Textile Antenna With Simultaneous Frequency and Polarization Reconfiguration for WBAN

SHAKHIRUL MAT SALLEH1, MUZAMMIL JUSOH2, (Member, IEEE), ABDUL HAFIIZH ISMAIL1, MUHAMMAD RAMLEE KAMARUDIN3, (Senior Member, IEEE), PHILIP NOBLES3, MOHAMAD KAMAL A. RAHIM4, (Senior Member, IEEE), THENNARASAN SABAPATHY2, MOHAMED NASRUN OSMAN2, MOHD ILMAN JAIS2, AND PING JACK SOH2, (Senior Member, IEEE)

1Faculty of Engineering Technology, Department of Electronic Engineering Technology, Universiti Malaysia Perlis, Padang Besar 02100, Malaysia
2Bioelectromagnetics Research Group, School of Computer and Communication Engineering, Universiti Malaysia Perlis, Arau 02600, Malaysia
3Centre for Electronic Warfare Information and Cyber, Cranfield Defence and Security, Cranfield University, Defence Academy of the United Kingdom, Shrivenham SN6 8LA, U.K.
4Advanced RF and Microwave Research Group, Communication Engineering Department, Faculty of Electrical Engineering, Universiti Teknologi Malaysia, Skudai 81310, Malaysia

Corresponding author: Muhammad Ramlee Kamarudin (ramlee.kamarudin@cranfield.ac.uk)

ABSTRACT
This paper proposes the design of a reconfigurable circularly polarized textile antenna. The circular polarization feature in the proposed antenna is generated by the edge truncation of a rectangular patch and the incorporation of a slotted ground plane, whilst the frequency reconfigurability feature is realized by slot size modification via the use of three embedded RF p-i-n diode switches. Consequently, the antenna operation can be switched between six frequencies (1.57, 1.67, 1.68, 2.43, 2.50, and 2.55 GHz) depending on the seven switch configurations. The proposed antenna is validated experimentally to be operable within the WBAN, WLAN, and GPS range in a compact and wearable format, with gains of up to 4.8 dBi.

INDEX TERMS
Circularly polarized antenna, reconfigurable antenna, textile antenna.

I. INTRODUCTION
A reconfigurable antenna is defined as an antenna with the capability to reconfigure one or more characteristic such as frequency, polarization and/or pattern in order to fulfill a specified requirement. Such antennas are capable of offering flexible operation across different frequency bands using a single hardware which is compact, flexible, and cost-effective without compromising performance. In recent years, frequency-reconfigurable antennas have received attention among the researcher and industry communities, especially for future wireless communication systems. Such operation of frequency reconfigurable antenna is potentially capable to reduce the size of front end system and also intended for performances improvement, especially to minimize interference with other wireless system and maximizing throughput [1].

Generally, the resonant frequency of an antenna is determined by the effective length of the radiator. There are several methods of switching that may be used to control the effective length such as; varying the patch [2], [3]; a reconfigurable matching network [4]; changing the current flow [5]; mechanical configuring using a metasurface [6]; and varying the length of the slot [7].

A reconfigurable monopole patch antenna proposed in [2] is capable of switching between up to eight different frequency bands using four PIN diodes. These RF switches are used to connect the main patch to four different smaller patches to enable the total radiating area of the antenna. Meanwhile, the antenna in [4] proposed a reconfigurable matching network using only two PIN diodes. As a result, three different frequencies bands can be realized. However, such method consumes more space for the intended matching and allows limited frequency reconfiguration. The current flow modification technique is described in a reconfigurable cedar-shaped microstrip antenna presented in [5]. Frequency re-configurability is controlled via six RF switches placed on the slits, hence altering the current flow of the cedar-shaped radiator. While copper strips are used to represent switches in this work, greater complexity is expected when this antenna is implemented using PIN diodes. Another alternative to embedded switching circuits for the purpose of enabling frequency re-configurability is by using metasurfaces [6].
The proposed metasurface located on top of a patch is rotated around the center to enable frequency reconfiguration.

