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Beamwidth Reconfigurable Magneto-Electric Dipole Antenna Based on Tunable Strip Grating Reflector

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ABSTRACT A new magneto-electric (ME) dipole antenna with a dynamic beamwidth control in the $H$-plane is presented. The design methodology uses tunable strip gratings placed on the sides of an ME dipole along its $H$-plane. Each strip is equally divided into 16 short parts and connected in series by using 15 PIN diodes; accordingly, by controlling the on/off-state of the PIN diodes, the strips can operate as a grating reflector or be transparent for the radiating wave. Therefore, the size of the reflector can be reconfigured, which leads to the tunable beamwidth. A fully functional prototype with an as wide as 40% impedance bandwidth (for SWR $\leq 1.5$) is developed and tested, demonstrating the $H$-plane beamwidth with a tuning range from $81^\circ$ to $153^\circ$. Radiation efficiencies are better than 90% in all the states of operation.

INDEX TERMS Reconfigurable antenna, beamwidth tunable, magneto-electric dipole.

I. INTRODUCTION

The evolution of wireless communications brings increasing demand for antennas with higher performance, such as wide operating bands, compact sizes and flexible radiation properties. Pattern reconfigurable antennas are very promising, because they can increase the spectrum utilization by dynamically adjusting their radiation characteristics to the system requirements and the surrounding environment. Switchable radiating direction attracts much attention during the last few years [1]–[10]. On the other hand, a dynamic control over their radiation beamwidth is required in antenna terminals to enhance the traffic capacity for wireless cellular networks [11]. In these mobile systems, antennas are desired to dynamically changing their radiation beamwidth in response to variations in the traffic distribution and, therefore, to help balance the traffic between different cells and improve the capacity efficiency [11]. For example, for base station antennas around areas of office buildings and highways, antennas can utilize the narrow $H$-plane beamwidth to concentrate the radiating power to office buildings during office hours but change to the wide $H$-plane beamwidth to cover highways during rush hours.

Recently, beamwidth reconfigurable antennas are discussed based on different types of antennas in the literature. Mechanical approaches by defocusing the feed of a reflector antenna were able to realize the capability [12]–[14]. But these antennas suffered from issues related to the mechanical reconfiguration, such as the movement of large masses, inaccurate alignment, and vibration. By controlling the number of the operating antenna elements, the directivity and beamwidth could be controlled [15]. However, the antenna size was too large and a wide tuning range depended on a large quantity of sources. By using a switchable partially reflective surface (PRS) antenna over a source antenna [16], [17], the beamwidth reconfiguration was achieved by varying the PRS reflectivity via embedded varactor diodes or MEMS switches. However, the complex structures and the narrow operating bandwidths (1.5% for [16], unmatched for [17]) limited the application of these antennas. In [18], a beamwidth tunable patch antenna was presented by adding two size-tunable parasitic patches to the left and right of a probe-fed patch along its $H$-plane. But the radiation performance could be maintained only within a very narrow band, and the impedance could not always be matched as the beamwidth changed from 50° to 110°. In the previous works [19], [20], the authors have proposed two methodologies for realizing the tunable $H$-plane beamwidth. By varying the phase distribution of a
three-element antenna array, the half-power beamwidth in the H-plane could be switched between $37^\circ$ and $136^\circ$ within a 15% overlapping impedance band [19]. In [20], the reconfigurable beamwidth was realized by adding tunable parasitic dipoles on the sides of a driven ME dipole along its H-plane. Each parasitic dipole was loaded with a varactor diode to change the strength of the mutual coupling; therefore, the overall radiation pattern produced by the driven ME dipole and the two parasitic dipoles could be continuously tuned. However, the beamwidth reconfiguration could only be realized over a less than 15% impedance band, which could not meet the requirements of many modern wireless applications. In this paper, a novel design is presented by using tunable strip gratings. The antenna consists of a ME dipole and three pairs of tunable thin strips. Each strip is equally divided into 16 short parts and connected in series by using 15 PIN diodes. By controlling the ON/OFF state of the PIN diodes, the strips can operate as a grating reflector or be transparent for the radiating wave. Therefore, the size of the reflector can be reconfigured, which leads to the tunable beamwidth. To demonstrate the functionality, a prototype was fabricated and measured, which shows the antennas with an H-plane beamwidth tuning range from $81^\circ$ to $153^\circ$ over a 40% impedance band. Details of the proposed design are described as follows. The antenna geometry and operation principle are presented in Section II. In Section III, simulated and measured results are given. A parametric study is built with discussions in Section IV followed by conclusions in Section V.

