Wireless Sensing for Monitoring of Coal Gangue Mixing Based on PT Symmetry

HAOYAN XI1,5, YONG DONG2,3,5, LEI ZHANG4, YANHONG LIU1,5, XIAOQIANG SU1,5, CAIXIA FENG1,5, FENG ZANG1,5, LIJUAN DONG1,5, AND YUNLONG SHI1,5

1Institute of Solid State Physics, Shanxi Datong University, Datong 037009, China
2Institute of Theoretical Physics, Shanxi University, Taiyuan 030006, China
3State Key Laboratory of Quantum Optics and Quantum Optics Devices, Shanxi University, Taiyuan 030006, China
4College of Coal Engineering, Shanxi Datong University, Datong 037009, China
5Shanxi Province Key Laboratory of Microstructure Electromagnetic Functional Materials, Shanxi Datong University, Datong 037009, China

Corresponding authors: Lijuan Dong (donglijuan_2012@163.com) and Yunlong Shi (shiyunlong@aliyun.com)

This work was supported in part by the National Natural Science Foundation of China under Grant 11874245, in part by the Key Research and Development Projects in Shanxi Province under Grant 201903D121026, in part by the Central Government Guides Local Science and Technology Development Funds under Grant YDZJSX2021B011, and in part by the Shanxi Province Higher Education Science and Technology Innovation Program Project under Grant 2020L0466.

ABSTRACT The challenge in using fully mechanized caving mining technology for thick coal seam mining is monitoring the mixing ratio of coal gangue during the top coal caving process. In this paper, we propose a passive wireless sensing system based on the second-order parity-time symmetric system operated around the exceptional point for the monitoring of coal gangue mixing, which has an LC resonance structure consisting of a spiral resonant coil and a parallel-plate capacitor at the wireless sensing end of the system. The parallel capacitor was designed as a sampling platform. When different proportions of the coal gangue mixture are placed on it, the capacitance value of the capacitor changes, changing the resonance frequency of the system. Our results indicated that the passive wireless sensing system could clearly distinguish the degree of mixing of the coal and gangue and has a higher sensitivity than the conventional system. The proposed system was compared with a mosquito resonant coil system of the same order, and the results indicated that the spiral resonant coil wireless sensing system has more significant advantages in the enhancement of sensitivity. This passive wireless sensing system provides an accurate method for the automatic identification of coal gangue in the top coal caving process; furthermore, it is inexpensive and highly operable.

INDEX TERMS Coal gangue mixture, passive wireless sensing, second-order PT symmetry system.

I. INTRODUCTION

Fully mechanized caving mining (FCM) technology is widely used for mining thick coal seams (\( \geq 3.5 \) m) in China [1]–[3]. Although this technology has the characteristics of a high yield and high efficiency, it largely relies on manual control in the top coal caving process [4]. Owing to the dusty working conditions of coal mining, it brings safety problems to the workers operating at the site. Additionally, it is difficult to accurately determine the mixing ratio of coal gangue of top coal manually, which inevitably leads to over-recovery or under-recovery conditions during the top coal caving process [5]. Over-recovery degrades the coal quality, and under-recovery reduces the coal recovery rate [4]. Therefore, the automatic identification of the coal gangue mixing degree in the FCM coal mining process is beneficial for increasing the coal recovery rate and enhancing the coal quality and the level of automation of the mining process. Thus, it plays a vital role in realizing ‘unmanned’ coal mining.

In recent years, wireless sensing technology has attracted the attention of many researchers and has been investigated in many fields. Wireless sensors as the functional devices, which can be used for non-contact continuous operation in harsh or closed environments where wired connections are not possible, because they do not require internal power sources [6], [7]. For coal mining industry, most wireless sensors are used to monitor underground environmental parameters [8], such as mine gases [9], [10], temperature [11] and dust [12]. There is almost no monitoring of the mixing ratio of coal gangue during the top coal caving process.