Overall, the method of achieving frequency reconfiguration can be categorized in two groups, namely patch modifications and ground plane modifications. In particular, the second category is more attractive since the DC biasing networks will have minimal effect on other characteristics of the antenna, such as cross polarization and radiation pattern. This is evident in [7] where the proposed antenna is capable of achieving frequency reconfiguration with minimal effect on cross polarization. Further investigations are conducted in the work presented here to introduce other antenna configurations. The contributions from this work can be summarized as follows. Firstly, the proposed antenna does not only can reconfigure frequency, but is also capable of switching polarization from CP to linear polarization. Secondly, a method to achieve frequency reconfiguration with specified lower frequency (1.575 GHz) and upper frequency (2.45 GHz) is proposed. Finally, an in-depth investigation is conducted of the location of the slots on the ground plane to ensure the antenna operates at 1.575 GHz with good axial ratio (AR) bandwidth. The presented reconfigurable antenna is fully fabricated using textiles to enable ease of integration with clothing and to ensure users’ comfort [8], [9]. This design was initially studied in [10] using ideal switch representation (copper strips), while its simulated axial ratio and radiation patterns were discussed in [11]. The design was then re-optimized and fabricated using three actual PIN diodes embedded on its ground plane. This design is capable of operating in dual-polarized mode: in circular polarization in the lower band (1.575 GHz) and in linear polarization in the upper frequency band (2.45 GHz) compared to [12] and [13] which are only linearly polarized. The simulated and measured performance of the antenna will be presented in the following sections.

II. ANTENNA DESIGN CONFIGURATION AND ANALYSIS

The methodology illustrated in Fig. 1 is used to design the proposed antenna. In this work, the frequency reconfigurable antenna is specifically designed to operate with $f_{\text{min}}$ of 1.575 GHz and $f_{\text{max}}$ of 2.45 GHz. Therefore, a simple and useful design strategy is proposed in this work, as follows. First, the conventional rectangular patch antenna is designed to operate at 1.575 GHz. Next, the antenna is modified with a truncation [denoted as r] to obtain circular polarization. The next step is the introduction of a slot on the ground plane of the antenna. The slot dimension, width and length are optimized to obtain $f_{\text{max}}$ resonance at 2.45 GHz. Finally, the position of the slot is parametrically shifted along the $\pm y$ axis to investigate the changes on reflection coefficient and axial ratio. With this strategy, an optimized slot location to result in the best axial ratio bandwidth can be identified. In the next stages, the positioning of the switches and modification of the ground plane for DC biasing network are performed. A detailed design and antenna analysis will be performed in the following subsection.

A. PARAMETER OPTIMIZATION OF THE CIRCULARLY POLARIZED (CPTA)

This section describes the technical procedure employed when designing the circularly polarized microstrip antenna based upon the truncation of two diagonal corners of a square.
In order to achieve circular polarization operation at 1.575 GHz, an analysis of the truncation lengths is performed by varying from 8 mm, 10 mm, 12 mm, 14 mm, 16 mm to 18 mm, as illustrated in Fig. 2.

Comparison of the six different truncation lengths as shown in Fig. 3 indicates that the antenna only achieved operation at 1.575 GHz using lengths of 10 mm, 12 mm and 14 mm. The best reflection coefficient of $-18.77$ dB is achieved using a truncation length of 12 mm, with an impedance bandwidth from 1.54 GHz to 1.60 GHz. Meanwhile, the truncation lengths of 10 mm and 14 mm also achieved satisfactory reflection coefficients of $-11.28$ dB and $-16$ dB, respectively. Further analysis for these selected lengths will consider the axial ratio to ensure the circular polarization feature of the antenna.

Fig. 4 shows the simulated axial ratios for six different truncation lengths, indicating that the truncated length of 14 mm results in CP behavior. Specifically, an axial ratio of 0.13 dB at 1.575 GHz with an AR bandwidth from 1.56 GHz to 1.62 GHz. Truncation lengths of 12 mm and 16 mm resulted in an axial ratio of 4.16 dB and 5.26 dB, which does not meet the minimum 3 dB requirement. Thus, the truncation length of 14 mm is chosen and used for further analysis.

### B. Optimizing the Slot Position on the Ground Plane of the Antenna

The key parameter impacting on in this design is the position of the slot on the ground plane. As discussed in [7], it is...
possible to configure the frequency by optimizing the slot size. However, the proposed antenna by author Majid is designed for linear polarization only. Unlike the antenna developed in this work, which needs to maintain a circular polarization pattern at 1.575 GHz. Thus, Fig 5 shows the analysis of different slot positions on the antenna ground plane.

