Design of Conformal Spiral Dual-Band Antenna for Wireless Capsule System

KUO LIU\textsuperscript{1,2}, RUIPENG LIU\textsuperscript{1,2}, WENJIE CUI\textsuperscript{1,2}, (Student Member, IEEE), KANGLONG ZHANG\textsuperscript{1,2}, (Member, IEEE), MENGJUN WANG\textsuperscript{1,2}, CHAO FAN\textsuperscript{1,2}, HONGXING ZHENG\textsuperscript{1,2}, (Senior Member, IEEE), AND ERPING LI\textsuperscript{1,3}, (Fellow, IEEE)

\textsuperscript{1}State Key Laboratory of Reliability and Intelligence of Electrical Equipment, Hebei University of Technology, Tianjin 300132, China
\textsuperscript{2}School of Electronics and Information Engineering, Hebei University of Technology, Tianjin 300401, China
\textsuperscript{3}University of Illinois at Urbana-Champaign Institute, Zhejiang University, Haining 314400, China

Corresponding author: Hongxing Zheng (hxzheng@hebut.edu.cn)

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\section*{ABSTRACT}
This paper presents a conformal spiral antenna that is miniaturized and with dual-resonant for the wireless implantable capsule system. The spiral antenna conforms to a swallowable capsule with a radius of 3 mm and a length of 26 mm without occupying the internal space of the capsule. The compact antenna adopts two spiral arms to extend the effective current path for miniaturization. Biocompatible flexible polyimide was used as the dielectric substrate and capsule shell, achieving conformal properties of the antenna as well as compatibility with human tissue. The antenna has been simulated in different environmental models. The bandwidth of the antenna can reach 39.16\% (1.82 GHz-2.76 GHz) and 12.06\% (5.36 GHz-6.06 GHz) at 2.4 GHz and 5.8 GHz. The maximum gains of $-35.2$ dBi and $-28.1$ dBi can be achieved at 2.4 GHz and 5.8 GHz, respectively. In addition, the transmission characteristics of the antenna were experimentally verified in the minced pork and pig intestine. By analyzing the communication link, the communication distance between transceivers at 2.4 GHz and 5.8 GHz can meet 14 m and 5 m. These results show that the proposed antenna is suitable for wireless implantable capsule systems.

\section*{INDEX TERMS}
Implantable capsule system, conformal antenna, dual-resonant, spiral antenna.

\section*{I. INTRODUCTION}
Nowadays, wireless technology is widely used in implantable medical devices as it gets rid of the body from the limitations of wired devices [1]. In recent years, implantable devices can be implanted into the human body for the auxiliary treatment of various diseases, including capsule endoscopes [2], cardiac pacemakers [3], and intracranial pressure monitoring [4].

A wireless implantable capsule system with dual-band wideband antennas is selected for transmission as capsule speculum and cardiac pacemaker, as showing in Fig. 1. The wireless implantable capsule is promising to be used in the digestive system as a capsule speculum, and the heart as a cardiac pacemaker as long as changing its internal structure. The operating band of the proposed antenna could cover 2.42-2.48 GHz and 5.725-5.850 GHz, both of which belong to the industrial, scientific, and medical (ISM) frequency bands [5].

With the development of medical technology, the demand for the transmission of real-time video is greater than for the transmission of simple pictures [6]. The transmission antenna with a wideband should be designed to meet the transmission needs of the implantable capsule system to be able to transmit video and other big data signals in real-time. In addition, to adapt to the complex implanted environment and improve the robustness of the antenna, it is required that the implanted antenna should be achieved...
a wideband [7]. Due to the requirements for high data transfer rates, the life cycle of the implanted system needs to be as long as possible [8]. To extend the battery life, the antenna can be made with dual-frequency or multi-frequency [9]. Features, so that the system has dual-mode working characteristics. Therefore, designing a dual-frequency and broadband implanted antenna has important research value and significance. In [10], a spiral patch, high-dielectric substrate, and an open-end ground slot were used to achieve the multi-frequency at 402 MHz, 1.6 GHz, and 2.4 GHz, and the maximum bandwidth of 219 MHz is obtained. Although this design implements multi-frequency features, the bandwidth is relatively small and takes up some space for implantable devices. In [11], the proposed antenna is designed to operate in 915 MHz and 2.45 GHz with the bandwidth of 107.5 MHz and 560 MHz, by adding an open-ended ground slot, shorting pin, and hexagonal and T-shaped slots in the radiator. Though its bandwidth can be increased, its complex structure increases the dimensions of the device. In studies [12], [13], although dual-band or multi-band characteristics are realized, the problems of narrow bandwidth and large internal space occupied still exist. Due to the limitations of space in implantable devices, how to maintain antenna dual-band and broadband while reducing the space occupied by the antenna is the top priority. Some miniaturization techniques, such as high dielectric constant substrate [14], [15], meandered line [16], spiral line [10], opening slot [17], and adding shorting pins [18], as well as stacked antennas [19], are used to reduce the space. However, these miniaturization technologies usually bring difficulties to the antenna design and production process and still occupy the limited space. Compared with the use of miniaturization, conformal can improve miniaturization performance. The conformal structure can effectively use the surface of the capsule, to avoid competing with the electronic components inside the capsule for the valuable space of capsules [20], [21]. The conformal characteristics are achieved by using flexible materials for bending, such as in studies [22], although the proposed antennas can be conformal with flexible materials, their performance fails to achieve multi-band and wide-band. Based on the above literature considerations, how to design a conformal antenna that has wide dual-band characteristics and reduces the contact area with the internal circuit is a problem worthy of consideration.