The passive wireless sensors based on the LC (Inductor-capacitor) resonance offer a solution. In 1967, Collins [13]
implemented an implantable intraocular pressure sensor using miniature spiral inductors and pressure-sensitive capacitors. Passive wireless sensors based on LC resonance have undergone rapid development in the past few decades and have been widely used in industrial (tire-pressure monitoring [14], [15], radiofrequency identification [16]) and medical (ocular-pressure monitoring [17]–[19], bone-healing monitoring [20], physiological monitoring [21]–[25]) applications. LC passive wireless sensors use inductive coupling of coils for energy transfer and data transmission, on the basis of the shift of the resonance frequency, i.e., the detuning changes in the inductive or capacitive elements to be measured (pressure [15], [17]–[19], [26], stress [27], temperature [28], [29], humidity [29], [30], etc.) [7], [31]. In 2018, Escobedo et al. [32] connected an inductive coil to a capacitive humidity sensor in series to form an LC resonant system. The dielectric constant of the humidity-sensitive material of the humidity sensor changed with respect to the humidity, which affected the capacitance of the temperature sensor, changing the resonance frequency of the LC resonant humidity sensor. This allowed wireless monitoring of the humidity. However, when the change to be measured was small, the shift in the resonance frequency was also small. Hence, the sensitivity of the sensor must be increased if monitoring of minute changes in the system is required.

Recent advances in non-Hermitian physics and parity-time (PT) symmetry have revealed that in optics and photonics, the eigenvalues, and the corresponding eigenvectors merge simultaneously around the PT phase transition point (exceptional point, EP) [33]–[35]. EP is distinctive features of non-Hermitian systems. They exchange energy with the environment and exhibit significantly amplified responses to small perturbations in gain- and loss-controlled systems, and they can be used to design resonant sensors with high sensitivities [35]–[37]. In addition, external perturbations dependent square root behavior of eigenfrequency splitting has been experimentally observed, according to the EP characteristics of optical resonators with second-order PT symmetry [38]. Similarly, for LC passive wireless sensors at the microwave end, the characteristic of eigenfrequency splitting leads to a shift in the resonance frequency of the system with respect to the square root of the external perturbation, when the change to be measured is applied to the second-order EP.

In this study, we designed a spiral LC passive wireless sensing system based on the second-order EP and applied the system to the top coal caving process to achieve the monitoring of the gangue content in the coal gangue mixture.

II. THERORITICAL MODEL FOR SECOND-ORDER PT SYMMETRIC SYSTEMS

The theoretical model of a second-order PT symmetric system is shown in Fig. 1, which consists of two linearly arranged passive resonators. The two resonators have the same resonance frequency $\omega_0$ and intrinsic loss $\Gamma$ and are subject to the same external radiation $\gamma$, where the transmitter resonator (blue circle) receives the input wave $\omega$. The nearest-neighbor coupling between the two resonators is $\kappa$. The equations of motion of this system can be described by coupled-mode theory [39], [40], as follows:

$$\frac{da_1}{dt} = (-i\omega_0 - \gamma - \Gamma) a_1 - i\kappa a_2 + \sqrt{2}\gamma s_{1+},$$  
(1)

$$\frac{da_2}{dt} = (-i\omega_0 - \gamma - \Gamma) a_2 - i\kappa a_1,$$  
(2)

where $a_{1,2} = A_{1,2} e^{-i\omega t}$ represents the resonant mode in each coil. The reflected waves are expressed as:

$$s_{1-} = -s_{1+} + \sqrt{2}\gamma a_1.$$  
(3)

By setting the zero reflected wave, substituting $s_{1-} = 0$ into Eq. (1), (2) and (3), the eigenvalues [41],[42] when solving for the perfect absorption state can be obtained:

$$H \left( \begin{array}{c} a_1 \\ a_2 \end{array} \right) = \omega \left( \begin{array}{c} a_1 \\ a_2 \end{array} \right).$$  
(4)

Here, the effective Hamiltonian quantity is:

$$H = \left( \begin{array}{cccc} \omega_0 + i\gamma - i\Gamma & \kappa \\ \kappa & \omega_0 - i\gamma - i\Gamma \end{array} \right).$$  
(5)

An ideal Hamiltonian can be established in this open system without considering the intrinsic losses $\Gamma$. The complex eigenfrequencies of the perfect absorbing states in the second-order PT symmetric system can be determined directly from the quadratic algebraic equation by solving for $|\omega I - H| = 0$:

$$\Delta^2 + \gamma^2 - \kappa^2 = 0.$$  
(6)

