Study of Conformal Switchable Antenna System on Cylindrical Surface for Isotropic Coverage

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***Abstract*—A conformal switchable antenna system mounted on a cylindrical surface is proposed, simulated, prototyped and measured. The antenna system is composed of several tri-polarization antennas operating at 2.4 GHz band. It is shown that this antenna system realizes a quasi-isotropic pattern without any nulls over a complete spherical surface. Specifically, it is shown that by using three tri-polarization antennas and switching among them, a complete spherical coverage could be achieved without any nulls and with a power gain larger than 2.5 dBi over more than 90 percent of a spherical surface surrounding the antenna system. Furthermore, it is shown that the performance of the antenna system does not deteriorate with the increase in the diameter of the mounting cylinder, thus facilitating the implementation of the proposed design in many applications including telemetry, satellites, and aircraft. Both simulation and experimental results of the radiation patterns are presented in this paper.**

***Index Terms*—Cylinder surface, isotropic coverage, radiation pattern, tri-polarization antenna.**

I. Introduction

THE research on antennas mounted on conducting cylindrical surface is significant to aerospace applications such as telemetry, telecommand of satellite, radio guidance and control of airborne craft. In most of these applications, a radiation pattern without a null covering an entire spherical surface around the antenna is desired. However, due to the blockage effect of mounting structures which are often made of metal, e.g., spacecraft, it seems extremely difficult to achieve that goal with simple antenna system structures. One common approach to obtain omnidirectional patterns is to use a number of discrete antennas arrayed along the circumference of the cylinder. A conformal cylindrical microstrip array was proposed in [1] for producing such a pattern. Patch antenna arrays mounted on cylindrical surface in both axial and circumferential modes were analyzed. An array of 4 to 16 printed dipoles mounted on a cylindrical surface was studied for obtaining an omnidirectional pattern [2]. A study of different kinds of cylindrical conformal antennas employed on cylindrical bodies with different diameters was also reported in [3]. Several studies of circularly polarized antenna elements on cylindrical structures are discussed in [4]–[6]. In most of these studies, however, the isotropic radiation property is considered only for one plane or several planes, but not for the complete spherical space around the antenna system.

Many other investigations were carried out focusing on the realization of quasi-isotropic radiation patterns. This includes the use of a combined dipole and two element slot antenna array in [7], the use of a large spherical slot antenna [8] and the use of a miniature antenna for circularly polarized quasi-isotropic coverage in [9]. As mentioned earlier, such full spherical coverage radiation pattern is important in many applications in order to maintain a communication link at all times. In these applications, therefore, it is important that the antenna system mounted on a conducting cylinder does not have any radiation nulls over a complete spherical surface surrounding it. In this paper, we describe an alternative approach for achieving a quasi-isotropic radiation pattern using the recently designed low-profile tri-polarization antenna described in [10].

Although several studies on isotropic antenna designs have been reported in literature, data on antenna systems on conducting cylinders with full isotropic spherical coverage is rather sparse. There are some reported isotropic radiators [7]–[9], but only a few of those reported provide full coverage when antennas are mounted on conducting cylinders [1]–[6]. Even in these cases, the reported designs do not achieve full omnidirectional coverage over a spherical surface; instead, omnidirectional radiation patterns in a plane perpendicular to the axis of the cylinder were reported.

In this paper, a conformal version of the low-profile tri-polarization antenna proposed in [10] is used as a basic element and building block to achieve full coverage over a complete spherical surface surrounding the conducting cylinder. It is shown that by using three tri-polarization antennas and switching among them, 100 percent coverage (0 dBi gain) can be obtained over a complete spherical surface. Furthermore, higher gains, 2.5 dBi, could be achieved with no null over more than 90 percent of the spherical surface. The proposed design compares favorably with earlier ones [1], [2] where 6 to 8 microstrip antennas were used to obtain omni-directional radiation patterns in a plane perpendicular to the axis of the cylinder.