In this approach, a dual-band spiral antenna is investigated. It is conformal to a wireless implantable capsule system with the size of $\pi \times 3^2 \times 26$ mm$^3$. We implanted the antenna in the large intestine model and heart simulation model to verify the stability. To ensure safety, the specific absorption rate (SAR) has been analyzed. The entire system is also conducted in the different aforementioned heterogeneous implanted organs. A lot of experiments have been verified our design. Minced pork and pig intestine are used as the measured materials environment to the simulated human body. A significant result has been obtained.

II. DESIGN AND ANALYSIS OF ANTENNA

A. THE STRUCTURE OF THE ANTENNA

The implantable antenna works inside the body; and the size must be small enough, without affecting the surrounding tissues. The conformal structure is one of the best for the antennas which takes up almost no space [23]. The antenna proposed in this work uses a conformal design of the spiral structure and the hemispherical structure of the capsule. The structure of the antenna is mainly made up of two spiral arms. One arm is composed of a rectangular patch surrounding a hemispherical function. Another is obtained by rotating the first arm 180 degrees around the center. The hemispherical parameter function is as follows

$$x_t = \sqrt{r^2 - \left(S \times t / 2\pi\right)^2 \times \sin t}$$

(1)

$$y_t = \sqrt{r^2 - \left(S \times t / 2\pi\right)^2 \times \sin t}$$

(2)

$$z_t = S \times t / 2\pi$$

(3)

In the above function, $t$ is a variable, the range of $t$ is $0-\pi \times 2\pi$, $n$ is the number of turns of the spiral, $r$ is the radius of the hemispherical spiral, and $S$ is the pitch. The $x_t$ is the position coordinate function in the $x$-direction of the variable $t$, the $y_t$ is the position coordinate function in the $y$-direction of the variable $t$ and the $z_t$ is the position coordinate function in the $z$-direction of the variable $t$. As illustrated in Fig. 2(a), the two spiral arms relate to two strip lines and are distributed on both sides of the annular dielectric substrate under the spiral arms.

![FIGURE 2. Structure of antenna and wireless implantable capsule, (a) antenna (b) wireless implantable capsule.](image)

The dielectric is polyimide with 0.15 mm thickness which has a relative permittivity $\varepsilon_r$ of 3.5, loss tangent $\tan\delta$ of 0.008. The antenna is installed inside the top of the capsule with a length of $K$ and a diameter of $d$ at both ends of the sphere. The thickness of the outer layer of the capsule is 0.15 mm thick.

B. THE SIMULATION ENVIRONMENT

The wavelength in the human body is shorter than in the free space due to the antenna is affected by the relatively high permittivity of the human tissue, which works to profitably miniaturize the physical size of the antenna [24]. A simple muscle model, a large intestine model, and a heart model were established to simulate different working environments.
Electromagnetic properties of human tissues in various parts are tabulated in Table 1 [25].

| Tissue type   | 2.4GHz | 5.8GHz |
|---------------|--------|--------|
|               | $\varepsilon_r$ | $\delta$ (S/m) | $\varepsilon_r$ | $\delta$ (S/m) |
| Muscle        | 52.791 | 1.705  | 48.485 | 4.962 |
| Fat           | 5.285  | 0.102  | 4.955  | 0.293 |
| Mucous Membrane | 42.923 | 1.5618 | 38.624 | 4.342 |

