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A SWITCHED-BEAM ANTENNA USING CIRCUMFERENTIAL-SLOTS ON A CONCENTRIC SECTORAL CYLINDRICAL CAVITY EXCITED BY COUPLING SLOTS

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Abstract—This paper presents a switched-beam antenna using circumferential-slot on a concentric sectoral cylindrical cavity excited by coupling slots to operate at 5.8 GHz. The advantages of this antenna are conformal structure, high directivity and capable of switched-beam pattern in six directions. The antenna design starts from a single sector which is capable of switching between radiating and non-radiating modes. The L-shaped coupling slots are proposed to accommodate the switching circuit. Each RF switch is made of two PIN diodes connected in a reverse series connection and placed across the slot at the appropriate location. Subsequently, the exciting probe is designed for matching TM_{01} mode of the circular waveguide. The measured results of the proposed antenna give a gain of 7 dBi and $|S_{11}|$ less than -20 dB at 5.8 GHz. This antenna is suitable for base station applications that require the switched-beam pattern in the azimuthal plane.

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1. INTRODUCTION

In modern wireless communications, the performance of the systems can be seriously degraded by multipath fading and co-channel interference. The multipath fading is caused by the several different path lengths with different arrival angles. The use of switched-beam antennas is one of the effective ways for reducing the multipath interference, which leads to higher data transmission rate [1–5]. Many researches on switched-beam antennas can be found in literatures [6–19]. A flat four-beam array antenna was proposed in [6, 7]. The antennas are suitable for wireless communications system but provide a gain of less than 5 dBi. In [8], a sectored phased array was introduced. This antenna is a four-element dipole array, with two active and two parasitic elements. A switched-beam and fully adaptive antenna array was designed in [9]. The array is uniform circular and consists of four-element dipole. Some switched-beam antennas using switched parasitic array antenna have been studied extensively recently [10–15]. Such an electronically steerable passive array radiator (ESPAR) antenna was designed and developed [10, 11]. The antennas consist of one active and a number of passive radiators that are suitable for beam steering and null steering applications. A planar switched parasitic array antenna was proposed in [12], where the antenna was integrated with the seven hexagonal central grounded patch elements and the control system. A disk-load monopole array antenna was proposed in [13, 14]. A SPA-PIFA array was proposed in [15]. This antenna offers four switching and symmetrical radiation patterns, with one active and three parasitic elements, covering the horizontal plane with directivity of 3.6 dBi. A compact six-sector antenna, based on microstrip Yagi-Uda array antennas, was introduced by [16]. A compact switched-beam antenna employing a four-element slot antenna array was proposed in [17]. This antenna is composed of a four-element antenna array based on L-shaped quarter-wavelength slot antenna elements. A switched angular diversity BSSA array antenna was presented [18]. However, the elevation pattern of the antennas in [12–18] is tilted. A switched-beam disc antenna was proposed in [19]. It offers beam steering over 360 degrees in the azimuthal plane with a complex beam steering mechanism. The radiation pattern reconfigurable square spiral microstrip antennas were proposed in [20], where RF MEMS switches were applied to reconfigure the square spiral but the radiation patterns were only reconfigured between endfire and broadside. A beam steering radial line slot array (RLSA) antenna with reconfigurable operating frequency was proposed in [21]. This antenna design is capable of steering its radiated beam to four different angles but the patterns have different beamwidths and gains. In [22], a novel beam switching antenna design was proposed. This antenna uses a dipole as the fed and a cylindrical metal enclosure with a stack of circular slits put around dipole. The antenna beam can be adjusted to the desired direction by changing on-off state of RF switches, where the beam moves about 30 degrees on the azimuthal plane for each switch set-up. However, this antenna has given a low gain.