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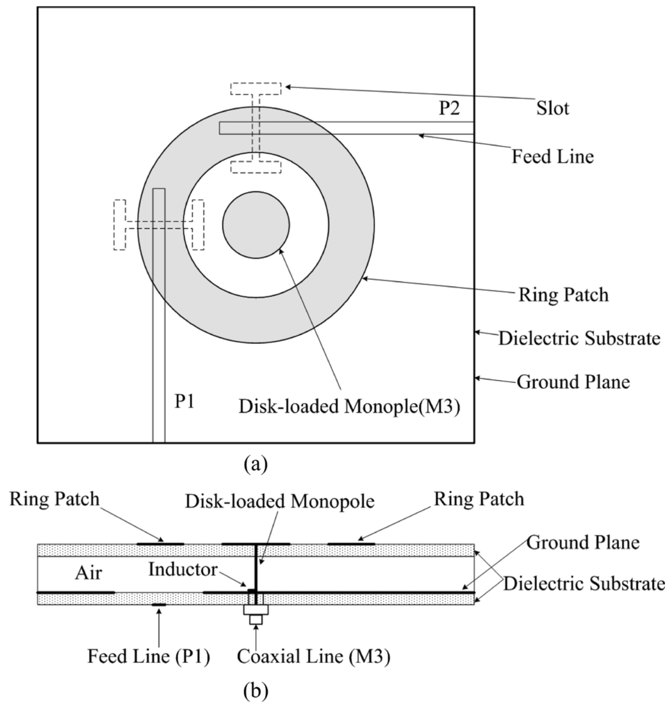

Fig. 1. Geometry of the tri-polarization antenna: (a) Top view; (b) side view.

Simulation results and experimental verification of the proposed conformal switchable tri-polarization antenna system on a cylinder surface are described in the following sections. Specifically, the tri-polarization antenna is briefly introduced in Section II, while simulation results are presented and discussed in the Section III and IV. Measurement procedure and obtained experimental results are shown in Section V.

II. Antenna System Design

The conformal and low profile tri-polarization antenna as proposed in [10] is a fundamental building block in the paper and is briefly introduced here. The configuration of the tri-polarization antenna is shown in Fig. 1, depicting two ring patch antennas and a disk-loaded monopole which compose the tri-polarization antenna. With the three ports of this antenna working independently, its far-field has three orthogonal linear polarizations. Specifically, the E-field radiated by the ring patch is parallel to the ground plane and can provide two orthogonal polarizations excited through P1 and P2, while the monopole provides the vertical polarization component and has an isotropic radiation in the azimuth plane.

The operating frequency of the tri-polarization antenna was chosen to be 2.4 GHz, and its total height is 5.8 mm. The volume of the tri-polarization is $94*94*5.8\ \mathrm{mm}^3$. Although here a planar structure was used for the convenience of fabrication, it is easy to design and make similar antennas which are totally conformal to cylindrical bodies.

Fig. 2 shows the simulated 3D radiation pattern of the tri-polarization antenna. It further shows that the radiation pattern of the monopole mode (port M3) and patterns of the patch mode (port P1 and port P2) have complementary properties.

The low profile advantage and the ease of its conformal integration on a cylindrical surface make the tri-polarization antenna an ideal choice of antenna systems for cylindrical structures. The ground plane of the tri-polarization antenna makes it particularly suitable for use on cylindrical metal structures. Besides, due to the fact that the three ports of this antenna radiate three polarized fields that are orthogonal to one another, this antenna can receive electromagnetic waves with any kind of polarization, thus avoiding instances of polarization mismatch.

Even more important than the above-mentioned advantages of the tri-polarization antenna is the fact that the patch antenna mode and the monopole antenna mode of the tri-polarization have complementing radiation properties. By switching among the three ports of the tri-polarization antenna, it is easy to obtain the full radiation coverage for a hemisphere. Therefore, for the antenna system mounted on cylinder body, just two tri-polarization antennas are required to realize the full coverage over the whole sphere.

To investigate the performance of the proposed switchable antenna system, different numbers of antenna elements were adopted to build switchable antenna systems. As shown in Fig. 3, two to four tri-polarization antennas were equally spaced along the circumference of cylinder body. Another situation described in this paper is the mounting of a switchable antenna on a cylinder surface with different diameters. The simulation tool IE3D was employed in calculating radiation patterns of each element and a program written in Matlab was used to synthesize the final radiation pattern of the complete antenna system.

III. Antenna System With Different Numbers of Elements

The proposed antenna system mounted on the surface of a conducting cylinder with a diameter of 0.5 m and a height of 1 m was studied. The reason of choosing 1 m, which is 8 wavelengths at 2.4 GHz, is that this length is sufficient when considering the influence of a cylindrical body on the performance of tri-polarization antennas. Even if tri-polarization antennas were mounted on a longer cylindrical structure, the resulting difference would be rather negligible. Simulation results demonstrate this finding. A comparison between gain patterns of 3-element antenna systems mounted on a cylinder with a height of 1 m and that on another cylinder with a height of 0.5 m was realized in a computer simulation. This result shows that gain patterns of these two situations are very similar in both shape and value. The antenna systems with two, three and four elements were analyzed and compared, respectively. As each tri-polarization antenna element has three ports, there are six, nine and twelve ports in antenna systems with two, three and four elements respectively. Since the main concern of this design is full radiation coverage of a complete spherical surface, the method of selecting maximum values among all ports was used to evaluate the performance of the antenna system, which means to firstly calculate the radiation patterns of each port and then select the maximum gain among patterns of all ports at each solid angle

