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DING, Chen; LUK, Kwai-Man

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A Low-Profile Dual-Polarized Magneto-Electric Dipole Antenna

CHEN DING, (Student Member, IEEE), AND KWAI-MAN LUK, (Fellow, IEEE)

1Department of Electrical Engineering, City University of Hong Kong, Hong Kong
2State Key Laboratory of Terahertz and Millimeter Wave, City University of Hong Kong, Hong Kong

Corresponding author: Kwai-Man Luk (eekmluk@cityu.edu.hk)

ABSTRACT A novel low-profile dual-polarized magneto-electric dipole antenna with two choices of feeding probes are proposed and investigated. The antenna utilizes a radiating structure which adopts equilateral triangular cavities with small gaps as the magnetic dipole while maintaining the original rectangular planar patches as the electric dipole, reducing the thickness to 0.15\(\lambda_0\) (where \(\lambda_0\) is the free-space wavelength at the center frequency). Each type of the feeding probe has its own merit and demerit in terms of mechanical robustness, performance and assembly tolerance. Measurement results show that the prototypes achieve wide impedance bandwidth of 48% (SWR < 2), high gain (7.7 to 11 dBi) and unidirectional radiation patterns with low cross-polarizations (< −22dB) and back-radiation level.

INDEX TERMS Low profile, magneto-electric dipole, unidirectional patterns, wideband antennas, dual-polarized antennas.

I. INTRODUCTION

Fast evolving wireless communication systems require smaller antennas with better performances in terms of bandwidth, gain and radiation patterns. Conventional designs such as horn, log-periodic and reflector antenna are incompatible with most modern wireless communication systems due to their bulky structure [1]. Microstrip patch antennas have been widely used for its low profile and convenience of fabrication. To cope with their major limit in narrow bandwidth, many techniques have been studied, such as aperture-coupled feed [2]–[4], capacitive feed [5], L-probe [6], M-probe feed [7]–[9] and high-order mode [10]–[13]. However, these designs have one or more disadvantages of large area, large gain variation, high cross-polarization and high back radiation. Therefore, compactness, bandwidth and radiation properties need to be considered simultaneously during designing process.

In 2006, Wong and Luk developed a new kind of complementary antenna called magneto-electric (ME) dipole which combines a shorted patch antenna with an electric dipole [14]. This type of antenna possesses advantages of wide bandwidth, high gain, low cross polarization and low backlobe radiation. However, a noticeable shortcoming of the ME dipole is its relatively large thickness of around 0.25\(\lambda_0\), resulting in inconvenience in practical applications. Throughout years, a series of studies have been done to lower down the thickness of linearly polarized ME dipole to less than 0.1\(\lambda_0\) [15]–[22].

Linearly polarized ME dipole antenna was later expanded to dual polarization [23]–[26]. Similar to linearly polarized designs, dual-polarized ME dipole exhibits wide bandwidth and good unidirectional radiation properties for both ports. However, the antennas kept the same height of 0.25\(\lambda_0\) to the original linearly polarized design and few efforts have been done to lower the thickness for dual polarization. In 2016, Lai developed a dual-polarized dual complementary source ME (DCS-ME) dipole antenna with thickness of 0.192\(\lambda_0\) using dual open-ended slot excitation [27]. Such design brings significant impairment to the radiation characteristics including the cross-polarization level. The design in [28] has a 0.16\(\lambda_0\) thickness for the radiating element yet requires cavity walls of 0.37\(\lambda_0\) in height.

In this paper, a new ME dipole with low profile with two options of feeding probes are presented. The design abandons the shorted patch as the source of magnetic current. Instead, it adopts equilateral triangular cavity with small gap to act as the magnetic dipole, reducing the thickness from 0.25\(\lambda_0\) to 0.15\(\lambda_0\) by 40%. Such modification does not result in impairing performance inherited from the original ME dipole.
antenna in terms of bandwidth and radiation properties. Two kinds of structures are provided to form the feeding probe of the antenna.