In Eq. (6), $\Delta = \omega - \omega_0$. When the radiation loss $\gamma$ and the coupling strength $\kappa$ satisfy the critical condition of $\gamma = \kappa$ simultaneously, the two eigenmode frequencies are concatenated at $\omega - \omega_0$. The second-order PT symmetric EP is achieved under this critical condition, which is called the second-order EP. If a perturbation $\varepsilon$ is added to the blue resonator, Eq. (1) and (2) becomes:

$$\frac{da_1}{dt} = (-i\omega_0 - \gamma - \Gamma - i\varepsilon) a_1 - i\kappa a_2 + \sqrt{2}\gamma s_{1+},$$  
(7)

$$\frac{da_2}{dt} = (-i\omega_0 - \gamma - \Gamma) a_2 - i\kappa a_1.$$  
(8)

Then, considering the normalization parameter ($\Gamma = 1$, $\gamma = \kappa = 0$), the corresponding effective Hamiltonian is

$$H = \left( \begin{array}{cc} \omega_0 + \varepsilon + i & 1 \\ 1 & \omega_0 - i \end{array} \right).$$  
(9)
Solving again for $|\omega I - H| = 0$, the complex eigen-frequency of its absorbing state is obtained as

$$\Delta = \frac{\epsilon}{2} \pm \sqrt{\frac{1}{4} \epsilon^2 + i \epsilon}. \quad (10)$$

Using a previously reported method [43], the following was obtained:

$$\text{Re}(\Delta_{EP2}) \sim \epsilon^{1/2}. \quad (11)$$

Eq. (11) indicates that the resonance-frequency shift around the EP of the second-order PT symmetric system has a 1/2 power relationship with the external perturbation.

### III. STRUCTURAL DESIGN OF SECOND-ORDER PT SYMMETRIC SYSTEM

A schematic of the structure of a spiral passive wireless sensing system based on second-order EP for coal gangue mixing monitoring is presented in Fig. 2(a), and Fig. 2(b) shows the structure of each component. The excitation coil, transmitter coil, receiver coil, and load coil were arranged from bottom to top, and a parallel-plate capacitor was connected to the transmitter coil in series. The transmitter and receiver coils were resonant coils, and according to the second-order EP theory and optimized experimental debugging, the two resonant coils were selected from a three-turn spiral structure with a wire diameter of 2 mm, a ring inner diameter of 136 mm, and a ring spacing of 10 mm, and all were loaded with an adjustable capacitor of 30 (±10) pF. And the structure of the resonant coils is obtained through multiple simulation optimizations. The two pole plates of the parallel-plate capacitor were 50 mm apart, and the thickness, length, and height of each pole plate was 1, 100, and 40 mm, respectively. These plates formed a LC resonant system with the transmitter coil, when different proportions of the coal gangue mixture are placed on plates, the capacitance value of the capacitor changes, changing the resonance frequency of the system. The excitation and emission coils were two identical non-resonant coils, each having a wire diameter of 2 mm and a ring diameter of 150 mm, which were connected to Ports 1 and 2, respectively, of the vector network analyzer (VNA) for monitoring the reflected spectrum $S11$.

The experimental setup for the passive wireless sensing system is presented in Fig. 3. As shown, four coils were placed on the same axis and were fixed on a transparent acrylic plate, and the two resonant coils had the same distance from each of the two non-resonant coils. The structure of the resonant coils and the details of the 30 pF fixed capacitor and 10 pF adjustable capacitor connected in series are presented on the right side of Fig. 3. The non-resonant coils were loaded with a 50 Ω small version A (SMA) at the opening and connected to the VNA at both ports via coaxial lines. During the experimental operation, the second-order PT symmetric system was supplied with the amount of perturbation causing capacitance change $\epsilon$, by placing different proportions of gangue mixture samples (as shown in Tab. 1) between the two poles of the parallel-plate capacitor. And, the coal and gangue samples were taken from Xiaotashan Coal Mine in Datong City, China.