In [23], we proposed a two-slot array on a concentric sectoral cylinder. This antenna consists of a single coupling slot and two circumferential-slot elements in vertical array for radiators. Hence, this antenna provides a narrow beam in elevation pattern. In this paper, a switched-beam antenna using circumferential-slot on a concentric sectoral cylindrical cavity excited by coupling slots is proposed using six sectoral antennas in [23] to obtain switched-beam pattern in six directions covering 360 degrees in the azimuthal plane. The L-shaped coupling slots are proposed for switching circuit connections. The switching mechanism of each sector is made of two PIN diodes connected in a reverse series connection. The antenna is intended for using in a wireless sensor network. A switched-beam antenna, compositing of several antennas covering different sensing areas, is desirable for a master node. The operating frequency of 5.8 GHz ISM band is used for the sensor-size minimization. The single sector antenna is shown in Section 2. The switching circuit, coupling slot, and feeding probe are shown in Section 3. The simulated and measured results are shown in Section 4. The conclusion is provided in Section 5.

2. A SINGLE SECTOR ANTENNA

In this paper, the initial parameters are taken from [23]. The antenna structure shown in Figure 1 consists of two parts, the concentric sectoral cylindrical cavity and the circular waveguide shorted at the top end. It is assumed that the TM_{01} dominant mode propagates in the circular waveguide with the inner radius of r_c. The inner and outer radii of the cavity are r_a and r_b, respectively. The coupling slot S_c is on the circular waveguide and centered at $(r = r_a,\ \phi = 0,\ z = l_{sc})$. The radiating slots, S_1 and S_2 are centered at $(r = r_b,\ \phi = 0,\ z = l_2)$ and $(r = r_b,\ \phi = 0,\ z = l_3)$, respectively. All slots are circumferentially oriented. The cavity is enclosed by conducting surfaces at the angles of $\phi = -\phi_1$ and $\phi = \phi_1$ where ϕ_1 is 30 degrees. The variables l_1 and l_3 are the distance from the top of the cavity to the center of the slot S_1 and the distance from the bottom of the cavity to the center of the slot S_2, respectively. These distances are 0.75λ where λ refers to the wavelength in freespace. The spacing between the radiating slots

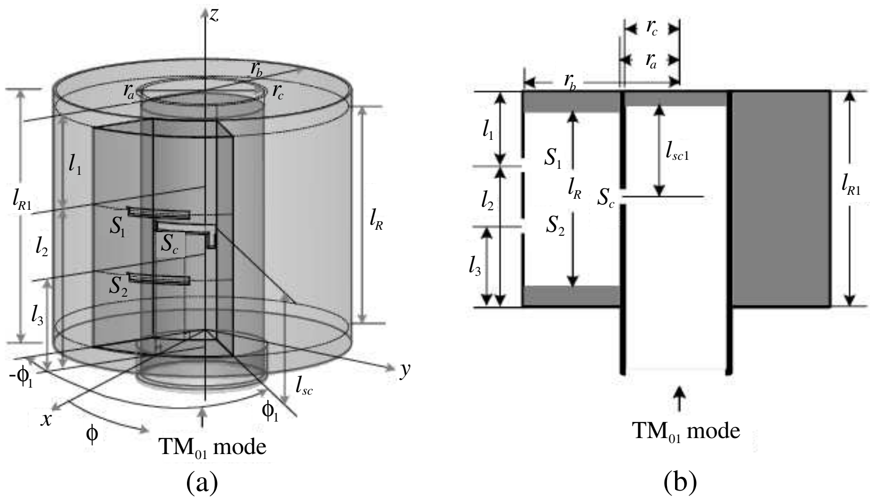

Figure 1. Geometry of a single sector antenna. (a) 3-D view. (b) 2-D view.

is fixed at 0.5λ, for the maximum. The variable l_{sc1}, which is the distance from the shorted end of the circular waveguide to the center of the coupling slot, is $0.5\lambda_g$, where λ_g refers to the guided wavelength of the TM_{01} mode of the circular waveguide. The internal length of the cavity is l_R. The metal wall thickness is 2 mm. The other parameters are also listed in Table 1. The coupling slot S_c is modified as L-shaped slot to accommodate the switching circuit. The dimensions of S_c are given in Section 3.2.