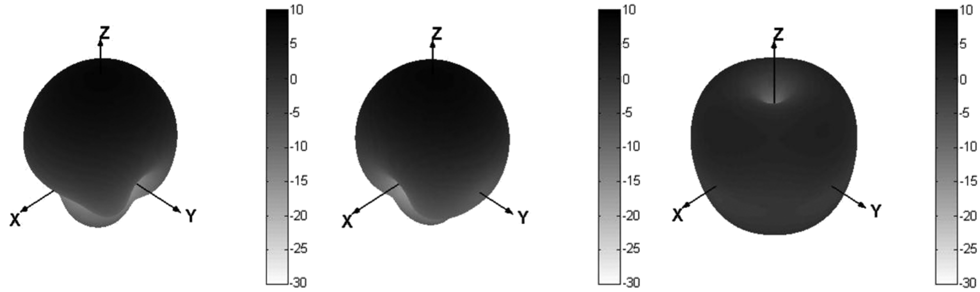

Fig. 2. 3D gain patterns of tri-polarization antenna. (a) Gain total—Port P1; (b) Gain total—Port P2; (c) Gain total—Port M3.

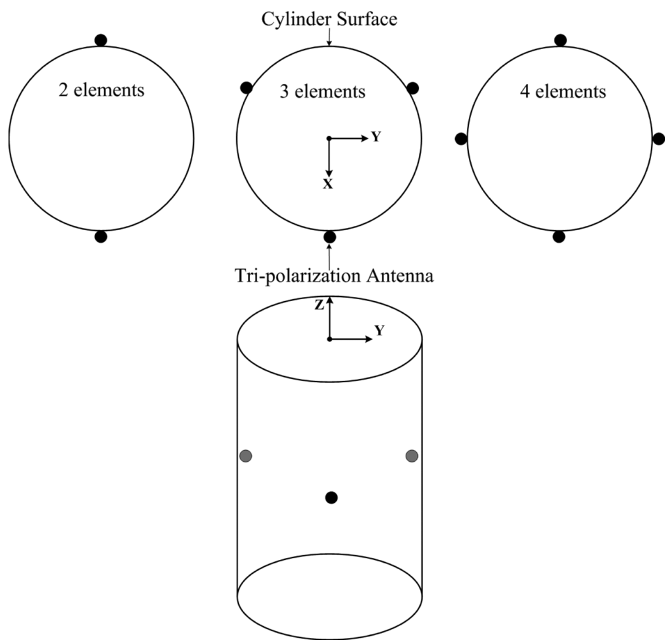

Fig. 3. Antenna arrangement around a cylindrical surface.

as the system gain. This radiation pattern could then be conveniently realized by switching among all ports to obtain the maximum received power value in real application. Thus, the gain of the antenna system can be expressed as

$$G_{system}(\theta,\phi) = \underset{i=1}{\overset{3N}{Max}} \left[G_{port(i)}(\theta,\phi)\right]. \tag{1}$$

Here, N is the number of tri-polarization antennas in a given antenna system, and $G_{port(i)}$ is the gain obtained by only exciting port i.

The simulated 3D gain patterns of antenna systems with 2 to 4 elements are shown in Fig. 4. The gain pattern of an antenna system with 2 elements shows that there are no nulls and that gain values are mostly above 0 dBi. Thus, even with just two tri-polarization antenna elements a quasi-isotropic radiation pattern could be obtained. It is also clearly shown in Fig. 4 that the performance of the antenna system continued to improve with the increase in the number of elements, as the radiation pattern continued to closely resemble those of an isotropic source. Here, axis z follows the axis of the cylinder. The main polarizations of the M3 and P2 ports of the tri-polarization antenna are both E phi in the X-Y plane, while the main polarization of the P1 port is E theta in the X-Y plane. Therefore, in the horizontal plane, the radiation patterns of E phi are averagely better than those of E theta. To better illustrate the gain pattern of antenna system over a complete spherical surface, the contour lines pattern of gain total of 3-element antenna system is also shown in Fig. 5.