This paper is organized as follows. Section II presents the principle of the radiating components of the dual-polarized ME dipole antenna. Section III and IV introduce the geometry, working principle and performance of dual-polarized ME dipoles with dual \( \Gamma \)-probes and flat \( \Gamma \)-probes, respectively. Comparison and discussion between two types of feeding structures are presented in Section V. A parametric study for several crucial parameters is conducted in Section VI. Finally, the conclusion is given in Section VII.

II. PRINCIPLE OF OPERATION

The original design of linearly polarized ME dipole [14] was interpreted as a combination of electric dipole and magnetic dipole placed orthogonally to each other. The electric dipole is constructed by a horizontal planar half-wave dipole while the magnetic dipole is realized by a shorted quarter-wavelength patch antenna. Similar configuration was found in the dual-polarized case, as shown in Fig. 1(a). The feeding probes are omitted for the convenience of demonstration. The two orthogonal gaps intersected in the middle cut the horizontal dipole plates and vertical shorted patches into four bi-symmetric parts. The whole radiating components could be illustrated as two complementary feeding sources with the same phase. Each source is composed of an electric and a magnetic current orthogonal to each other. The relatively large thickness mainly results from the vertically placed magnetic dipole. Therefore, the direction of reducing the height should be focused on improving the magnetic dipole.

The radiation of a shorted quarter-wavelength patch antenna as the magnetic dipole is mainly from the open end, by the classical cavity model theory. The open end could be treated as the virtual magnetic current, which could also be generated by an equilaterally triangular metallic cavity of \( \lambda_0/2 \) perimeter with open end at one of its vertex, as shown in [29]. Inspired by this idea, the magnetic dipoles in dual-polarized ME dipole could also be replaced by a pair of triangular cavities located orthogonally, as shown in Fig. 1(b). The feeding probes are omitted and will be illustrated with detail in section III and IV. Each triangular cavity is designated to serve one polarization. The metallic walls of two cavities are connected to each other in the central intersection. The electric dipoles remain unchanged and connected to the triangular cavity in the central gap. By applying this configuration, the thickness of dual-polarized ME dipole could be reduced from 0.25\( \lambda_0 \) to 0.15\( \lambda_0 \) by 40%. The equivalent circuit is shown in Fig. 1(c). The impedance formula could be found in [30]. No metamaterial [31], [32] is deployed for thickness reduction since this work focuses on structural evolution.

TABLE I. Dimensions for the proposed antenna with dual \( \Gamma \)-probes.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>( l_1 )</th>
<th>( l_2 )</th>
<th>( W )</th>
<th>( G )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value (mm)</td>
<td>(0.267( \lambda_0 ))</td>
<td>(0.263( \lambda_0 ))</td>
<td>(0.143( \lambda_0 ))</td>
<td>(0.023( \lambda_0 ))</td>
</tr>
<tr>
<td>Value (mm)</td>
<td>(0.153( \lambda_0 ))</td>
<td>190</td>
<td>3.2</td>
<td>31.7</td>
</tr>
<tr>
<td>Value (mm)</td>
<td>(0.135( \lambda_0 ))</td>
<td>48.8</td>
<td>8.8</td>
<td>31.7</td>
</tr>
<tr>
<td>Value (mm)</td>
<td>(0.105( \lambda_0 ))</td>
<td>48.8</td>
<td>13.1</td>
<td>(0.06553( \lambda_0 ))</td>
</tr>
</tbody>
</table>

III. DUAL-POLARIZED ME DIPOLE ANTENNA WITH DUAL \( \Gamma \)-PROBES

A. ANTENNA GEOMETRY

The geometry of the proposed dual-polarized ME dipole antenna with dual \( \Gamma \)-probes is illustrated in Fig. 1. All parts of the design are made of metal. The ground plane is made of aluminum with thickness of 2 mm, while all other parts except the connectors are made of brass plates with thickness of 0.2 mm. All dimensions of the proposed design, which are optimized by simulation using High Frequency Structure Simulator (HFSS), are shown in Table I.
The structure of the radiating element is described in section II. There are four radiating parts in total, located bisymmetrically around the central axis. The bottoms of the radiating elements are fixed to the ground plane by screws. The size of the ground plane is $1 \lambda_0 \times 1 \lambda_0$, where $\lambda_0$ refers to the free-space wavelength at the centre frequency.

