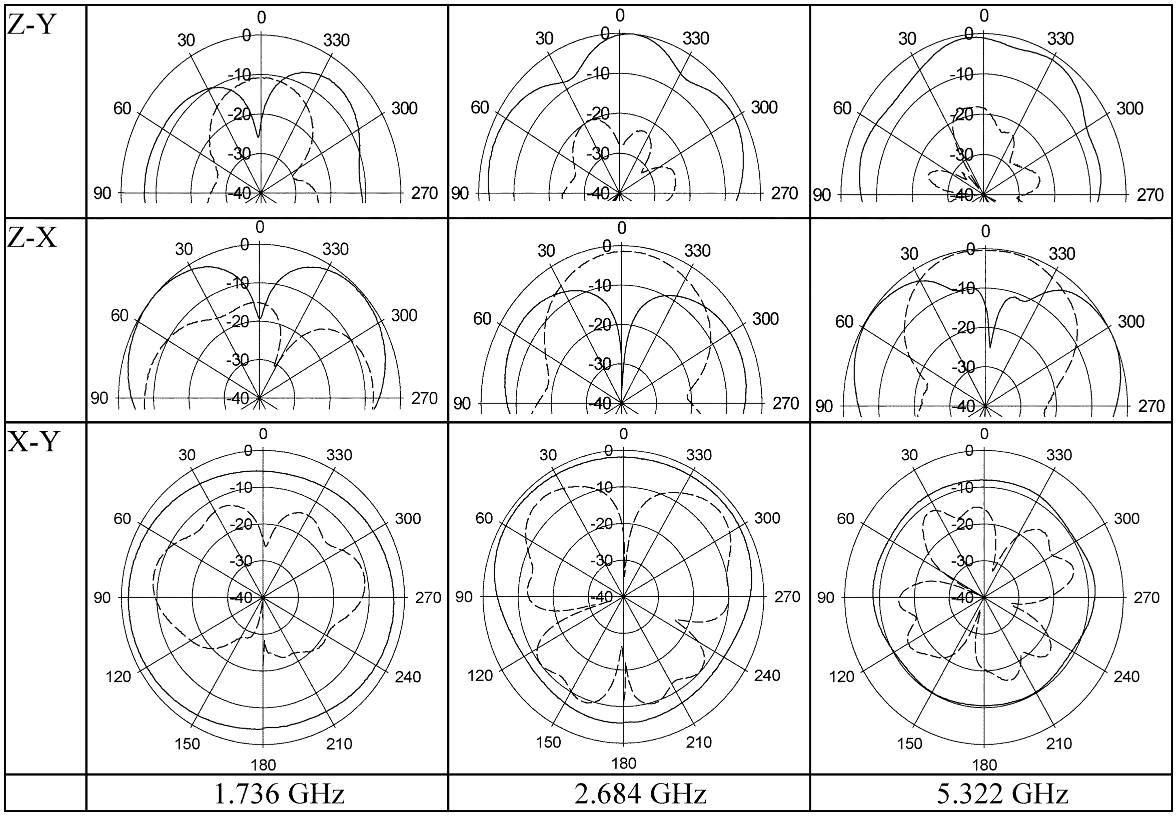

Fig. 12. Measured radiation pattern for the antenna shown in Fig. 10.

are shown in Fig. 9(a) and (b) respectively The results of a vertically fed configuration is also shown in Fig. 9(c) for comparison. From the input return loss results, it is clear that the vertical type configurations provide a better impedance match than the planar type. The resonances were obtained at approximately 1.39, 2.82, 3.90, and 5.04 GHz, where frequency ratios between the bands are 0.49, 0.72, and 0.77. Despite the prescribed frequency ratio of 0.8, the first two resonances are similar to that of the shorted Sierpinski gasket shown in Fig. 2. This again implies a shorted loop mode. Frequency allocation can also be observed on the upper resonances where their ratios are around 0.75. Nevertheless, these resonances are very much perturbed by the presence of the feed monopole.

IV. Bandwidth Improved Performance

As noted above, the truncated currents of the monopole configuration has caused deviation of the fundamental band performance from its expected log periodic behavior. Another design proposed which attempts to attenuate the residual current sufficiently was to include an additional frame [12], hence maintaining the log-periodic behavior of the antenna. To apply this to the antenna above, two shorting pins are placed at the edge of the antenna. This generates an additional mode, formed by the external frame and shorting pin. Fig. 10 shows the initial mode represented by the dash line (- - -) while the additional current mode is shown as hard line (——). The antenna of Fig. 10 has a height h of 40 mm, and ζ of 0.8. It is printed on FR4 substrate with a thickness of 0.5 mm. The ground plane size is 15 $\times$ 15 cm and the height h_m of the feed is 5 mm.

Fig. 11 shows the input return loss of the dual shorting pin antenna in comparison to the vertical and planar type shorted Parany antenna described in the previous sections. It can be seen that the first and second bands are merged together (see marker A of Fig. 11), which produce significant impedance bandwidth improvement. Using S_{11} at -6 dB reference point, the antenna is matched from about 1.52 GHz to 2.85 GHz, giving about 30% bandwidth. By varying the spacing between the frame and the edge of the Parany antenna, the two current paths can be tuned to provide this broadband effect. Comparing the S_{11} performance with other antennas result shown in Fig. 11, the second band of all antennas (see marker B) remained similar at about 2.6 GHz, indicating that it is independent of the additional shorting pin. The measured radiation pattern of the first (1.736 GHz) and second resonance (2.684 GHz) are shown in Fig. 12. The next band of interest at 5.3 GHz was also measured. Comparing these results with those obtained in Fig. 5 for the antenna shown in Fig. 2, a good degree of consistency can be concluded for these antennas operating with the shorted vertical configuration.