### IV. EXPERIMENTAL PROTOCOL AND RESULTS

First, we investigated the conventional spiral passive wireless sensing system, as shown in Fig. 4(a), which features a single-turn excitation coil connected to a VNA, forming the active
monitoring end, and a multi-turn receiver coil connected in series with fixed and a tunable capacitor and a parallel-plate capacitor, forming the passive sensing end. The parameters of each component were consistent with those for the aforementioned second-order PT symmetric system. For the conventional system, when the samples between the two pole plates of the parallel-plate capacitor were all coal samples, the optimal value of the reflection spectrum $S_{11}$, i.e., the value at the resonance frequency, was determined according to theoretical guidance and experimental optimizations. Then, the gangue content of the samples between the two pole plates were varied sequentially from 10% to 100%, as shown in Tab. 1, and the results obtained are presented in Fig. 4(b). The dielectric constant of gangue exceeds that of coal, and according to the equation:

$$ f_n = \frac{1}{2\pi \sqrt{L_S(C_S+C_n)}}. \tag{12} $$

the resonance frequency of the conventional spiral passive wireless sensing system decreases with an increase in the gangue content. The trend of the leftward shift of the resonance frequency in Fig. 4(b) was consistent with this equation. In Eq. (12), $L_S$ represents the transmitter-coil inductance, $C_S$ represents the capacitance of the parallel-plate capacitor, and $C_n$ (the subscripts correspond to the test sequence numbers in Tab. 1) represents the varying capacitance under different gangue contents.

To simplify the problem, by expressing $\epsilon$ as a small perturbation acting on the frequency, a first-order linear relationship was obtained from Eq. (12):

$$ \epsilon = |f_n - f_0| \sim f_n \sim C_n, \tag{13} $$

where $|f_n - f_0|$ represents the resonance-frequency shift. Fig. 4(c) and (d) show the resonance frequency $f_n$ and the resonance-frequency shifts $|f_n - f_0|$, respectively, for different gangue contents. The red solid lines are first-order linear fitting curves. As shown, the resonance frequency and its shift for the conventional spiral passive wireless sensing system had a first-order linear relationship with the gangue content.

Then, the second-order spiral system was investigated according to the results for the conventional spiral passive wireless sensing system. When the gangue content in the mixed sample was 0, the position of the EP of this second-order system was determined by adjusting the distance between the coils, as shown in the image of the perturbation $\epsilon$ for 0 in Fig. 5(a). At this time, the positions of the four coils were fixed. The coal gangue mixture samples of different proportions were placed in sequence, and the reflection spectra measured at different perturbation intensities ($\epsilon$) were obtained, as shown in Fig. 5(a). With an increase in the perturbation $\epsilon$, the reflection spectrum gradually shifted to the left, and a new obvious resonance peak appeared on the right side. The former phenomenon occurred because the dielectric constant of the gangue was larger than that of the coal, and the latter occurred because the change in
the coupling strength between the two resonant coils due to the change in the gangue mixture content around the EP of the second-order system led to the splitting of the intrinsic frequency, which was consistent with the theoretical result of Eq. (10). As the perturbation \( \varepsilon \) increased, the splitting tendency became increasingly obvious.

Fig. 5(b) presents the resonance-frequency offset \( |f'_n - f'_0| \) in Fig. 5 alongside the theoretical \( \varepsilon^{1/2} \) curve calculated using Eq. (11). As shown, the two agreed well. The results shown in Fig. 5(c) were obtained by taking the logarithmic coordinates of the values in Fig. 5(b). The experimental test results for the second-order spiral passive wireless sensing system had the same slope as the red curve (\( y = \varepsilon^{1/2} \)), which agreed with the theoretical results corresponding to Eq. (9). This finding indicated that for the second-order spiral passive wireless sensing system, the shift of the resonance frequency \( |f'_n - f'_0| \) had a 1/2 power relationship with the perturbation \( \varepsilon \). The same result was observed around the EP of the second-order PT system.

To clarify the advantages of the proposed second-order spiral passive wireless sensing system, the results were compared with those for a second-order mosquito passive wireless sensing system. The structure of the mosquito system is shown in Fig. 6; the difference from the second-order spiral system was the different winding of the resonant coil. The inner ring diameter of the resonant coil was 68 mm, the ring spacing was 20 mm, the wire diameter of the non-resonant coil was 100 mm, the resonant coil was loaded with a fixed capacitor of 40 pF and an adjustable capacitor of 10 pF, and the remaining parameters were similar to those for the second-order spiral system. The experimental test results for the second-order mosquito passive wireless sensing system are shown in Fig. 7. Once again, the reflection spectrum gradually shifted to the left and exhibited a distinct resonance peak as the gangue content increased, and the resonance-frequency shift \( |f'_n - f'_0| \) and the perturbations \( \varepsilon \) were also consistent with a 1/2 power relationship.