The two feeding probes are located orthogonally inside the triangular cavities formed by slanted walls and the ground. Each probe is soldered to the inner conductor of the SMA connector in the lower center. From the connection point, it divides into two opposite microstrip lines with characteristic impedance of 100 Ohms. At the end of the microstrip line, it is connected to two $\Gamma$-shaped flat strips. The cropped corners at 90-degree bends of probes are the same as those in microstrip line bends. The upper horizontal parts of the two probes are different in height so the two ports are isolated. When the probe is near the triangular cavity, the gap between them is 2 mm.

Each probe could be treated as three parts in the perspective of circuit. The first part is the microstrip line which transmits the energy from the SMA connector. The second part, which acts as a balun, is the portion that passes through the gap between the opposing triangular cavities. The third part is at the end of $\Gamma$-shaped flat strip, acting as a capacitor and coupling energy from probe to the nearby walls.

**B. WORKING PRINCIPLE**

During operation, signals are launched into the two dual $\Gamma$-shaped probes through the two SMA connectors. For each polarization, the signal is then divided into two branches and carried by the microstrip line formed by the brass strip and the adjacent ground or slanted walls. This microstrip line with 3.2 mm strip width and 2 mm strip-ground distance has characteristic impedance of 100 Ohms. The signal then passes through the crossed gap which acts as a balun and excites the horizontal planar dipoles and triangular cavities at the same time.

The benefit of complementary antenna such as wide bandwidth and good unidirectional radiation pattern results from the electric dipole and magnetic dipole excited simultaneously with similar amplitude. To further investigate the operating principle of the proposed antenna, the simulated current distributions on the antenna surface and the electric fields in the gaps between upper patches for both ports at different phases of the center frequency are analyzed as shown in Fig. 3. At time $t = 0$, the currents on the horizontal patches reach maximum strength, whereas the electric fields in the gaps between patches attain minimum strength. This indicates that the electric currents in the electric dipole and the magnetic currents in the magnetic dipole reach maximum magnitude at the same time. At time $t = T/4$, where $T$ is one period of the operation, the currents on the horizontal patches attain minimum strength, whereas the electric fields in the gaps between patches reach maximum strength. This indicates that both the electric currents in the electric dipole and the magnetic currents in the magnetic dipole attain minimum. These results show that two degenerate modes of similar magnitude in strength are excited on the planar dipole (electric dipole) and the gaps of the triangular cavities.
C. Antenna Performance

A prototype of the antenna as shown in Fig. 4 was fabricated to verify the proposed design. Measurement of SWRs and port isolations were accomplished using an Agilent E5071C network analyzer. Radiation patterns and antenna gains were measured by a Satimo Starlab near-field measurement system.

Simulated and measured SWRs along with the gains are shown in Fig. 5. The measured impedance bandwidths are 48% (SWR < 2) from 1.22 to 2 GHz for both ports. The operating frequency ranges for the two ports are slightly different due to the unequal heights of the two orthogonal probes. When compared to the simulation, the operating frequency bands for both ports are shifted to higher frequency due to fabrication error. Within operating frequency range, the measured boresight gain varies from 8.1 to 10.6 dBi and from 7.9 to 11 dBi for port 1 and 2, respectively. Nearly identical antenna gains are obtained for the two ports due to the bisymmetrical geometry of the proposed design. As shown in Fig. 6, the measured isolation between the two ports is larger than 28 dB over the operating frequency range, which is agrees well with the simulation.

The measured and simulated radiation patterns at 1.2, 1.6 and 2 GHz for port 1 and 2 are depicted in Fig. 7 and 8, respectively. Good agreement between measurement and
FIGURE 8. Simulated and measured radiation patterns for port 2 of the proposed antenna with dual 0-probes.

TABLE 2. Measured 3-dB beamwidth of the proposed antenna with dual 0-probes.