3. PROPOSED DESIGNS: SWITCHING CIRCUIT, COUPLING SLOT, AND FEEDING PROBE

3.1. Switching Circuit

The structure of the proposed switching circuit is depicted in Figure 2. Each RF switch is made of two PIN diodes HMPP-3895-TR1 connected in a reverse series connection and placed across the slot at the appropriate location. HMPP-3895-TR1 has low impedance of 4 ohms at low forward current of 1 mA [24]. The inductor of 5.1 nH is an RF choke and the capacitor of 1 pF is used as a decoupling capacitor. The circuit is fabricated on an FR4 substrate with thickness 0.8 mm and placed on the coupling slot. The point 'a' and 'b' are electrically connected to the edges of the slot. The coupling slot is designed such that the slot works when the diodes are forward bias and connect points 'a' and 'b' with low impedance. If the diodes are reverse biased, the electromagnetic fields on the coupling slot will be disturbed and the slot will be disabled at the desired frequency. In other words, the antenna is switched off.

Table 1. Antenna parameters.

Antenna parameters	**Electrical Size** [λ]	**Physical size 5.8 GHz** [**mm**]
Inner radius of the cavity (r_a)	0.507	26.20
Outer radius of the cavity (r_b)	1.126	58.23
Inner radius of the circular waveguide (r_c)	0.469	24.20
Internal length of the cavity (l_R)	0.700	36.20
External length of the cavity (l_{R1})	2.000	103.44
Length of the radiating slots S_1 and S_2 (L_{S1} and L_{S2})	0.500	25.86
Width of the radiating slots S_1 and S_2 (W_{S1} and W_{S2})	0.058	3.00

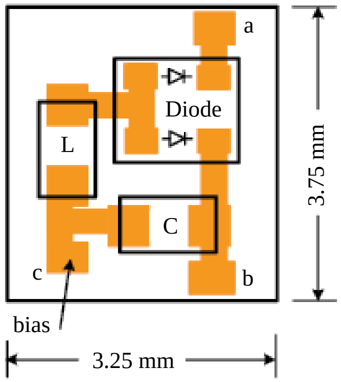

Figure 2. Structure of the proposed switching circuit.

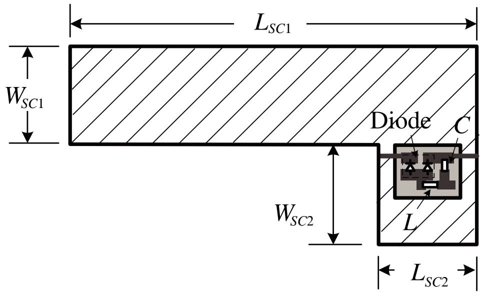

Figure 3. L-shaped coupling slot with switching circuit.

Table 2. L-shaped slot parameters.

L-shaped slot parameters	Length [mm]
L_{SC1}	24.83
L_{SC2}	4.00
W_{SC1}	4.00
W_{SC2}	8.00

Table 3. Parameters of disc-loaded probe.

Parameters of disc-loaded probe	Length [mm]
d_d (diameter of disc)	10.0
l_f (length of the probe)	19.5
l_d (distance from plate to disc)	8.0

3.2. Coupling Slot

The L-shaped slot is proposed for the coupling slot because the length of the coupling slot in [23] is fit to the available area. To disable the coupling slot, the length of the slot must be extended to disturb the electromagnetic fieldson the slot. The L-shaped slot extends the slot in vertical direction. The horizontal length of the slot can be kept as the original dimension in [23]. The L-shaped coupling slot with the switching circuit is shown in Figure 3. The dimensions of the slot are listed in Table 2.

3.3. Feeding Probe

To excite the antenna, a coaxial-to-waveguide transition is needed. In this work, the disc-loaded probe is used as a coaxial-to-waveguide transition [25, 26]. The structure in Figure 4 is used for CST simulation as a two-port device where port 1 is a TM_{01}-mode circular waveguide and port 2 is a coaxial cable. The dimensions of the probe are adjusted such that $|S_{11}|$ is below -30 dB at 5.8 GHz. The dimensions are listed

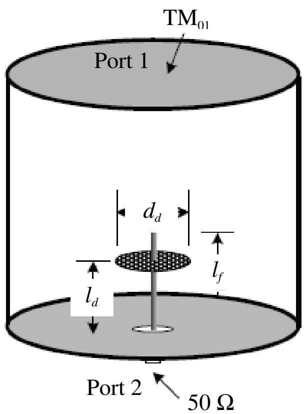

Figure 4. Disc-loaded probe.