C. PARAMETER STUDY AND DISCUSSION

We implant the antenna in the single muscle simulation model which dimension is $\pi \times 50 \times 100$ mm$^3$ as shown in Fig. 3. According to the effective current distribution at 2.4 GHz and 5.8 GHz of the antenna in Fig. 4, we can see that different parts of the antenna excite the resonance at different frequencies. We analyze some important antenna structural parameters. Firstly, the antenna mainly depends on the spiral arm radiation, so the spiral arm around the number of turns parameter $n$ and the winding line width $L$ of the spiral arm have a great impact on the performance of the antenna. $|S_{11}|$ with different numbers of turns $n$ and the winding line width $L$ are presented in Fig. 5.

![FIGURE 3. Antenna working in the single muscle simulation model.](image)

It is observed that as the turns of the spiral arm changed, the effective path of the current increased, and the whole operating frequency moved with $n$ changing from 0.85 to 1.6, as shown in Fig. 5 (a). The $|S_{11}|$ with different $L$ is presented in Fig. 5 (b). It is observed the higher frequency point decrease and bandwidth in the low band increases as the winding line width $L$ increases, which means that the change of $L$ has a more obvious impact on the high frequency. According to the above results, the optimal $n$ is 1.35, and the optimal size $L$ is 0.5 mm.

In addition to the spiral arm, we have studied the influence of the size of the ground plane and the width of the antenna’s microstrip. The $|S_{11}|$ with different heights of the ground $H$ is shown in Fig. 6 (a). The $|S_{11}|$ with different widths of the antenna’s microstrip $W$ is shown in Fig. 6(b). The $|S_{11}|$ has not changed much when change the $H$ and $W$, which means that the antenna is stable.

The parameter $n$ affects the bandwidth at 2.4 GHz, and $L$ affects the frequency at 5.8 GHz as shown in Fig. 5.

![FIGURE 4. The effective current distribution of the antenna at (a) 2.4 GHz, and (b) 5.8 GHz.](image)

![FIGURE 5. Simulated $|S_{11}|$ with different the number of turns $n$ and winding line width of the spiral arm $L$. (a) is $n$ with different size, and (b) is $L$ with different size.](image)

We studied the influence of the parameter $n$ on the gain at 2.4 GHz and the influence of parameter $L$ on the gain at 5.8 GHz as shown in Fig. 7. The parameter $n$ and $L$ affects both bandwidth and gains at 2.4 GHz and 5.8 GHz.

According to the above results, the optimal size of the antenna is tabulated in Table 2.

| Dimensions of the proposed system (unit: mm). |
|------------------------------------------------|
| $n$ | $S$ | $L$ | $H$ | $W$ | $d$ | $K$ |
| 1.35 | 1.45 | 0.5 | 1.8 | 1 | 6 | 26 |

D. SIMULATION WITH COMPLEX HUMAN MODEL

After analyzing the parameters of the antenna, the antenna was placed in a more complex simulation environment
FIGURE 6. Simulated $|S_{11}|$ with different the height of the ground $H$ and the width of the antenna’s microstrip $W$, (a) is $H$ with different size, and (b) is $W$ with different size.

FIGURE 7. The influence of the parameters on the gain, (a) is the influence of the parameter $n$ on the gain at 2.4 GHz, and (b) is the influence of the parameter $L$ on the gain at 5.8 GHz.

FIGURE 8. The environment of the proposed system is a capsule speculum working in the large intestine model.

FIGURE 9. The environment of the proposed system as a cardiac pacemaker working in the heart model.

FIGURE 10. Simulation of antenna $|S_{11}|$ in different environments.