### TABLE 1. Dimensions of the proposed antenna.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>$G_W$</th>
<th>$G_L$</th>
<th>$W$</th>
<th>$L$</th>
<th>$H$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Values/mm</td>
<td>58</td>
<td>111</td>
<td>40</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td>(0.36λ)</td>
<td>(0.70λ)</td>
<td>(0.25λ)</td>
<td>(0.25λ)</td>
<td>(0.25λ)</td>
</tr>
<tr>
<td>Values/mm</td>
<td>$s$</td>
<td>$a$</td>
<td>$b$</td>
<td>$c$</td>
<td>$d$</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>6</td>
<td>6</td>
<td>1</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>(0.127λ)</td>
<td>(0.006λ)</td>
<td>(0.038λ)</td>
<td>(0.006λ)</td>
<td>(0.114λ)</td>
</tr>
</tbody>
</table>

$\lambda$ is the free-space wavelength referring to the center frequency at 1.9 GHz.

### II. ANTENNA GEOMETRY AND OPERATION PRINCIPLE

#### A. ANTENNA GEOMETRY

The geometry of the proposed beamwidth reconfigurable ME dipole antenna is shown in Fig. 1 with detailed dimensions in Table 1. The antenna consists of a typical ME dipole fed by a $\Gamma$-shaped probe feed [21] and three pairs of tunable thin strips. The ME dipole is chosen because of its advantages of unidirectional radiation and stable beamwidth over a wide frequency range [22], [23]. The ME dipole is located above a small rectangular reflector (with dimensions of $G_L \times G_W$) which is printed on the top side of a horizontal substrate (thickness = 0.787 mm, $\epsilon_r = 2.33$). Three pairs of tunable strips are placed on the sides of the ME dipole along the $x$-axis. Strip 1 and 2 are printed on the top side of the horizontal substrate, while Strip 3 is printed on two small vertical substrates (thickness = 0.787 mm, $\epsilon_r = 2.33$) which are oriented vertically to the horizontal substrate. Each long strip is equally divided into 16 short parts by 15 PIN diodes. The 15 PIN diodes are connected in series and can be simultaneously forward biased by supplying the two ends of the long strip with a proper DC voltage (15 V in the proposed design).

In this design, the PIN diode is chosen as Infineon BAR50-02V [24]. Each diode can be well forward biased to ON state with a DC voltage that provides higher than 100 mA biasing current, whereas it will be in OFF state if left unbiased. DC lines are printed on the bottom of the substrates to bias the PIN diodes. Some ferrite beads, model BLM18G [25] are used along the DC lines to cut off the coupled RF signals while allowing the DC signals to pass. Therefore, the PIN diodes on the 3 pairs of strips (Strip 1, Strip 2, Strip 3) can be controlled by three DC signals ($U_1$, $U_2$, $U_3$), respectively.

#### B. OPERATION PRINCIPLE

When the strips are OFF, which means the PIN diodes on the strips are OFF, the strips are divided into very short parts (0.038$\lambda$). Therefore, the strips are nearly transparent.
TABLE 2. States of strips for different operation states.

<table>
<thead>
<tr>
<th>State</th>
<th>Strip 1</th>
<th>Strip 2</th>
<th>Strip 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>State 1</td>
<td>OFF ($U_1 = 0$ V)</td>
<td>OFF ($U_2 = 0$ V)</td>
<td>OFF ($U_3 = 0$ V)</td>
</tr>
<tr>
<td>State 2</td>
<td>ON ($U_1 = 15$ V)</td>
<td>OFF ($U_2 = 0$ V)</td>
<td>OFF ($U_3 = 0$ V)</td>
</tr>
<tr>
<td>State 3</td>
<td>ON ($U_1 = 15$ V)</td>
<td>ON ($U_2 = 15$ V)</td>
<td>OFF ($U_3 = 0$ V)</td>
</tr>
<tr>
<td>State 4</td>
<td>ON ($U_1 = 15$ V)</td>
<td>ON ($U_2 = 15$ V)</td>
<td>ON ($U_3 = 15$ V)</td>
</tr>
</tbody>
</table>

for the radiating waves, and the ME dipole is backed with a small reflector. When the strips are ON, which means the PIN diodes on the strips are ON, the strips function as grating reflectors. On this condition, the strips operate similar to the reflectors in the outdoor grid antennas [26] where strip gratings are used as reflectors to reduce the wind loading. Accordingly, the ME dipole is with a large reflector. Thus, different operation states can be realized by controlling the ON/OFF states of the strips as illustrated in Table II. Fig. 2 shows the electric field distribution in the H-plane at 1.9 GHz when all the strips are OFF (State 1) and ON (State 4). It can be observed that when all the strips are OFF, the strips cannot block the radiating wave of propagating to the sides. Accordingly, the wide beamwidth is contributed by the small ground plane in this state. On the other hand, when all the strips are ON, the strips together with the rectangular ground work as a cavity; and the radiating wave is concentrated in the broadside direction. Therefore, the narrow beamwidth can be achieved in this state. Fig. 3 describes the equivalent structures of different states. The equivalent structures are just approximate conditions used for describing the operation principle of the antenna. Consequently, by controlling the numbers of the strip gratings, the size of the reflector can be reconfigured, which leads to the tunable beamwidth.