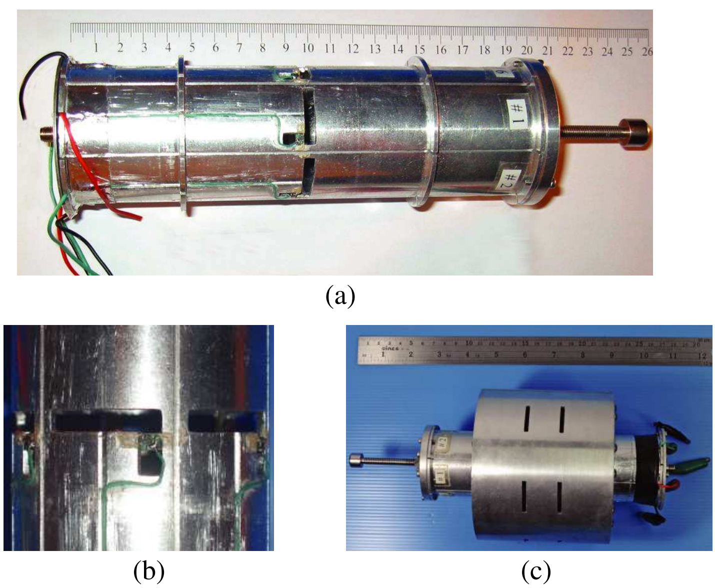

Figure 5. Fabricated antenna. (a) Circular waveguide. (b) Coupling slots. (c) Assembled antenna.

in Table 3. The diameter of the probe is 1 mm and the thickness of the disc is 0.5 mm.

4. SIMULATED AND MEASURED RESULTS

The proposed antenna was simulated using CST software and fabricated on aluminum as shown in Figure 5. The single sector antenna was simulated and measured. The reflection coefficients for an operating mode and a disabled mode are shown in Figures 6

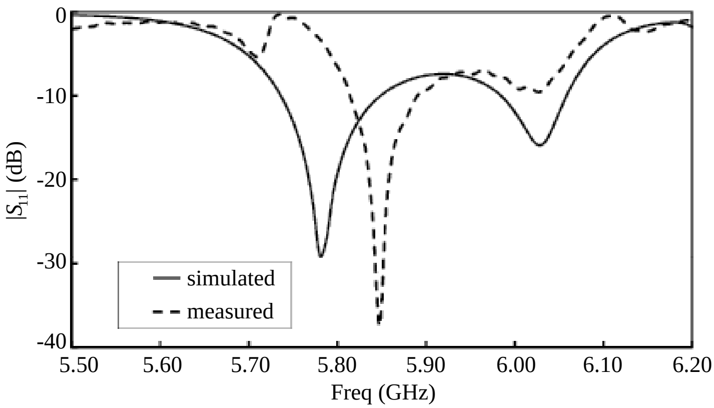

Figure 6. Reflection coefficient of single sector antenna for operating mode.

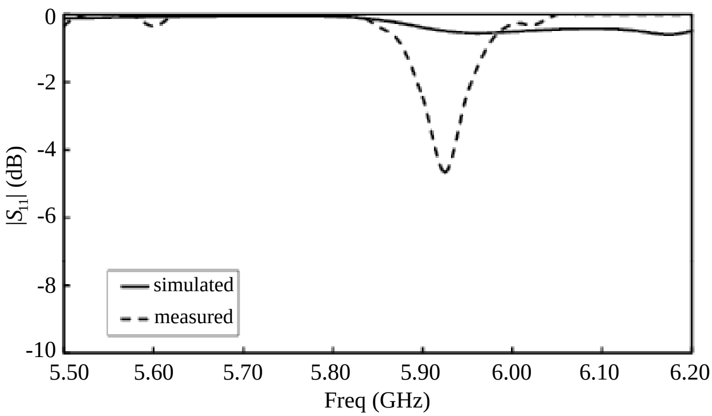

Figure 7. Reflection coefficient of single sector antenna for disabled mode.

and 7, respectively. Figure 6 shows that the simulated result has wider bandwidth than the measured one but they are in a similar pattern. Figure 7 shows the measured $|S_{11}|$ of -6 dB at about 5.9 GHz.