Subsequently, we analyzed and compared the experimental test results of two passive wireless sensing systems, second-order spiral and second-order mosquito, as shown in Fig. 8. Fig. 8(a) and (b) give the comparative plots of the resonance frequency \( f'_n \) and the sensitivity enhancement factor \( |f'_n - f'_0|/\varepsilon \) of the systems for the two systems with different gangue contents, respectively. In the second-order spiral and mosquito passive wireless sensing systems, the initial frequencies were 27.320 and 27.532 MHz for 0% gangue content \( X \), and the resonance frequencies were 26.994 and 26.990 MHz for 100% gangue content \( X \). The resonance frequencies of the two systems decreased by 0.326 and 0.542 MHz, respectively, from 0% to 100% gangue content \( X \).

From Fig. 8(b), the sensitivity enhancement factor of both systems \( |f'_n - f'_0|/\varepsilon \) decreased with the increase in gangue content \( X \) in the sample mixture of coal gangue. This result showed that the lesser the gangue content, the greater the sensitivity enhancement factor obtained by the passive wireless sensing system, based on the second-order PT symmetric system, i.e. the smaller the amount of perturbation the easier it was to identify. At the same time, it can be seen that the sensitivity enhancement factors of the second-order spiral and mosquito passive wireless sensing systems were 8.45, 4.38, 3.26 and 6.36, 2.87, 2.19, respectively, when the content \( X \) of gangue in the measured samples was 10%, 50% and 90%, and this result indicated that the sensitivity enhancement factor of the second-order spiral system was greater than that of the second-order mosquito system. This is due to the high quality factor of the spiral self-resonant coil. A higher quality factor means a system with higher sensitivity and resolution [37]. Therefore, the spiral passive wireless sensing system based on the second-order PT symmetric system proposed in this paper was more advantageous in coal gangue mixing ratio monitoring.
the following fitting functions correspond to the spiral and mosquito systems, respectively, with lines in Fig. 8(a), where the black and red solid lines correspond to the spiral and mosquito systems, respectively, and the two curves in (a) are fitted curves.

According to these two equations, the relationship between the gangue content X and the resonance frequency y is obtained as follows:

\[ X(\%) = -49.8 \ln \left( \frac{y - 26.953}{0.346} \right) \]
\[ X(\%) = -66.6 \ln \left( \frac{y - 26.877}{0.628} \right) \]

where \( X = x \times 100 \). Hence, for mixed samples with unknown proportions of gangue, according to the resonance frequency y measured by the system, Eq. (16) and (17) can be used to predict the gangue contents, to achieve the monitoring of such samples.

V. CONCLUSION

A spiral passive wireless sensing system for coal gangue mixing ratio monitoring based on the theoretical model of the second-order PT symmetric system was proposed. When the system was operated around the second-order EP, the amount of perturbation acting on the intrinsic frequency of coal gangue mixture samples with different contents exhibited a 1/2 power relationship with the shift in the resonance frequency of the system, which increased the sensitivity of the system. Additionally, the spiral system always had a larger sensitivity enhancement factor than the mosquito system. The relationship between the gangue content and the resonance frequency of the system was determined by fitting the experimental data; thus, the monitoring of mixed coal gangue samples was realized. The results of this study have implications for numerous capacitive passive wireless sensors that would be ubiquitous in the Industrial Internet of Things, Healthcare Systems, Cultural Relic monitoring, and even Bionic Robotics applications.

ACKNOWLEDGMENT

The authors would like to thank the Shanxi Province Key Laboratory of Microstructure Electromagnetic Functional Materials and MOE Key Laboratory of Advanced Micro-Structured Materials, Tongji University for their comprehensive support.