III. RADIATION PERFORMANCE EVALUATION

A. RADIATION PERFORMANCE AT DIFFERENT ORIENTATIONS

When the antenna enters the human digestive tract, its position and orientation will be changed. We study the radiation-performance stabilities in different environments, including the human large intestine and heart models. The large intestine model is established to simulate the environment inside the human body, and the heart model is used to simulate the working environment of a cardiac pacemaker. The large intestine model consists of fat, muscle, and mucosa membrane from the outermost layer to the innermost layer, with thicknesses of 15 mm, 20 mm, and 30 mm, respectively. The heart model consists of fat, outer mucosa membrane, muscle, and internal mucosa membrane with thicknesses of 10 mm, 5 mm, 10 mm, and 35 mm, respectively. The simulation models are a cylinder with a height of 100 mm and a sphere with a radius of 60 mm, respectively. The simulation results show that the proposed antenna can perform stably in these different environments due to the stability of the antenna structure and the protective effect of the capsule shell.
pattern in different orientations 0, 45, and 90 degree-directed as shown in Fig. 11. The radiation patterns at 2.4 GHz are shown in Fig. 12. By increasing the direction angle, the antenna radiation pattern is changed. The gains at 2.4 GHz are $-35.2 \, \text{dBi}$, $-35.0 \, \text{dBi}$ and $-35.0 \, \text{dBi}$ at orientations 0, 45 and 90 degree-directed, respectively. The gains at 5.8 GHz are $-28.1 \, \text{dBi}$, $-27.6 \, \text{dBi}$ and $-25.9 \, \text{dBi}$ at orientations 0, 45 and 90 degree-directed, as shown in the Fig. 13. And the peak radiation efficiencies at 2.4 GHz and 5.8 GHz are 1.23 % and 1.47 %, respectively. So high-quality performance of the antenna can be ensured at different capsule orientations inside the body.

![FIGURE 11. The system is inserted inside the model with three typical orientations of 0 degree, 45 degree, and 90 degree-directions.](image)

![FIGURE 12. Simulated 2D far-field patterns with three typical implant orientations at 2.4 GHz, (a) is 0 degree, (b) is 45 degree-directions, (c) is 90 degree-directions.](image)

![FIGURE 13. Simulated 2D far-field patterns with three typical implant orientations at 5.8 GHz, (a) is 0 degree, (b) is 45 degree-directions, (c) is 90 degree-directions.](image)

**B. THE SAR OF SYSTEM**

The safety problem of the implantable antenna should be considered, where the specific absorption rate (SAR) is usually regarded as the evaluation standard for the implantable antenna, that the SAR levels averaged over 1-g of human tissue should be less than 1.6 W/kg [25]. Fig.14 displays the SAR of the antenna in different simulation models at 2.4 GHz. The simulation models are the large intestine and heart simulated models as shown in Fig. 8 and Fig. 9. The maximum averaged SAR in 1-g of the large intestine and the heart at 2.4 GHz and 5.8 GHz are listed in Table 3 when the input power is 1W. According to the results, we can calculate the maximum input power of the antenna in the large intestine simulation model and heart simulated model at 2.4 GHz and 5.8 GHz when the SAR of the antenna is less than 1.6 W/kg. The SAR and the max allowed input power are listed in Table 3.

![FIGURE 14. SAR of the antenna in the simulation model at 2.4 GHz, (a) in the large intestine simulated model, (b) in the heart simulated model.](image)

![FIGURE 15. SAR of the antenna in the simulation model at 5.8 GHz, (a) in the large intestine simulated model, (b) in the heart simulated model.](image)

**TABLE 3. Maximum SAR values (input power = 1 W) and allowed input power for the antenna in the large intestine and heart.**

| Frequency | Maximum SAR(W/kg) | Maximum allowed power (mW) |
|-----------|-------------------|----------------------------|
| 2.4 GHz   | large intestine   | heart                      |
| 5.8 GHz   | 802.3             | 868.2                      |

The comparison with the proposed antennas in the previous work is displayed in Table 4. Compared with other dual-band or multi-band antennas, the proposed antenna achieved wide dual-band and conformality.

**IV. MEASUREMENT RESULTS ANALYSIS**

Fig 16 is the antenna designed according to Table 2, measured in minced pork and pig intestine. The antenna is composed of a radiating patch wrapped around the capsule shell to verify the performance of the designed antenna structure.

Fig. 17 is the simulated and measured $|S_{11}|$ of the antenna in minced pork and pig intestine, and the result shows the bandwidth of the antenna could cover 2.42-2.48GHz and
TABLE 4. Compared of the proposed antenna with prior work.