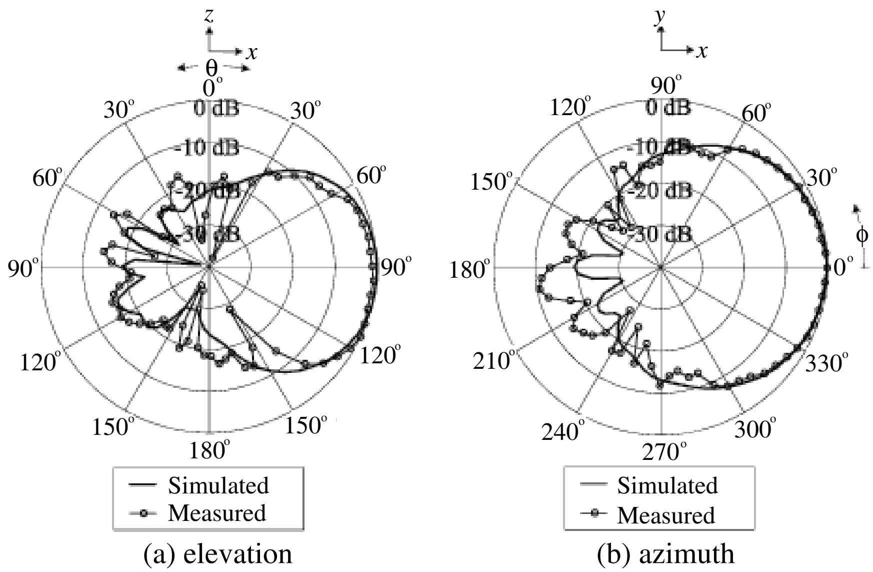

Figure 8. Radiation pattern of single sector antenna in operating mode.

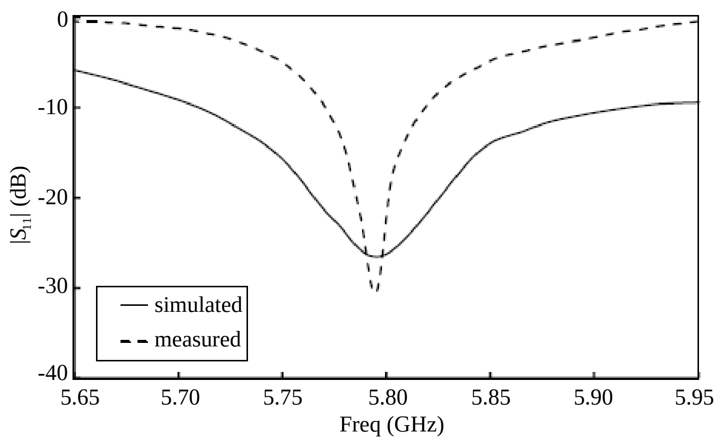

Figure 9. Reflection coefficient of six-sector antenna in operating mode.

This could be due to the bias wirings which are not included in the simulation. The results show that the antenna can be switched on and off. The measured bandwidth is about 75 MHz. Figure 8 shows the radiation patterns of the single sector antenna in the operating mode. It shows that the main beam in the elevation plane is symmetric. The measured half power beamwidth in the elevation and azimuthal planes are 68 degrees and 80 degrees, respectively. The measured gain of the antenna is 7.2 dBi which is similar to the simulated gain of 8.2 dBi.

The six-sector antenna was simulated and measured when one of the coupling slots was forward biased and others were reverse biased. The reflection coefficient is shown in Figure 9. The results show that the simulated result has wider bandwidth than the measured one. This could be due to the large mesh used in the simulation to minimize the memory usage. The measured bandwidth is about 34 MHz. The radiation patterns of the six-sector antenna are shown in Figures 10 and 11. The measured half power beamwidth in the elevation and azimuthal planes are 59 degrees and 84 degrees, respectively. Figure 10 shows the radiation patterns when only the sector#1 is forward biased in both cut planes and compares the operating pattern with the pattern when all sectors are reverse biased. The results show that