V. Conclusion

In this paper, we have described the design of a novel multiband antenna using a halved fractal Sierpinski gasket geometry and a shorting pin. As with the unperturbed Sierpinski gasket, the halved structure is also sensitive to scaling ratio, which enables frequency allocation and tuning. This has been successfully implemented on a halved size Parany antenna with a scale factor ratio of 0.7. The design can also be realized with a planar configuration with good matching, provided that the antenna is sufficiently far from the ground plane. The addition of a shorting pin with a frame has also been described which gives improved bandwidth at the lower band, and covers the DCS, PHS, PCS, DECT, UMTS, Bluetooth, 802.11b, and 802.11a bands.

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REFERENCES

[1] D. H. Werner and R. Mittra, *Frontiers in Electromagnetics*. Piscataway, NJ: IEEE Press, 2000.

[2] J. P. Gianvittorio and Y. Rahmat-Samii, "Fractal antennas: a novel antenna miniaturization technique, and applications," *IEEE Antennas Propagat. Mag.*, vol. 44, pp. 20–36, Feb. 2002.

[3] D. H. Werner and S. Ganguly, "An overview of fractal antenna engineering research," *IEEE Antennas Propagat. Mag.*, vol. 45, pp. 38–57, Feb. 2003.

[4] C. Puente, J. Romeu, R. Pous, X. Garcia, and F. Benítez, "Fractal multiband antenna based on the Sierpinski gasket," *IEE Electron. Lett.*, vol. 32, no. 1, pp. 1–2, Jan. 1996.

[5] C. Puente, "Fractal Antennas," Ph.D. dissertation, Dept. of Signal Theory and Communications, Universitat Politècnica de Catalunya, June 1997.

[6] N. Cohen, "Fractal antenna applications in wireless telecommunications," in *Proc. Professional Program Electronics Industry Forum*, 1997, pp. 43–49.

[7] C. Puente, C. Romeu, R. Pous, and A. Cardama, "On the behavior of the Sierpinski multiband fractal antenna," *IEEE Trans. Antennas Propagat.*, vol. 46, pp. 517–524, Apr. 1998.

[8] C. Puente, J. Romeu, R. Pous, J. Ramis, and A. Hijazo, "Small but long Koch fractal monopole," *Electron. Lett.*, vol. 34, pp. 0009–0010, 1998.

[9] C. Puente, J. Romeu, R. Bartolome, and R. Pous, "Perturbation of the Sierpinski antenna to allocate operating bands," *Electron. Lett.*, vol. 32, pp. 2186–2188, 1996.

[10] C. Puente, M. Navarro, J. Romeu, and R. Pous, "Variation on the fractal Sierpinski antenna flare angle," in *Proc. IEEE Int. Symp. Ant. and Propag.*, Atlanta, GA, June 1998, pp. 2340–2343.

[11] J. Soler, J. Romeu, and C. Puente, "Mod-P Sieripinski fractal multiband antenna," in *Proc. AP2000*, Davos, Apr. 2000.

[12] J. Soler and J. Romeu, "Dual band Sierpinski fractal monopole antenna," in *Proc. IEEE Int. Symp. APS 2000*, Salt Lake City, UT, pp. 1712–1715.

[13] C. T. P. Song, P. S. Hall, H. Ghafouri-Shiraz, and I. Henning, "Fractal antenna research at University of Birmingham," in *Proc. 11th IEE ICAP*, Manchester, U.K., 2001, pp. 724–727.

[14] C. T. P. Song and P. S. Hall, "Advances in discrete self-similar fractal multiband antennas," presented at the Proc. 24th ESTEC Antenna Workshop on Innovative Periodic Antennas: Photonic Bandgap, Fractal and Frequency Selective Structures, 30 May–1 June 2001, pp. 35–40.

[15] C. Borja and J. Romeu, "Multiband Sierpinksi fractal patch antenna," in *Proc. IEEE-APS Int. Symp. 2000*, Salt Lake City, UT, pp. 1708–1711.

[16] K. Fujimoto, A. Henderson, K. Hirasawa, and J. R. James, *Small Antennas*. New York: Research Studies Press, Wiley, 1993.

[17] K. Hirasawa and M. Haneishi, *Analysis, Design and Measurement of Small and Low-Profile Antennas*. Norwood, MA: Artech House, 1992.

[18] C. T. P. Song, P. S. Hall, and P. S. Ghafouri-Shiraz, "Shorted Sierpinski gasket monopole antenna," *IEE Electron. Lett.*, vol. 37, no. 16, pp. 1000–1001, 2001.

[19] C. T. P. Song, P. S. Hall, H. Ghafouri-Shiraz, and I. Henning, "Shorted Sierpinski gasket monopole antenna," in *Proc. IEEE AP-S Int. Symp.*, vol. 3, Boston, MA, 2001, pp. 138–141.

[20] E. Lee, P. S. Hall, and P. Gardner, "Dual band folded monopole/loop antenna for terrestrial communication systems," *IEE Electron. Lett.*, vol. 36, no. 24, pp. 1990–1991, Nov. 2000.

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