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Port 1</th>
<th>Port 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.2 GHz</td>
<td>56°</td>
<td>65°</td>
</tr>
<tr>
<td>1.6 GHz</td>
<td>55°</td>
<td>60°</td>
</tr>
<tr>
<td>2 GHz</td>
<td>49°</td>
<td>50°</td>
</tr>
</tbody>
</table>

simulations is achieved. The antenna exhibits good unidirectional radiation characteristic. The measured cross-polarization levels for two ports are below −24 dB in both E- and H-plane. The measured front-to-back ratios are over 12 dB over the operating frequency range. The measured 3-dB beamwidth for both ports are listed in Table 2. The 3-dB beamwidth in both E- and H-planes decreases with frequency due to the electrical size of the antenna and the ground plane as the reflector.

IV. DUAL-POLARIZED ME DIPOLE ANTENNA WITH FLAT Γ-PROBES

A. ANTENNA GEOMETRY

The geometry of the dual-polarized ME dipole antenna with flat Γ-probes is illustrated in Fig. 9. All designs are the same to the previous antenna except for the structure of the two probes. All dimensions of the proposed design, which are optimized by simulation, are shown in Table 3.

The two feeding probes are located orthogonally inside the triangular cavities, as in the dual 0-probes design. The lower middle part of each probe is soldered to the central core of SMA connector. The probe is originally flat with two trapezoidal parts at the sides and one rectangular part in the middle and is bent to Γ-shape at the two junctions between the rectangle and the two trapezoids. The brass strip of the probe, together with two adjacent slant walls, forms a modified stripline structure with the strip perpendicular to the ground and the strip width changes with the cavity width. The surfaces of adjacent metallic walls perform as the ground planes and the middle probe strip transmits the signal. The gap distance between the probe strip and the triangular cavity is 1.2 mm. The middle horizontal parts of the two probes are different in height so the two ports are isolated.

Each probe could be treated as three parts in the perspective of circuit. The first part is the transmission line which transmits the energy along the gap between the edge of the flat Γ-probe and the triangular cavity from the SMA connector. The second part, which acts as a balun, is the portion that passes through the gap formed by opposing triangular cavities. The third part is at the end of Γ-shaped flat probe whose

TABLE 3. Dimensions for the proposed flat Γ-probes.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$P_{d1}$</th>
<th>$P_{d2}$</th>
<th>$P_{d3}$</th>
<th>$P_{d4}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value (mm)</td>
<td>(0.168λ₀)</td>
<td>(0.126λ₀)</td>
<td>(0.252λ₀)</td>
<td>(0.081λ₀)</td>
</tr>
<tr>
<td>Value (mm)</td>
<td>(19.9)</td>
<td>(0.0995λ₀)</td>
<td>(0.252λ₀)</td>
<td>(0.077λ₀)</td>
</tr>
</tbody>
</table>
gap with the triangular cavity acts as a capacitor and couples energy to the radiating elements.

**B. WORKING PRINCIPLE**

During operation, signals are launched into two flat $\Gamma$-shaped probes through the two SMA connectors. For each polarization, the signal is then transmitted through the modified stripline with varying strip width formed by the flat strip and the surfaces of adjacent triangular cavity. The signal then passes through the intersection between the two triangular cavities which acts as a balun and excites the horizontal planar dipoles and triangular cavities at the same time. The working principles of the radiating elements are the same with the previous antenna design with dual $\Gamma$-probes.

**C. ANTENNA PERFORMANCE**

A prototype of the antenna was fabricated to verify the proposed design. The fabricated flat $\Gamma$-probes are shown in Fig. 10. Measurement of SWRs, port isolations, radiation patterns and antenna gains were accomplished by the same instruments used by the previous design. Measured antenna performances are also similar to the previous design.

**V. COMPARISON BETWEEN TWO TYPES OF PROBES**

The two types of probes adopted in the design of the low-profile ME dipole antenna have different operating principles, performances and mechanical structures. The cross section of the electric fields between the probes and the triangular cavity for two types of probes are shown in Fig. 11. The edge of dual $\Gamma$-probe works as a standard microstrip line with gap $g_1 = 2$ mm. The characteristic impedances of this microstrip line is around 100 Ohms. The flat $\Gamma$-probe works as a modified stripline structure with the strip perpendicular to the ground and gap $g_2 = 1.2$ mm. The strip width changes with the triangular cavity. Each type of the probes has its own merits and demerits in different aspects. Mechanically, the flat $\Gamma$-probe is more robust due to simpler structure and larger area. In comparison, the dual $\Gamma$-probe is more susceptible to vibration and deformation, resulting from its long and thin metal strips. On the other hand, the dual $\Gamma$-probe is more tolerant to assembly error than the flat $\Gamma$-probe, since the gap distance $g_1$ is much larger than $g_2$. For more stable fixture of the probes, light foams could be applied to fix the probes against vibration and deformation without affecting the performance.