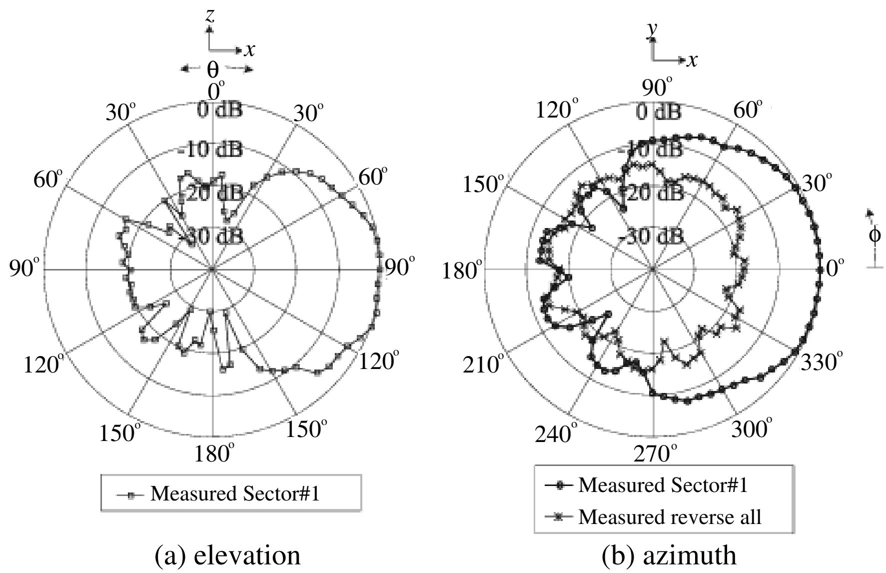

Figure 10. Comparison of radiation pattern of six-sector antenna when only sector#1 is forward biased and when all sectors are reverse biased.

the radiating power is more than 15 dB down in the desired direction when the antenna is switched off. Figure 11 shows the radiation patterns when each sector is forward biased. The results show that the radiation pattern can be switched in 6 different directions covering all 360 degrees. The radiation patterns of the antenna are similar in all directions. The measured gain is 7 dBi which is similar to the simulated gain of 8.3 dBi and the front-to-back ratio is higher than 10 dB.

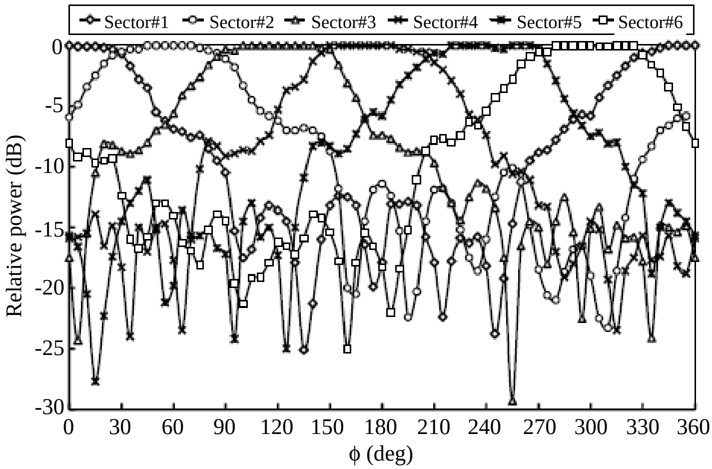

Figure 11. Radiation pattern of six-sector antenna in operating modes.

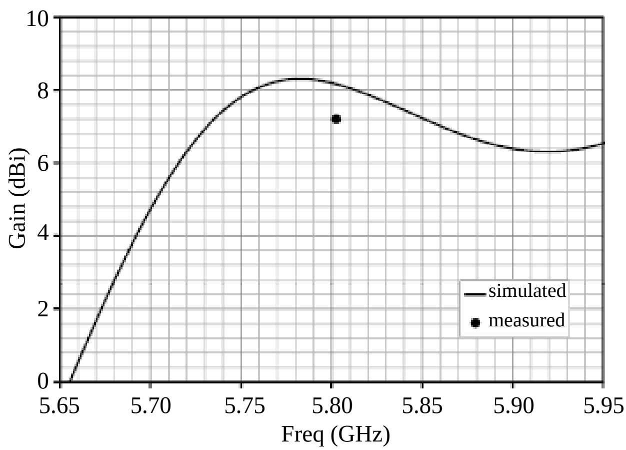

Figure 12. Gain of single sector antenna in operating mode.