III. SIMULATED AND MEASURED RESULTS

A fully functional prototype of the proposed antenna as depicted in Fig. 4 was fabricated to verify the proposed design. Simulation was accomplished using Ansys HFSS [27]. Measured results of reflection coefficients ($|S_{11}|$), antenna gains, radiation efficiencies and far-field radiation patterns were obtained by an Agilent N5230A network analyzer and a Satimo Starlab near-field measurement system.

The simulated and measured SWRs are shown in Fig. 5 with good agreement. From this figure, the measured impedance bandwidth is about 40% for SWR $\leq 1.5$ from 1.52 to 2.28 GHz, which agrees well with the simulated impedance matching from 1.58 to 2.27 GHz. In addition, as we can observe, the impedance matching is nearly invariable for different states. Fig. 5 also shows the measured broadside gains in different states. Within the operating frequencies, the measured antenna gain is as high as 7.4 dBi in State 4; however, the measured peak gain in State 1 is only approximately 5.6 dBi. The gain difference is due to the large H-plane beamwidth variation between different states. Table III lists the measured radiation efficiencies greater than 90% for different operation states.

The simulated and measured radiation patterns at frequencies of 1.6, 1.9 and 2.2 GHz are presented in Fig. 6 and 7 for different states. It can be observed that good agreement is achieved between simulated and measured results. The antenna exhibits unidirectional radiation patterns with back radiation levels lower than $-8$ dB and cross-polarization levels lower than $-24$ dB throughout the entire overlapping band. The front-to-back ratio rises as the
FIGURE 5. Simulated and measured SWRs and peak gains: (a) simulated results; (b) measured results.

TABLE 3. Measured peak gains, efficiencies, E-plane & H-plane beamwidths, and front-to-back ratio of the proposed antenna.

<table>
<thead>
<tr>
<th>Operation State</th>
<th>Peak Gain/dBi</th>
<th>Efficiency (%)</th>
<th>E-plane Beamwidth /deg</th>
<th>H-plane Beamwidth /deg</th>
<th>F/B Ratio/°</th>
</tr>
</thead>
<tbody>
<tr>
<td>State 1</td>
<td>5.6 ± 0.4</td>
<td>91 ± 3</td>
<td>77 ± 3</td>
<td>153 ± 9</td>
<td>8</td>
</tr>
<tr>
<td>State 2</td>
<td>5.9 ± 0.5</td>
<td>91 ± 3</td>
<td>78 ± 3</td>
<td>123 ± 6</td>
<td>10</td>
</tr>
<tr>
<td>State 3</td>
<td>6.4 ± 0.8</td>
<td>91 ± 3</td>
<td>77 ± 2</td>
<td>109 ± 7</td>
<td>16</td>
</tr>
<tr>
<td>State 4</td>
<td>7.3 ± 0.3</td>
<td>92 ± 3</td>
<td>76 ± 2</td>
<td>81 ± 3</td>
<td>20</td>
</tr>
</tbody>
</table>


operation state switches from State 1 to State 4, which is caused by the increasing size of the reflector. In addition, the E-plane patterns are stable for different states, whereas the H-plane patterns vary significantly. Fig. 6 and 7 also show the 3-dB beamwidths in the E- and H-planes of the proposed antenna with the details in Table III. It is observed that the beamwidth in the E-plane is approximately 77° across the band for different states. On the other hand, the beamwidth in the H-plane continuously varies from 153° in State 1 to 81° in State 4.

IV. PARAMETRIC STUDY

To understand how the dimensions of the antenna affect the performance, a parametric study was performed using HFSS. Throughout the study, the DC biasing lines are removed and the metallic layers are assumed to have zero thickness for relatively fast computation. Only H-plane radiation patterns in State 1 and 4 are given, which is enough to describe the effect of the concerned parameters. When one parameter is studied, the others are kept constant. The results provide a useful guideline for practical designs.

First, the effect of the switch is studied. When ideal switches are used, each switch is represented by a short circuit in ON state and is represented by an open circuit in OFF state. Fig. 8 describes the radiation patterns in State 1 and 4 of the proposed antenna with ideal switches or PIN diodes (BARS0-02V). As we can observe, when ideal switches are used, stable radiation patterns including stable 3-dB beamwidths are produced. On the other hand, PIN diodes introduce greater changes on the H-plane patterns in State 1. In State 4, ideal switches and practical PIN diodes bring similar H-plane radiation patterns.