**VI. PARAMETRIC STUDY**

In order to investigate the effect of parameter dimensions on the performance of the antenna design, a parametric study was performed by simulation. Since the performance of the antenna with two proposed probes are similar, only the design in Section III is used in the simulation.

**A. ELECTRIC DIPOLE**

To study the effect of the electric dipole on the antenna performance, the edge lengths of the rectangular patches, $L_1$ and $L_2$, were studied. Fig. 12 shows the effect on SWR and gain by varying $L_1$ for both ports with $L_2$ fixed. It can be observed that by increasing $L_1$, the impedance matching becomes worse and the first resonance of port 1 is shifted to a lower frequency while a fixed second resonance occurs at around 1.65 GHz. This phenomenon indicates that the first resonance is formed by the electric dipole. The local peaks of the gain curve move with the resonance point. The performance of port 2 is less affected by $L_1$. Fig. 13 shows the effect on SWR and gain by varying $L_2$ for both ports with $L_1$ fixed. Compared to Fig. 12, the effect on port 1 and port 2 are interchanged since $L_1$ is the length of the electric dipole of port 1 while $L_2$ is the length of the electric dipole of port 2. To balance between impedance bandwidth and impedance matching, $L_1$ and $L_2$ were chosen to be 50 mm and 49 mm, respectively.

**B. MAGNETIC DIPOLE**

The vertical height of the slanted walls under the rectangular patches $H$ was studied firstly. It can be seen from Fig. 14 that by increasing $H$, the impedance matching becomes worse and the second resonances of both port 1 and port 2 are shifted to...
a lower frequency while a fixed resonance occurs at around 1.25 GHz. This indicates that the second resonance is formed by the magnetic dipole. It could be noticed that the impedance matching in the middle part of the operating band will deteriorate if the two resonant frequencies are far away from each other. Separation of the two resonances of electric and magnetic dipoles will defeat the purpose of complementary sources and create two separate frequency bands instead of a coherent wide band. And yet two overlapped resonances will result in a narrow usable band. Therefore, $H$ was chosen to be 28 mm.

Fig. 15 shows the impact to antenna performance by width of the slanted wall $W$, while keeping wall height $H$ and inclination angle constant. The impedance matching and gain are sensitive to the value of $W$. Relatively small $W$ will result in impedance mismatch while relatively large $W$ will narrow the impedance bandwidth. Hence, $W$ should be neither too large nor too small and was chosen to be 26 mm.

C. METALLIC REFLECTOR

The metallic ground acts as a reflector, making the antenna radiate unidirectionally. Fig. 16 show the simulated SWR and front-to-back ratio for different ground size $G_L$. It can be observed that the ground length has minor effect on the impedance matching of the antenna. However, it greatly affects the front-to-back ratio since the metallic ground reflects the energy to boresight and reduce the backlobe radiation. As the ground size $G_L$ increases, the front-to-back ratio becomes larger. However, the antenna size cannot be infinitely large due to the requirement of compactness.
Thus, the ground length $G_L$ was chosen to be 190 mm, which is exactly $1\lambda_0$.

VII. CONCLUSION

A novel low-profile dual-polarized magneto-electric dipole antenna with two choices of feeding probes has been proposed and investigated in this paper. The antenna design has a radiating structure which adopts equilateral triangular cavity with small gap on the top as the electric dipole while keeping the original rectangular planar patches as the electric dipole, reducing the antenna thickness to 0.15$\lambda_0$. Each type of the feeding probe has its own merit and demerit in terms of mechanical robustness, performance and assembly tolerance. Measurement result shows that the low-profile ME dipole with dual $\Gamma$-probes has impedance bandwidth of 48% (SWR < 2) from 1.22 to 2 GHz for both ports with port isolation more than 28 dB. Within operating frequency range, its measured boresight gain varies from 8.1 to 10.6 dBi and from 7.9 to 11 dBi for port 1 and 2, respectively. The antenna design with flat $\Gamma$-probes has a similar performance. Both designs have excellent unidirectional radiation patterns with low cross-polarizations ($< -23$ dB) and back-radiation level. With low profiles and good electrical characteristics, the proposed antenna will find applications in various wireless communication systems.