Fig 6 indicates that the operating frequency shifts in line with changing slot position. The slot positions of 104 mm, 24 mm and 95 mm have lower operating frequencies of 1.68 GHz, 1.71 GHz and 1.86 GHz. Meanwhile, the slot positions of 86 mm, 77 mm and 68 mm produce a resonant frequency at 2.10 GHz, 2.41 GHz and 2.81 GHz respectively. The other slot positions do not achieve an operating frequency between 1 GHz to 3 GHz. The changing slot position changes the geometry of the antenna and affects the surface current behavior. By locating the slot towards the top or bottom edges of the antenna, the geometry of the antenna reflection to
the patch remains similar and the antenna achieves a certain operating frequency. However, when the slot is placed at the middle of the ground plane, the geometry of the antenna is divided into two parts and the surface current behavior changes. For this geometry, none of the slot positions achieve the targeted operating frequency as the main consideration is to achieve a CP pattern while the frequency can be configured by adding switching.

The slot positions of 41 mm, 32 mm and 24 mm resulted in less than 3 dB of AR, with AR bandwidths centered at 1.575 GHz, as shown in Fig 7. Specifically, slot position 41 mm resulted in an AR bandwidth from 1.56 GHz to 1.58 GHz, slot position 32 mm from 1.56 GHz to 1.59 GHz and 24 mm from 1.57 GHz to 1.58 GHz.

**C. OPTIMIZATION OF THE FREQUENCY-RECONFIGURABLE TEXTILE ANTENNA USING PIN DIODES**

This section provides a brief description of the proposed antenna structure and its principal of operation with respect to the switched PIN diode configuration. The main challenge in designing this antenna is to enable frequency reconfiguration whilst maintaining circular polarization at 1.575 GHz. Therefore, the reconfigurable antenna must be designed with care to ensure the circular polarization property of the antenna is not altered with each switching condition.

The frequency re-configurability feature is enabled by varying the total length of the ground plane slot. Initially dimensioned with a width and length of 2 and 84 mm, respectively, the three BAR50–02V PIN diodes located along this slot are switched between ON and OFF states to enable different effective slot lengths. The other optimized antenna dimensions are the feed length, $B = 22$ mm, feed width, $C = 7$ mm, the ground plane slot position at $d = 23$ mm, and the positions of $\text{Switch 2}$ and $\text{Switch 3}$ at $e = 11$ mm.

![FIGURE 11. Simulated and measured axial ratios for different configurations: (a) T1 and T3, (b) T5 and T7, and (c) T2, T4 and T6.](image)

![FIGURE 12. Surface current distribution of the proposed antenna with configuration T7: (a) 0° phase, (b) 90° phase, (c) 180° phase, and (d) 270° phase.](image)
Another four 0.5 mm vertical slots connect the horizontal slots and the edge of the ground plane for DC biasing circuitry purposes. Twelve RF capacitors, each with a value of 100 pF are mounted along these four vertical slots to preserve RF current flow on the ground plane whilst blocking direct current (DC). Conversely, DC is used to switch the PIN diodes to the ON state.

The geometry of the optimized frequency-reconfigurable textile antenna is shown in Fig 8. Metallic elements (ground and patch) are fabricated using ShieldIt Super which is 0.17 mm thick with an estimated conductivity of $1.18 \times 10^5$ S/m [15]. Felt is used as its substrate, with 1.7 mm thickness and measured permittivity ($\varepsilon_r$) of 1.22 at 1.575 GHz and 1.18 at 2.45 GHz. The dimensions of the patch are $L_p \times W_p = 83$ mm, and it is placed on a substrate of size $L_s \times W_s (113 \times 99$ mm$^2$) for operation at 1.575 GHz. The two opposite corners are truncated with $A$ of 14 mm to obtain circular polarization [14].

### III. Results and Discussion

In Fig 10, the prototype of the proposed antenna shown in Fig 9 is compared to simulations in terms of reflection coefficient ($S_{11}$) for different switch configurations. Results indicate satisfactory matching with at least $-10$ dB of $S_{11}$ at each frequency band. The slight deviation between the simulated and measured reflection coefficients tabulated in Table 2 is due to small fabrication inaccuracies of the PIN diodes. Also, the additional thickness of the self-adhesive upon the rear of the ShieldIt Super textile may affect its final performance.