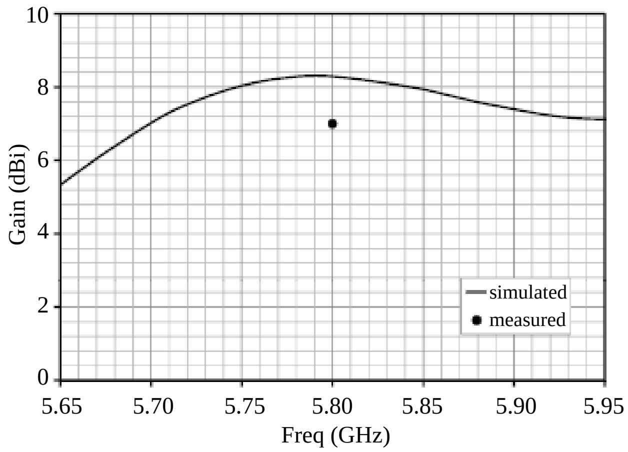

Figure 13. Gain of six-sector antenna in operating mode.

Figures 12 and 13 show the simulated gains in the frequency band for the single sector antenna and the six-sector antenna, respectively. It shows that the gain bandwidths for both antennas are more than 250 MHz or 4.3%. For the application of a wireless sensor network having a slow-bit-rate data, only narrow bandwidth is required. The measured gain is only performed at 5.8 GHz which is the desired operating frequency.

5. CONCLUSION

In this paper, a switched-beam antenna using circumferential-slots on a concentric sectoral cylindrical cavity excited by coupling slots is designed, fabricated, and measured. The L-shaped slot is proposed to reduce the required length of the slot in horizontal direction and is integrated with proposed switching circuit to enable the switched-beam pattern. The disc-loaded probe is designed for matching TM_{01} mode of the circular waveguide. The antenna shows a very good response. The measured results of the proposed antenna gives a gain of 7 dBi, $|S_{11}|$ less than -20 dB at 5.8 GHz and a radiation pattern switched in 6 different directions covering all 360 degrees.

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REFERENCES

1. Perini, P. L. and C. L. Holloway, "Angle and space diversity comparisons in different mobile radio environments," *IEEE Trans. Antennas Propagat.*, Vol. 46, No. 6, 764–775, Jun. 1998.
2. Varlamos, P. K. and C. N. Capsalis, "Electronic beam steering using switched parasitic smart antenna arrays," *Progress In Electromagnetics Research*, Vol. 36, 101–119, 2002.
3. Mitilineos, S. A., C. A. Papagianni, G. I. Verikaki, and C. N. Capsalis, "Design of switched beam planar arrays using the method of genetic algorithms," *Progress In Electromagnetics Research*, Vol. 46, 105–126, 2004.
4. Sotirio, A. I., P. K. Varlamos, P. T. Trakadas, and C. N. Capsalis, "Performance of a six-beam switched parasitic planar array under one path Rayleigh fading environment," *Progress In Electromagnetics Research*, Vol. 62, 89–106, 2006.
5. Ares-Pena, F. J., G. Franceschetti, and J. A. Rodriguez, "A simple alternative for beam reconfiguration of array antennas," *Progress In Electromagnetics Research*, Vol. 88, 227–240, 2008.
6. Kura, N. and H. Arai, "A flat four-beam switched array antenna," *IEEE Trans. Antennas Propagat.*, Vol. 44, No. 9, 1227–1230, Sep. 1996.
7. Krairiksh, M., P. Ngamjanyaporn, and C. Kessuwan, " A flat four-beam compact phased array antenna," *IEEE Microwave Wireless Comp. Lett.*, Vol. 12, No. 5, 184–186, May 2002.
8. Kalis, A. and M. J. Carras, "A sectored phased array for DBF applications," *IEEE Trans. Veh. Technol.*, Vol. 54, No. 6, 1932–1936, Nov. 2005.
9. Mitilineos, S. A. and N. Capsalis, "A new, low-cost, switched beam and fully adaptive antenna array for 2.4 GHz ISM applications," *IEEE Trans. Antennas Propagat.*, Vol. 55, No. 9, 2502–2508, Sep. 2007.
10. Gyoda, K. and T. Ohira, "Design of electronically steerable passive array radiator (ESPAR) antennas," *IEEE Antennas Propagat. Soc. Int. Symp. Dig.*, Vol. 2, 922–925, Jul. 2000.
11. 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.
12. Chen, W. H., J. W. Sun, X. Wang, Z. H. Feng, F. L. Chen, Y. Furura, and A. Kuramoto, "A novel planar switched parasitic array antenna with steered conical beam," *IEEE Trans. Antennas*

Propagat., Vol. 55, No. 6, 1883–1887, Jun. 2007.