There are usually several ways to evaluate the isotropic performance of an antenna system. First, the radiation pattern of an isotropic antenna should not have nulls over a complete spherical surface. Another method used with considerable success in evaluating the quality of an antenna system's isotropic coverage is to calculate the coverage factor [8]. The coverage factor is the ratio of the surface by which the gain exceeds a given threshold value over total antenna radiation field surface. The coverage factor (CF) is defined as

$$CF(G_{threshold}) = \frac{100}{4\pi} \iint_{\Omega:G(\theta,\phi)>G_{threshold}} \sin\theta d\theta d\phi \quad (\%). \tag{2}$$

The surface of integration Ω is determined by a given threshold value.

$$\Omega : G(\theta,\phi) > G_{threshold}.$$

Here, $G(\theta,\phi)$ is the gain function (i.e., relative to isotropic source) and $G_{threshold}$ is the given threshold value. In this paper, the coverage factor method is used to evaluate the performance of radiation coverage of the proposed antenna system.

The calculated coverage curve of the gain of E-total, E-theta and E-phi are shown in Fig. 6, Fig. 7 and Fig. 8, respectively. The coverage curves are plotted with the coverage factor defined by (2) as y-axis, and with given thresholds as x-axis. As shown in Fig. 6, for the threshold of E total larger than 0 dBi, the antenna system with 2 elements can obtain nearly full coverage (98%) over the whole sphere, and 100 percent coverage is achieved for the antenna system employing 3 or 4 elements. Furthermore, not only full coverage of the whole sphere is achieved, but also gains larger than 2.5 dBi were obtained for more than 90 percent of the sphere when the antenna system employed 3 or 4 elements. For the gains of E-theta and E-phi patterns shown in Fig. 7 and Fig. 8, it may be noted that using 3 elements compares very favorably to an antenna system with only 2 elements. For the criteria of 0 dBi, the coverage values of E-theta are 61%,

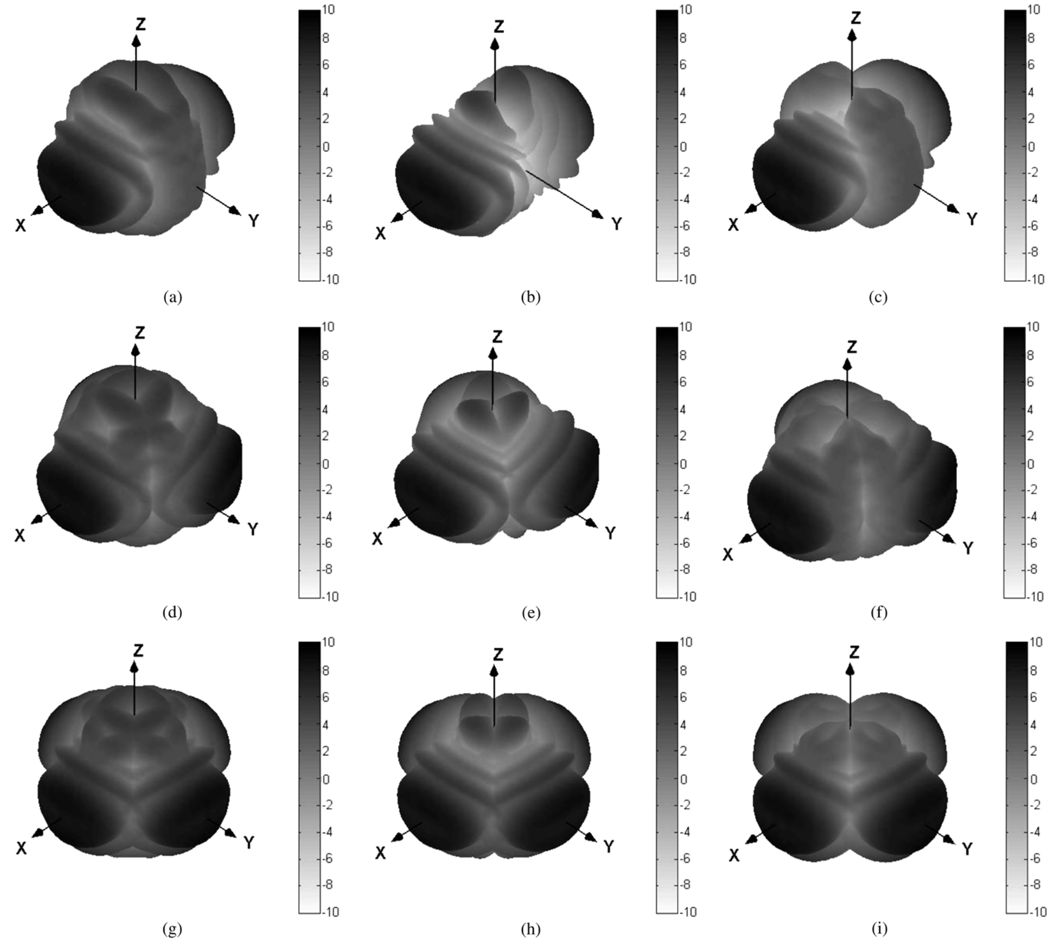

Fig. 4. 3D gain patterns of antenna system with different numbers of elements. (a) Gain total—2 elements; (b) Gain theta—2 elements; (c) Gain phi—2 elements; (d) Gain total—3 elements; (e) Gain theta—3 elements; (f) Gain phi—3 elements; (g) Gain total—4 elements; (h) Gain theta—4 elements; (i) Gain phi—4 elements.