The current distribution of the antenna is simulated and shown in Fig 12. At 0$^\circ$ phase, the majority of current is going downwards while at 90$^\circ$ phase, the current turns clockwise towards the left. The current flows move in a clockwise direction at 180$^\circ$ and 270$^\circ$ phase, indicating a left handed CP. Fig 13 depicts the simulated and measured radiation patterns for configurations $T_2$ and $T_7$. Overall, the proposed antenna features a directional pattern in the lower band of 1.57 GHz for both configurations. Meanwhile, these configurations produce a bidirectional and omnidirectional pattern at the higher frequency of 2.45 GHz. Simulations indicated relatively higher gains at 1.575 GHz which decline with increase in frequency. The measured gain of the proposed antenna varies from 0.2 dBi to 4.8 dBi and efficiency varies from 17.1% to 47.2%. Table 2 indicated the summarized simulated and measured of resonant frequency, bandwidth, gain and efficiency of proposed antenna.

Table 3 summarizes the performances of the available reconfigurable frequency/polarization antenna. The first two antenna comparison [6], [7] are designed for frequency configuration only. While, the following two antennas [16], [17] only can perform polarization configuration. The antennas design from [18] and [19] are capable to performed frequency and polarization reconfigurable. Where, the polarization covers the Vertical Linear Polarization (VLP), Horizontal Linear Polarization (HLP), Right-Hand Circular

<table>
<thead>
<tr>
<th>Research By</th>
<th>Frequency Configuration</th>
<th>Polarization Configuration</th>
<th>Material Used</th>
<th>Flexible</th>
</tr>
</thead>
<tbody>
<tr>
<td>[7]</td>
<td>1.98 GHz - 3.41 GHz</td>
<td>None</td>
<td>Taconic RF35</td>
<td>No</td>
</tr>
<tr>
<td>[6]</td>
<td>4.77GHz – 5.51 GHz</td>
<td>None</td>
<td>Roger R04350B</td>
<td>No</td>
</tr>
<tr>
<td>[16]</td>
<td>None</td>
<td>RHCP, LHCP</td>
<td>RT/duroid 5880</td>
<td>No</td>
</tr>
<tr>
<td>[17]</td>
<td>None</td>
<td>LP, RHCP, LHCP</td>
<td>Taconic RF35</td>
<td>No</td>
</tr>
<tr>
<td>[18]</td>
<td>1.17 GHz – 1.58 GHz</td>
<td>VLP, HLP, RHCP, LHCP</td>
<td>Arlon AD450</td>
<td>No</td>
</tr>
<tr>
<td>[19]</td>
<td>1.5 GHz – 2.4 GHz</td>
<td>LVP, HLP, RHCP, LHCP</td>
<td>Roger 5880 RT</td>
<td>No</td>
</tr>
<tr>
<td>Proposed Antenna</td>
<td>1.57 GHz – 2.64 GHz</td>
<td>LP, LHCP</td>
<td>Felt fabric</td>
<td>Yes</td>
</tr>
</tbody>
</table>

TABLE 3. Comparison of the proposed reconfiguration simultaneous frequency and polarization reconfiguration textile antenna with previous researches.
Polarization (RHCP) and Left-Hand Circular Polarization (LHCP). However, it can be noticed that most previous antenna fabricated using rigid board material. This may result the uncomfortable to user while applying in to the human body. In contrast, the approach proposed antenna in this work using fabric material and compromise the use for on/off wireless body application. Most importantly, the previous reported wearable antennas usually do not have the configuration future like frequency or polarization in single antenna.

IV. CONCLUSION

In this paper, a frequency reconfigurable textile antenna has been presented. This design has successfully achieved frequency re-configurability through modification of the slot at the ground plane. The slot size is controlled by three embedded RF PIN Diode switches on the intersection of the underneath slot. The proposed antenna is capable of varying the operating frequency from 1.54 GHz to 2.82 GHz with a ratio of 1.83:1. In addition, the antenna achieves circular polarization at certain frequencies. The proposed design has the potential to improve wireless communication systems that require multiple frequencies with the ability to perform CP suitable for GPS and WiFi applications.