| Ref. | Frequency (MHz) | BW (MHz) | Gain (dBi) | SAR (W/kg) | Conformal |
|------|----------------|----------|------------|------------|-----------|
| [2]  | 402            | 110.6(27.5%) | -30.8       | 289.0      | Yes       |
| [6]  | 1200           | 64.8(5.4%)  | -18.7       | 214.9      | Yes       |
| [10] | 402            | 356-504(36.8%) | -30.5       | 588        | No        |
| [11] | 1600           | 1520-1693(10.8%) | -22.6       | 441        | No        |
| [12] | 2450           | 2316-2528(8.7%) | -18.2       | 305        | No        |
| [13] | 915            | 107.5(11.7%)  | -27.65      | 730.07     | No        |
| [15] | 2450           | 560(22.9%)    | -22.99      | 591.40     | Yes       |
| This | 404            | 402-450(0.74%) | -8          | -          | No        |
| work | 1413.5         | 1395-1432(3.3%) | -9          | -          | No        |
|      | 403            | 393-440(11.7%) | -29.7       | 216.6      | Yes       |
|      | 915            | 888-973(9.3%)  | -24.9       | 92.4       | Yes       |
|      | 2450           | 2213-2700(19.9%) | -18.2       | 98.5       | No        |
|      | 902            | 800-1000(22.2%) | -26.71      | -          | No        |
|      | 2400           | 2200-2630(17.9%) | -17.5       | -          | No        |
|      | 2400           | 1820-2760(39.2%) | -35.2       | 258.84     | Yes       |
|      | 5800           | 5360-6060(12.1%) | -28.1       | 802.30     | Yes       |

5.725-5.850 GHz in different environments. Fig. 18 compares the simulated radiation patterns in the large intestine model and heart model and measured radiation patterns. Fig. 18(a) and Fig. 18(b) show the comparison of the simulation results and actual measurement of radiation pattern when the antenna at 2.4 GHz and 5.8 GHz. According to the compare results, the antenna has good radiation characteristics in the simulation and measurement environment.

V. LINK BUDGET ANALYSIS

Since different tissues and organs in the human body have their electrical characteristics, their coal-consuming characteristics will absorb electromagnetic waves. Energy, internal and external objects will reflect, diffract, scatter, and absorb electromagnetic fields to varying degrees, so the communication channel between the implanted antenna and the external device will be more complicated. To prove that the designed antenna can work normally and measure the effective communication distance of the implanted antenna in actual work, it is necessary to analyze the communication link. To simplify the calculation and make a preliminary assessment of the communication performance of the implantable antenna, we simply set the external channel environment as a free-space propagation model, with dB as the unit, the formula of path loss $L_f$ is as follows [26]

$$L_f = 20 \log_{10} \left(\frac{4\pi d}{\lambda}\right)$$

where $d$ is the distance between the transmitting and receiving antennas, and $\lambda$ is the free-space working wavelength. Link margin (LM) with the change of communication distance is used to measure the communication performance of the implanted antenna. The expressions related to the link margin are as follows [26]

$$LM = CNR_{link} - CNR_{required}$$

FIGURE 17. Simulated and measured $|S_{11}|$ of proposed antenna in minced pork and pig intestine.

FIGURE 18. Comparison of the simulated and measured far-field radiation gain patterns. (a) 2.4 GHz. (b) 5.8 GHz.
TABLE 5. Communication link budget-related parameters.

| Parameter                        | 2.4 GHz | 5.8 GHz |
|----------------------------------|---------|---------|
| Transmitter                      |         |         |
| Operating frequency (GHz)        | 2.4 GHz | 5.8 GHz |
| Tx power $P_t$ (dBm)             | 7.60    | 2.60    |
| Tx antenna Gain $G_t$ (dBi)      | -34.0   | -40.4   |
| Receiver                         |         |         |
| Rx antenna Gain $G_r$ (dBi)      | 2.15    | 2.15    |
| Polarization                     | CP      | CP      |
| Ambient temperature $T_a$ (K)    | 293     | 293     |
| Receiver Noise Figure $NF$ (dB)  | 3.5     | 3.5     |
| Boltzmann constant $k$           | $1.38 \times 10^{-23}$ | $1.38 \times 10^{-23}$ |
| Noise power density (dB/Hz)      | -199.95 | -199.95 |
| Signal quality                   |         |         |
| Bit rate $B_r$ (Mb/s)            | 1       | 1       |
| Bit error rate                   | $1.0 \times 10^{-5}$ | $1.0 \times 10^{-9}$ |
| $E_b/N_0$ (ideal-BPSK) (dB)      | 9.6     | 9.6     |
| Coding gain $G_c$ (dB)           | 0       | 0       |
| Fixing deterioration $G_d$ (dB)  | 2.5     | 2.5     |

FIGURE 19. Link budget analysis at 2.4 GHz and 5.8 GHz when antenna works in minced port and pig intestine.

\[
\begin{align*}
\text{CNR}_{\text{link}} &= P_t + G_t - L_f + G_r - N_0 \\
\text{CNR}_{\text{required}} &= E_b/N_0 + 10 \log_{10} B_r - G_c + G_d \\
N_0 &= 10 \log_{10} (k) + 10 \log_{10} (T_i) \\
T_i &= T_0(NF - 1)
\end{align*}
\]