13. Kamarudin, M. R., P. S. Hall, F. Colombel, and M. Himd, "CPW-FED switchable top disk-loaded monopole array antenna," *Journal of Electromagnetic Waves and Applications*, Vol. 23, Nos. 11–12, 1631–1638, 2009.
14. Kamarudin, M. R. B., P. S. Hall, F. Colombel, and M. Himdi, "Electronically switched beam disk-loaded monopole array antenna," *Progress In Electromagnetics Research*, Vol. 101, 339–347, 2010.
15. Dimousios, T. D., C. D. Nikolopoulos, S. A. Mitilineos, and C. N. Capsalis, "A new low-profile and cost SPA-PIFA for mobile 2.4 GHz ISM applications," *Journal of Electromagnetic Waves and Applications*, Vol. 24, No. 7, 881–891, 2010.
16. Honma, N., T. Seki, K. Nishikawa, K. Tsunekawa, and K. Sawaya, "Compact six-sector antenna employing three intersecting dual-beam microstrip Yagi-Uda arrays with common director," *IEEE Trans. Antennas Propagat.*, Vol. 54, No. 11, 3055–3062, Nov. 2006.
17. Lai, M. I., T. Y. Wu, J. C. Hsieh, C. H. Wang, and S. K. Jeng, "Compact switched-beam antenna employing a four-element slot antenna array for digital home applications," *IEEE Trans. Antennas Propagat.*, Vol. 56, No. 9, 2929–2936, Sep. 2008.
18. Fasseeta, S. and A. Sibille, "Switched angular diversity BSSA array antenna for WLAN," *Electron. Lett.*, Vol. 36, No. 8, 702–703, Apr. 2000.
19. Cerri, G., R. D. Leo, V. M. Primiani, C. Monteverde, and P. Russo, "Design and prototyping of a switching beam disc antenna for wideband communications," *IEEE Trans. Antennas Propagat.*, Vol. 54, No. 12, 3721–3726, Dec. 2006.
20. Huff, G. H. and J. T. Bernhard, "Integration of packaged RF MEMS switches with radiation pattern reconfigurable square spiral microstrip antennas," *IEEE Trans. Antennas Propagat.*, Vol. 54, No. 2, 464–469, Feb. 2006.
21. Jamlos, M. F., O. A. Aziz, T. A. Rahman, M. R. Kamarudin, P. Saad, M. T. Ali, and M. N. Md Tan, "A beam steering radial line slot array (RLSA) antenna with reconfigurable operating frequency," *Journal of Electromagnetic Waves and Applications*, Vol. 24, Nos. 8–9, 1079–1088, 2010.
22. Liao, W. J., H. T. Chou, and W. L. Hu, "A novel beam switching antenna using RF switches," *IEEE Antennas Propagat. Soc. Int. Symp. Dig.*, 5865–5868, 2007.

23. Wounchoum, P., D. Worasawate, C. Phongcharoenpanich, and M. Krairiksh, "A two-slot array antenna on a concentric sectoral cylindrical cavity excited by a coupling slot," *Progress In Electromagnetics Research*, Vol. 86, 135–154, 2008.
24. HPMM-389x Series, [Online]. Available: http://www.avagotech.-com/docs/AV02-0653EN.
25. Sumathy, M., S. K. Chhotray, and L. Kumer, "Analysis and simulation of a TM_{01}-mode launcher for an overmoded waveguide," *Vacuum Electronics Conference, IVELEC 2006*, 499–500, 2006.
26. Macphie, R. H., M. Opie, and C. R. Ries, "Input impedance of a coaxial line probe feeding a circular waveguide in the TM_{10} mode," *IEEE Trans. Microwave Theory Tech.*, Vol. 38, No. 3, 334–337, Mar. 1990.