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REFERENCES


SHAKHIRUL MAT SALLEH received the bachelor’s and master’s degrees in communication engineering from Universiti Malaysia Perlis (UniMAP), in 2013 and 2016, respectively. He is currently a Lecturer with the Department of Electronic Engineering Technology, Faculty of Engineering Technology, UniMAP. His research interests include antenna design, textile antennas, wearable antennas, reconfigurable antennas, and wireless communication systems.

MUZAMMIL JUSOH received the bachelor’s degree in electrical, electronic and telecommunication engineering and the M.Sc. degree in electronic telecommunication engineering from Universiti Teknologi Malaysia (UTM), in 2010 and 2006, respectively, and the Ph.D. degree in communication engineering from Universiti Malaysia Perlis (UniMAP) in 2013. He was an RF and Microwave Engineer with the Telekom Malaysia Berhad (TM) Company from 2006 to 2009. He was an Engineer (Team Leader) with the Specialized Network Services Department, TM Senai, Johor. He was involved in the preventive and corrective maintenance of ILS, NDB, DVOR, repeater, microwave system, VHF, and UHF based on contract wise. He was with the Department Civil Aviation, TUDM, PDRM, ATM, Tanjung Pelepas Port, MCMC, and IPS (Hidrologi Department). He is currently an Associate Professor and a Researcher with the School of Computer and Communication Engineering, UniMAP. He is supervising a number of Ph.D. and M.Sc. students and also managing a few grants under the Ministry of Higher Education Malaysia. He has published a number of quality journals such as the IEEE Antennas and Wireless Propagation Letters, Microwave and Optical Technology Letters, The International Journal of Antennas and Propagation, Progress in Electromagnetics Research, and Radio Engineering and over 70 conference papers. His research interests include antenna design, reconfigurable antennas, multi-in multi-out, ultra-wideband, and wireless communication systems.
ABDUL HAFIZH ISMAIL received the B.E. and Ph.D. degrees from Ibaraki University, Japan, in 2003 and 2011, respectively, and the M.E. degree from Universiti Teknologi Malaysia, Malaysia, in 2005. He is currently a Senior Lecturer with the Faculty of Engineering and Technology, Universiti Malaysia Perlis. His research interests include vehicle to vehicle communication, multi-in multi-out orthogonal frequency-division multiplexing, cognitive radios, and Internet of Things.

MUHAMMAD RAMLEE KAMARUDIN (M’08–SM’13) received the bachelor’s (Hons.) degree in electrical and telecommunication engineering from Universiti Teknologi Malaysia (UTM), Johor Bahru, Malaysia, in 2003, and the M.S. degree in communication engineering and the Ph.D. degree under the supervision of Prof. P. Hall from the University of Birmingham, Birmingham, U.K., in 2004 and 2007, respectively. He was an Associate Professor at the Wireless Communication Centre, UTM, until 2017. He is currently a Senior Lecturer at the Centre for Electronic Warfare, Information and Cyber, Cranfield Defence and Security, Cranfield University, Defence Academy of the United Kingdom, Shrivenham, U.K. He holds an H-index of 19 (SCOPUS) and over 1420 citations (SCOPUS). He is an author of a book chapter of a book entitled Antennas and Propagation for Body Centric Wireless Communications and has published more than 210 technical papers in journals and proceedings including the IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION, the IEEE ANTENNAS AND WIRELESS PROPAGATION LETTERS, the IEEE Antenna Magazine, the IEEE Access, the International Journal of Antennas and Propagation, Progress in Electromagnetics Research, Microwave and Optical Technology Letters, and Electronics Letters. His research interests include antenna design for 5G, wireless on-body communications, in-body communications (implantable antenna), RF and microwave communication systems, and antenna diversity. He has been a member of IET since 2011, an Executive Member of Antenna and Propagation (AP/MTT/EMC), Malaysia Chapter, and a member of the IEEE Antennas and Propagation Society, the IEEE Communication Society, the IEEE Microwave Theory and Techniques Society, and the IEEE Electromagnetic Compatibility Society. He is also an Associate Editor of Electronics Letters and the IET Microwaves, Antennas and Propagation and an Academic Editor of the International Journal of Antennas and Propagation.