The second parameter studied was the length of the short strips $b$. As the strips are desired to be transparent for radiating waves when the strips are OFF, a large $b$ would...
increase the effect of the strips on the radiating waves. A comparison between $b = 6$ mm and $b = 13$ mm is given in Fig. 9. When $b = 13$ mm, the long strip is equally divided into 8 short parts; and 7 PIN diodes are used. It can be observed from Fig. 9 that the H-plane beamwidth decreases enormously at 2.2 GHz when $b = 13$ mm in State 1. For lower frequencies, the impact of a large $b$ is smaller, which is because the short strips have larger electrical length at higher frequencies ($b = 13$ mm = 0.1 $\lambda$ at 2.2 GHz). Smaller $b$ and more PIN diodes can lead to weaker effect of the short strips on the radiating waves; but a more complicated structure and higher DC biasing voltages would be produced. Therefore, $b = 6$ mm was selected.

The third parameter studied was the distance of the adjacent strips $d$. Fig. 10 shows the effect of $d$ on the H-plane radiation patterns. In State 1, the pattern at 2.2 GHz is most sensitive to the variation of $d$ compared to lower frequencies.
Therefore, when \( d = 8 \) mm or 28 mm, the beamwidth variation is larger than that when \( d = 18 \) mm. In State 4, a large \( d \) decreases the beamwidth, which is due to the large size of the reflector when \( d \) is large. Thus, \( d = 18 \) mm was selected for a stable beamwidth variation during the entire operating band.

V. CONCLUSION

A new ME dipole antenna with beamwidth reconfiguration in the H-plane has been presented. Three pairs of tunable strips loaded with PIN diodes are placed on the sides of the driven ME dipole along its H-plane to create an H-plane beamwidth reconfiguration. A prototype was designed, fabricated, and measured, which shows that a 40% impedance bandwidth for \( \text{SWR} \leq 1.5 \), unidirectional radiation patterns with low cross-polarization and back radiation levels are achieved in all states of operation. The H-plane beamwidth can be varied from \( 81^\circ \) to \( 153^\circ \). It should be noted that the design is a low cost solution as the used PIN diodes are very cheap. With the wide beamwidth variation and wide impedance bandwidth, the proposed design is attractive for stationary terminals and base stations in mobile communications. In addition, besides the linearly polarized ME dipoles, the proposed design methodology can also be applied in other linearly polarized or dual-polarized antenna types for beamwidth or beam direction reconfiguration.

REFERENCES


KWAI MAN LUK (M’79–SM’94–F’03) was born in Hong Kong. He received the B.Sc. (Eng.) and Ph.D. degrees in electrical engineering from The University of Hong Kong in 1981 and 1985, respectively. He joined the Department of Electronic Engineering, City University of Hong Kong, in 1985, as a Lecturer. He was with the Department of Electronic Engineering, The Chinese University of Hong Kong, where he spent four years. He returned to the City University of Hong Kong in 1992, where he is currently the Chair Professor of Electronic Engineering. He holds five U.S. and over ten PRC patents on the design of a wideband patch antenna with an L-shaped probe feed. He has authored three books, ten research book chapters, over 333 journal papers, and 250 conference papers. His recent research interests include design of patch antennas, magneto-electric dipole antennas, and dense dielectric patch antennas for various wireless applications. He is a fellow of the Chinese Institute of Electronics, PRC, a fellow of the Institution of Engineering and Technology, U.K., a fellow of the Institute of Electrical and Electronics Engineers, USA, and a fellow of the Electromagnetics Academy, USA. He received the Japan Microwave Prize, at the 1994 Asia Pacific Microwave Conference, in Chiba, in 1994, the Best Paper Award at the 2008 International Symposium on Antennas and Propagation, in Taipei, in 2008, and the Best Paper Award at the 2015 Asia-Pacific Conference on Antennas and Propagation, in Bali, in 2015. He also received the very competitive 2000 Croucher Foundation Senior Research Fellow in Hong Kong and the 2011 State Technological Invention Award (2nd Honor) of China. He was the Technical Program Chairperson of the 1997 Progress in Electromagnetics Research Symposium, the General Vice-Chairperson of the 1997 and the 2008 Asia-Pacific Microwave Conference, the General Chairman of the 2006 IEEE Region Ten Conference, the Technical Program Co-Chairperson of the 2008 International Symposium on Antennas and Propagation, the General Co-Chairperson of the 2011 IEEE International Workshop on Antenna Technology, the General Co-Chair of the 2014 IEEE International Conference on Antenna Measurements and Applications, and the General Co-Chair of the 2015 International Conference on Infrared, millimeter, and Terahertz Waves (IRMMW-THz 2015). He was a Chief Guest Editor of a Special Issue on Antennas in Wireless Communications published in the Proceedings of the IEEE in 2012. He is a Deputy Editor-in-Chief of the PIERS journals and an Associate Editor of the IET Microwaves, Antennas and Propagation.