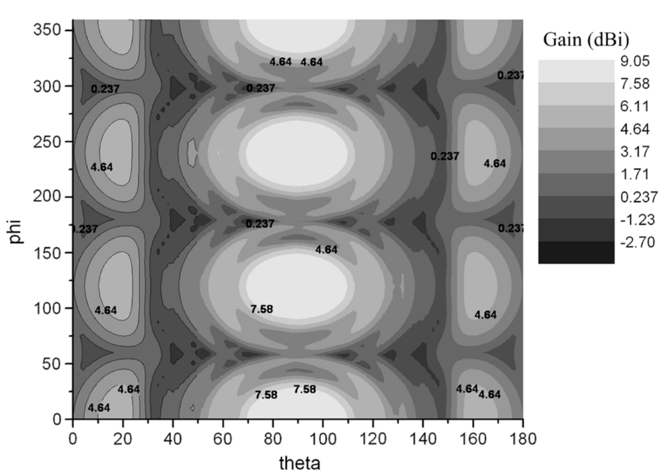

Fig. 5. Gain total contour lines—3 elements.

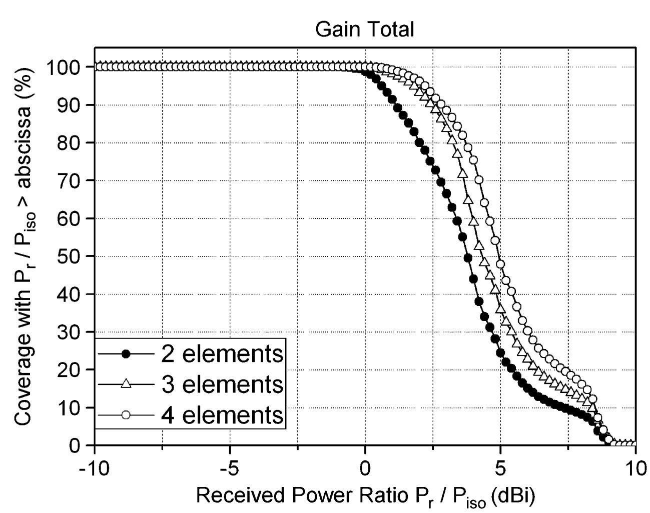

Fig. 6. Coverage curves of gain total for the proposed switchable antenna systems with different numbers of elements.

88% and 96% for antenna system with 2, 3 and 4 elements, respectively. For E-phi, they are 83%, 97% and 97%, respectively. Therefore, antenna systems with more than 3 elements can achieve nearly full coverage over the whole sphere for both polarizations.

From the results of the coverage curves, it is clear that better performance of the antenna system can be obtained by increasing the number of elements used. However, antenna systems with more elements require more complex switching systems and higher switching speeds. It is this tradeoff between performance and complexity of the switching structure that will ultimately determine the final design of the antenna system.

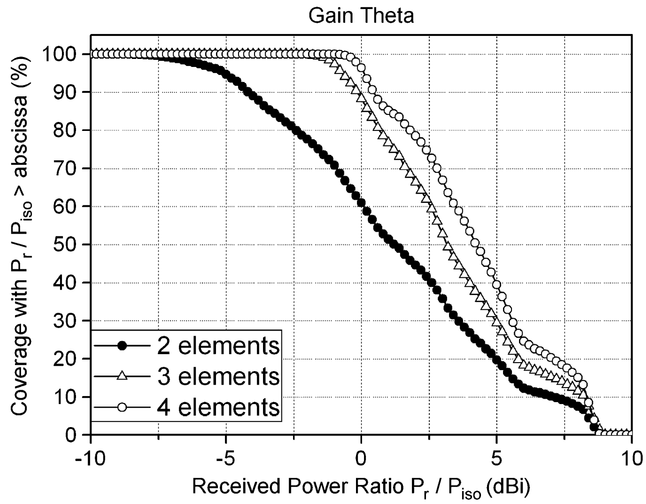

Fig. 7. Coverage curves of gain theta for the proposed switchable antenna systems with different numbers of elements.