PHILIP NOBLES received the M.Eng. degree in electronic and electrical engineering and the Ph.D. degree from the University of Wales, Swansea, in 1991 and 2000, respectively. In 1991, he joined the Electrical Engineering Department, University of Wales, where his indoor radio propagation research contributed to the IEEE802.11 working group and his work on wireless cameras for the BBC received the Royal Television Society Award. He joined Cranfield University in 1999, where he is currently the Head of the Communications and Networks Group, Centre for Electronic Warfare, Information and Cyber. His current research interests include secure wireless networking, cybersecurity, military communication systems, and Internet of Things.

MOHAMED NASRUN OSMAN was born Jitra, Malaysia, in 1987. He received the electrical engineering degree in telecommunication and the Ph.D. degree in electrical engineering from Universiti Teknologi Malaysia, in 2010 and 2016, respectively. He is currently a Senior Lecturer with Universiti Malaysia Perlis, Malaysia. His research interests include reconfigurable antenna design, RF design, and wireless multi-in multi-out systems.

MOHADILMAN JAIS received the bachelor’s and M.Sc. (Hons.) degrees in communication engineering from Universiti Malaysia Perlis, Malaysia, in 2011 and 2014, respectively, where he is currently pursuing the Ph.D. degree in computer engineering. His research interests include reconfigurable antennas, fuzzy inferences systems, embedded systems, and Internet of Things.

MOHAMAD KAMAL A. RAHIM was born in Alor Setar, Kedah, Malaysia, in 1964. He received the B.Eng. degree in electrical and electronic engineering from the University of Strathclyde, U.K., in 1987, the master’s degree in engineering from the University of New South Wales, Australia, in 1992, and the Ph.D. degree in the field of wideband active antenna from the University of Birmingham, U.K., in 2003. From 1992 to 1999, he was a Lecturer with the Faculty of Electrical Engineering, Universiti Teknologi Malaysia, where he was a Senior Lecturer with the Department of Communication Engineering from 2005 to 2007. He is currently a Professor with Universiti Teknologi Malaysia. His research interests include the design of active and passive antennas, dielectric resonator antennas, microstrip antennas, reflect-array antennas, electromagnetic bandgap, artificial magnetic conductors, left-handed metamaterials, and computer-aided design for antennas.
PING JACK SOH (SM’15) was born in Kota Kinabalu, Malaysia. He received the bachelor’s and master’s degrees in electrical engineering (telecommunication) from Universiti Teknologi Malaysia, in 2002 and 2006, respectively, and the Ph.D. degree in electrical engineering from KU Leuven, Belgium, in 2013. From 2002 to 2004, he was a Test Engineer with Venture Corporation, focusing on hardware and software test solutions for the manufacturing of all-in-one printers. In 2005, he joined Motorola Solutions Malaysia as a Research and Development Engineer. He focused on the characterization and testing of new two-way radios’ antennas and RF front ends. Since 2006, he has been a Lecturer with the School of Computer and Communication Engineering (SCCE), Universiti Malaysia Perlis (UniMAP). He went on leave from UniMAP in 2009 for his research in KU Leuven. He was first a Research Assistant from 2009 to 2013 and then a Post-Doctoral Research Fellow from 2013 to 2014. From 2014 to 2017, he was the Deputy Dean of the Research Management and Innovation Center, UniMAP. He is currently an External Research Affiliate with the ESAT-TELEMIC Research Division, and an Associate Professor with SCCE-UniMAP. He publishes actively in his areas of research interest: conformal antennas, metamaterials, on-body communication, electromagnetic safety and absorption, and wireless and radar techniques for healthcare applications. He was a recipient of the IEEE Antennas and Propagation Society Doctoral Research Award in 2012, the IEEE Microwave Theory and Techniques Society (MTT-S) Graduate Fellowship for Medical Applications in 2013, and the International Union of Radio Science Young Scientist Award in 2015. He received the second place in the IEEE Presidents’ Change the World Competition and the IEEE MTT-S Video Competition in 2013. Two of his co-authored journals received the CST University Publication Award in 2011 and 2012. As an Advisor, his supervised projects have also received prizes such as the first place in the 2015 IEEE Malaysia Section Final Year Project Competition (Telecommunication Track), the first place in the 2016 Innovate Malaysia Design Competition (Motorola Track), and the 2016 IEEE MTT-S Undergraduate Scholarship. He also serves in the IEEE MTT-S Education Committee and the IEEE MTT-S Meetings and Symposiums Committee.