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REFERENCES

CHEN DING (S’16) was born in Weifang, Shandong, China. He received the B.S. degree in mathematics from The Chinese University of Hong Kong, in 2012, and the M.S. degree in electronic and information engineering from the City University of Hong Kong, in 2015, where he is currently pursuing the Ph.D. degree in electrical engineering with the Department of Electrical Engineering.

He joined the industry as an Electronic and Software Engineer, from 2012 to 2014. From 2015 to 2016, he was a Research Assistant with the State Key Laboratory of Millimeter-Waves, City University of Hong Kong. His current research interests include low-profile antennas, millimeter-wave antennas, circularly-polarized antennas, and antenna measurement methods. He is the First Prize Winner of Best Student Paper Award at the IEEE International Symposium on Antennas and Propagation (AP-S 2019) which was held in Atlanta, USA, in 2019. He is also the Winner for the Best Student Paper Prize at the Asia-Pacific Microwave Conference (APMC 2019) held in Singapore, in 2019.

KWAI-MAN LUK (M’79–SM’94–F’03) 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, as a Lecturer, in 1985. Two years later, he moved to the Department of Electronic Engineering, The Chinese University of Hong Kong, where he spent four years. In 1992, he returned to the City University of Hong Kong, where he served as the Head of the Department of Electronic Engineering, from 2004 to 2010, and the Director of the State Key Laboratory of Millimeter Waves, from 2008 to 2013, where he is currently the Chair Professor of electronic engineering. He is the author of four books, 11 research book chapters, over 360 journal articles, and 250 conference articles. His recent research interests include design of patch antennas, magneto-electric dipole antennas, dense dielectric patch antennas, and open resonator antennas for various wireless applications.

Prof. Luk is a Fellow of the UK Royal Academy of Engineering, the Chinese Institute of Electronics, PRC, the Institution of Engineering and Technology, U.K., the Institute of Electrical and Electronics Engineers, USA, and the Electromagnetics Academy, USA. He was awarded ten US and more than ten PRC patents on the design of a wideband patch antenna with an L-shaped probe feed. He received the Japan Microwave Prize at the 1994 Asia Pacific Microwave Conference held in Chiba, in December 1994, the Best Paper Award at the 2008 International Symposium on Antennas and Propagation held in Taipei, in October 2008, and the Best Paper Award at the 2015 Asia-Pacific Conference on Antennas and Propagation held in Bali, in July 2015. He was awarded the very competitive 2000 Croucher Foundation Senior Research Fellow in Hong Kong. He also received the 2011 State Technological Invention Award (2nd Honor) of China. He was a recipient of the 2017 IEEE APS John Kraus Antenna Award. He was the Technical Program Chairperson of the 1997 Progress in Electromagnetics Research Symposium (PIERS), the General Vice-Chairperson of the 1997 and 2008 Asia-Pacific Microwave Conference (APMC), the General Chairman of the 2006 IEEE Region Ten Conference (TENCON), the Technical Program Co-Chairperson of 2008 International Symposium on Antennas and Propagation (ISAP), and the General Co-Chairperson of 2011 IEEE International Workshop on Antenna Technology (IWAT), and the General Co-Chair of 2014 IEEE International Conference on Antenna Measurements and Applications (CAMA) and the 2015 International Conference on Infrared, millimeter, and Terahertz Waves (IRMMW-THz 2015). He is also the General Chair of the 2020 Asia-Pacific Microwave Conference to be held in Hong Kong, in November 2020. He was the Chief Guest Editor for a special issue on Antennas in Wireless Communications published in the Proceedings of the IEEE, in July 2012. He is also the Deputy Editor-in-Chief of PIERS Journals and an Associate Editor of the IET Microwaves, Antennas and Propagation.