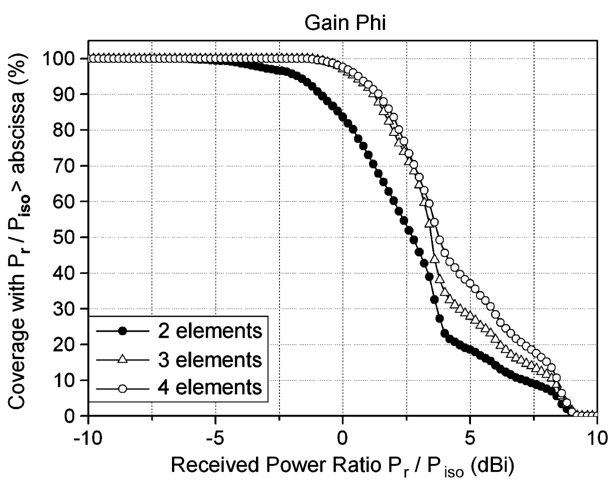

Fig. 8. Coverage curves of gain phi for the proposed switchable antenna systems with different numbers of elements.

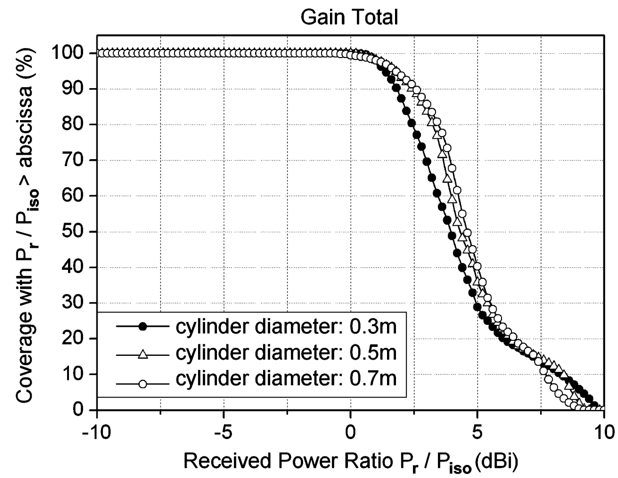

Fig. 9. Coverage curves of gain total for the proposed switchable antenna systems for cylinder with different diameters.

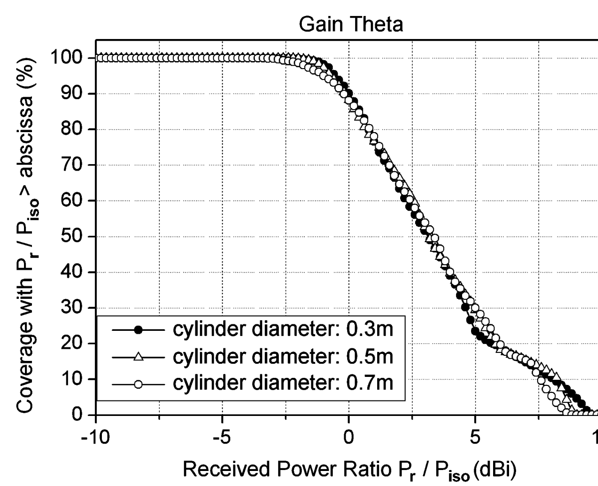

Fig. 10. Coverage curves of gain theta for the proposed switchable antenna system for cylinders with different diameters.

Considering the distinct advantages of a 3 elements antenna system as compared with 2 elements, and with a relatively small improvement when employing 4 elements, it is possible to conclude that antenna systems with 3 elements is preferable and may be considered best choice. Therefore, an antenna system with 3 elements will be used in Section IV to investigate the effect of different diameters of cylindrical bodies on the performance of the antenna system.

IV. Antenna System Mounted on Cylinders With Different Diameters

To study the influence of the diameter of the cylinder on the performance of the antenna system, an antenna system with three elements is analyzed when mounted on cylinders with diameters of 0.3 m, 0.5 m and 0.7 m, respectively. The simulation results show that when mounted on cylinder bodies with different diameters, the shape of 3D radiation patterns are similar. The radiation pattern resulting for a cylinder with a diameter of 0.5 m has been presented in Fig. 4(d), (e) and (f). As shown in the radiation patterns, no distinct null exists over a complete spherical surface, which means full radiation coverage is achieved. For the purpose of saving space, the 3D radiation patterns for the other two situations are not presented here. The calculated coverage curve results for cylinders with different diameters are depicted in Figs. 9–11. Fig. 9 shows the coverage curves of gain of E total, and Fig. 10 and Fig. 11 show the coverage curves of gain of E theta and E phi, respectively. From these three figures, it is safe to draw the conclusion that there is no distinctive influence of the diameter of cylinders on performance of the proposed antenna system. The proposed antenna system with 3 elements can achieve full coverage over the whole sphere for cylinders with different diameters. The performance of the antenna system does not deteriorate when the diameter of the cylinder increases. This conclusion is meaningful in real application, because in traditional solutions for omnidirectional coverage by using antenna arrays mounted on a cylinder surface, usually more antenna elements are required when the diameter of the cylinder becomes larger. However, even without adding more elements, the proposed antenna system can be conveniently used on cylinder carriers with different diameters, such as aircraft and satellite.