The $\text{CNR}_{\text{link}}$ refers to the ratio of the signal power received by the external antenna at a certain distance and the noise power density when the implanted antenna is transmitted at a certain power. The $\text{CNR}_{\text{required}}$ refers to the carrier-to-noise ratio required by the receiving end to meet the requirements of a certain communication rate and bit error rate and is related to the sensitivity of the receiver. Here we adopt the BPSK modulation method, the bit error rate is required to be less than $1 \times 10^{-5}$, and the bit rate $B_r$ is 1 Mb/s. Currently, the input power of the antenna working at 2.4 GHz and 5.8 GHz frequency is 7.60 dBm and 2.60 dBm, and the external receiving antenna adopts a circularly polarized antenna with a gain of 2.15 dBi. The above other values are listed in Table 5. The above formula can calculate the change of the communication link margin with the distance, as shown in Fig. 19. The transceiver distance reaches 14 m and 5 m when the communication link margin reached more than 20 dB at 2.4 GHz and 5.8 GHz.

VI. CONCLUSION

A spherical spiral structure and the conformal characteristics of the capsule shell are used to design a miniaturized implantable antenna that can be used as a capsule speculum and cardiac pacemaker. The Dual-band feature is implemented at 2.4 GHz and 5.8 GHz. In the simple muscle model established, the influence of the structure of the proposed antenna on the antenna is studied. The actual working environment of the antenna is simulated by building the large intestine model and heart model. The situation of different angular angles of the antenna in the process of the digestive tract system is also considered for simulation. Through the IEEE C95.1-1999 guidelines, the study of SAR ensures the safety of the proposed antenna to patients. Then compared with the previously proposed dual-band implantable antenna, the proposed antenna is distinct from the previously proposed antenna. We made a comparison of measured results in minced pork and pig intestines with the simulation to verify the feasibility of the antenna designed. Finally, by analyzing the communication link, the transceiver distance can reach 14 m and 5 m when the communication link margin reached more than 20 dB at 2.4 GHz and 5.8 GHz.

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CHAO FAN was born in Hunan, China, in 1987. He received the Ph.D. degree in condensed matter physics from the Institute of Semiconductors, Chinese Academy of Sciences, Beijing, in 2015. He is currently working as an Associate Professor with the School of Electronics and Information Engineering, Hebei University of Technology, Tianjin, China. He has more than 30 journal articles on the fields of low-dimensional electronic systems, opt-electron devices, and radiofrequency devices based on low-dimensional materials.

HONGXING ZHENG (Senior Member, IEEE) received the Ph.D. degree in electronic engineering from Xidian University, Xi’an, China, in 2002. He is currently a Professor with Hebei University of Technology, Tianjin, China. He has authored six books and book chapters and more than 200 journal articles and 100 conference papers. He holds 50 Chinese patents, issued in 2020. His current research interests include wireless communications, the design of microwave circuits and antennas, and computational electromagnetics.

He is also a Senior Member of the Chinese Institute of Electronics (CIE). He received the Young Scientists Award, in 2008, presented by the Tianjin Municipality, China.

ERPING LI (Fellow, IEEE) received the Ph.D. degree in electrical engineering from Sheffield Hallam University, Sheffield, U.K., in 1992. From 1993 to 1999, he was a Senior Research Fellow, the Principal Research Engineer, an Associate Professor, and the Technical Director at Singapore Research Institute and Industry. In 2000, he joined Singapore National Research Institute of High-Performance Computing as the Principal Scientist and the Director of the Department of the Electronic and Photonics. He also holds the post of a Distinguished Professor at Zhejiang University. He authored or coauthored more than 400 papers, published in various conference proceedings, and two books. His research interests include electrical modeling and design of micro/nano-scale integrated circuits, 3-D electronic package integration, and nano-plasmonic technology.

He is a fellow of the MIT Electromagnetics Academy, USA. He has received numerous awards including the IEEE Electromagnetic Compatibility (EMC) Richard Stoddard Award for Outstanding Performance. He has served as an Associate Editor for a number of IEEE TRANSACTIONS AND LETTERS. He has served as the general chair and the technical chair for many international conferences. He was the founding General Chair for the 2008, 2010, and 2012 Asia-Pacific EMC Symposium. He has been invited to give numerous invited talks and plenary speeches at various international conferences and forums.