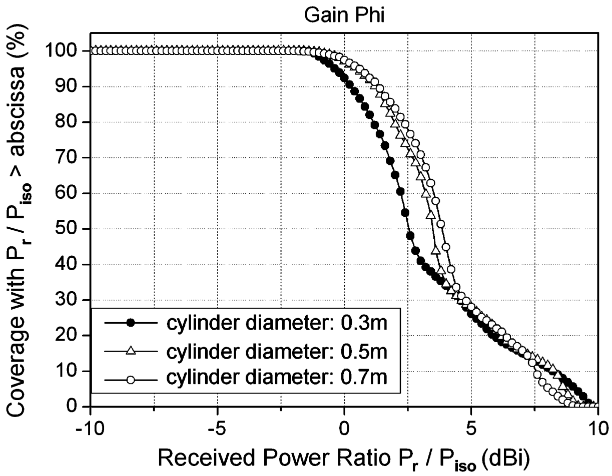

Fig. 11. Coverage curves of gain phi for the proposed switchable antenna system for cylinders with different diameters.

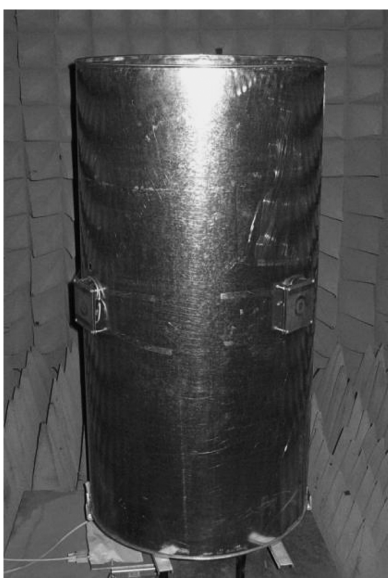

Fig. 12. Photograph of the proposed antenna system.

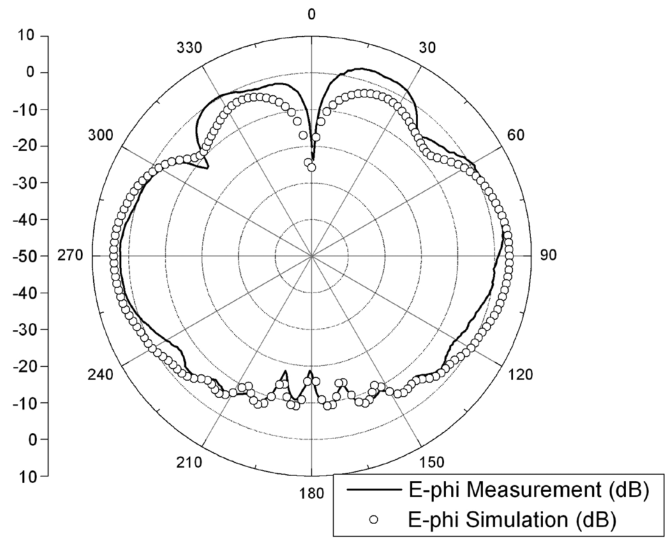

Fig. 13. Measured and simulated radiation patterns of the M3 port.

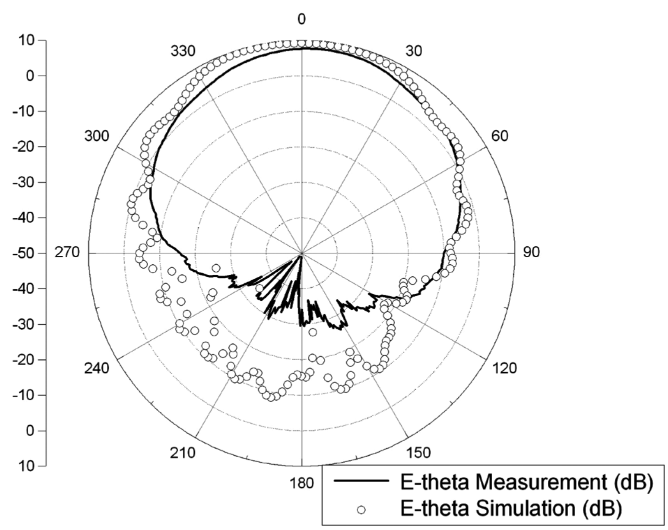

Fig. 14. Measured and simulated radiation patterns of the P1 port.

It is also important to emphasize that focus in this study was placed on achieving a complete spherical coverage using the proposed design. This is clearly important in wireless communications type of applications and, to this end, the design is considered satisfactory. In other radar and navigation-type applications, however, the phase center identification and its possible shifting as a result of switching needs to be further considered and carefully investigated. This will be addressed in a future publication as communications-type applications have been the focus of this study.

V. Experimental Verification

Experiments have been conducted to verify the above simulation results. A metal cylinder body with a diameter of 0.5 m and a height of 1 m was fabricated. As shown in Fig. 12, the antenna system was mounted on the cylinder surface. Due to the large volume of the cylinder, it is difficult to measure the 3D radiation pattern with our measurement equipment. However, the radiation patterns in the circumferential plane can be measured. When comparing the measured radiation patterns in the circumferential plane of the cylinder with the simulated results, we can still verify the validity of the results in the above sections. Therefore, the radiation pattern of each port of the tri-polarization antenna mounted on the cylinder surface was measured. Fig. 13, Fig. 14 and Fig. 15 show the comparison of the simulation results and the measurement results of three ports of the tri-polarization antenna.

Figs. 13, 14, and 15, show both simulated and measured radiation patterns of each port of one tri-polarization antenna element mounted on the cylinder surface at 2.4 GHz. The radiation patterns were measured by exciting one port while leaving all other ports open-circuit. Because these patterns were measured in the circumferential plane of the cylinder body and refer to the axis of the cylinder, the main polarizations of port M3 and port P2 are both E phi, and the main polarization of port P1 is E theta. As shown by these figures, the measurement results corroborate the simulation results. Small discrepancies are a result of the manufacturing tolerance.

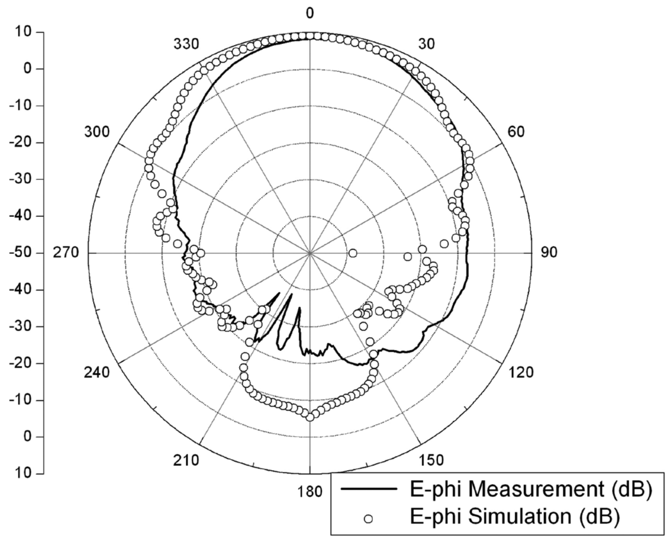

Fig. 15. Measured and simulated radiation patterns of the P2 port.

VI. Conclusion

In this paper, a conformal switchable antenna system mounted on cylinder surface is proposed, designed, simulated and experimentally tested for isotropic coverage. This antenna system consists of several tri-polarization antennas. Studies of this antenna system show that full coverage over a complete spherical surface can be achieved by using even just two elements. Considering the performance of the antenna system and the complexity of the switching structure, a design with three elements is recommended. Specifically, this design could provide 100 percent coverage with a gain larger than 0 dBi over a complete spherical surface. Gain values as high as 2.5 dBi could be achieved over 90% of a spherical surface when using a three elements design antenna system. Furthermore, it is shown that the performance of the antenna system does not deteriorate with an increase in the diameter of the cylinder. Therefore, without adding more elements, the proposed antenna system can be conveniently used on different cylindrical carriers with different diameters, such as aircraft and satellite. The proposed antenna system is, therefore, very useful and could be used in many aerospace applications.

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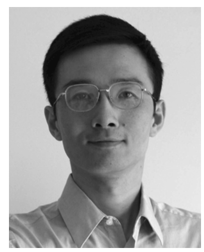

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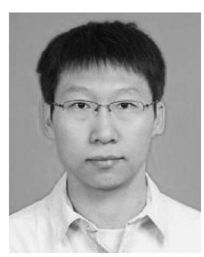

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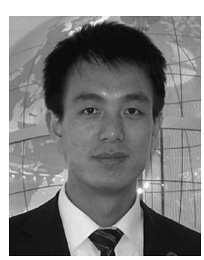

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