REFERENCES

[1] S.-H. Tu, Y. Yong, Y. Zhen, X.-T. Ma, and W. Qi, “Research situation and prospect of fully mechanized mining technology in thick coal seams in China,” Proc. Earth Planet. Sci., vol. 1, no. 1, pp. 35–40, Sep. 2009, doi: 10.1016/j.proeps.2009.09.008.
[2] Q. Zou and B. Lin, “Fluid–solid coupling characteristics of gas-bearing coal subjected to hydraulic slotting: An experimental investigation,” Energy Fuels, vol. 32, no. 2, pp. 1047–1060, Feb. 2018, doi: 10.1021/acs.energyfuels.7b02358.
[3] Y. Ling, L. Li, X. Li, K. Wang, J. Chen, Z. Sun, and X. Yang, “Study on roof-coal caving characteristics with complicated structure by fully mechanized caving mining,” Shock Vibrat., vol. 2019, p. 6519213, Apr. 2019, doi: 10.1155/2019/6519213.
[4] J. Wang, “Development and prospect on fully mechanized mining in Chinese coal mines,” Int. J. Coal Sci. Technol., vol. 1, no. 3, pp. 253–260, Oct. 2014, doi: 10.1007/s40789-014-0017-2.
[5] Y. Yang, Q. Zeng, G. Yin, and L. Wan, “Vibration test of single coal gangue particle directly impacting the metal plate and the study of coal gangue recognition based on vibration signal and stacking integration,” IEEE Access, vol. 7, pp. 106784–106805, 2019, doi: 10.1109/ACCESS.2019.2932118.
[6] A. Deivasigamani, A. Daliri, C. H. Wang, and S. John, “A review of passive wireless sensors for structural health monitoring,” Modern Appl. Sci., vol. 7, no. 2, p. 57, Jan. 2013, doi: 10.5539/mas.v7n2p57.
[7] C. Li, Q. Tan, P. Jia, W. Zhang, J. Liu, C. Xue, and J. Xiong, “Review of research status and development trends of wireless passive LC resonant sensors for harsh environments,” Sensors, vol. 15, no. 6, pp. 13097–13109, Jun. 2015, doi: 10.3390/s150613097.
[8] L. Muduli, D. P. Mishra, and P. K. Jana, “Application of wireless sensor network for environmental monitoring in underground coal mines: A systematic review,” J. Netw. Comput. Appl., vol. 106, pp. 48–67, Dec. 2018, doi: 10.1016/j.jnca.2017.12.022.
[9] Z.-C. Zhu, G.-B. Zhou, and G.-Z. Chen, “Chain-type wireless underground mine sensor networks for gas monitoring,” Adv. Sci. Lett., vol. 4, no. 2, pp. 391–399, Feb. 2011, doi: 10.1166/asl.2011.1241.

[10] G. Zhou, P. Zhang, Z. Zhu, and S. Xia, “Congestion avoidance for band-typed wireless sensor networks in coalmine tunnel,” in Proc. Int. Conf. Sens. Netw., Wuhan, China, Jan. 2015, pp. 55–58.

[11] Q. Zhao, Y.-H. Zhang, Y.-C. Ji, Z.-A. Huang, and Y. K. Gao, “Mechanism research and application on distributed optical fibre temperature measurement in coalmine goaf area based on the sensor network,” Int. J. Sens. Netw., vol. 20, no. 2, pp. 104–110, Feb. 2016, doi: 10.1051/isn/2016074699.

[12] O. Mahdvipour, T. Mueller-Simons, D. Fahimi, S. Crosheere, P. Pilatsch, J. Menkh, V. Z. Baruffa, J. Sabino, K. Tran, G. Alanis, P. Solomon, P. Wright, R. M. White, and L. Gundel, “Wireless sensors for automated control of total incombustible content (TIC) of dust deposited in underground coal mines,” in Proc. IEEE SENSORS, Busan, South Korea, Nov. 2015, pp. 1–4.

[13] C. C. Collins, “Miniature passive pressure transensor for implanting in the eye,” IEEE Trans. Biomed. Eng., vol. BME-14, no. 2, pp. 74–83, Apr. 1967, doi: 10.1109/TBME.1967.4522474.

[14] R. Matsuzaki and A. Todoroki, “Passive wireless strain monitoring of tires using capacitance and tuning frequency changes,” Smart Mater. Struct., vol. 14, no. 4, p. 56, May 2005, doi: 10.1088/0964-1726/14/4/014.

[15] R. Matsuzaki and A. Todoroki, “Wireless flexible capacitive sensor based on ultra-flexible epoxy resin for strain measurement of automobile tires,” Sens. Actuators A, Phys., vol. 140, no. 1, pp. 32–42, Oct. 2007, doi: 10.1016/j.sna.2006.07.014.

[16] X. Hu, K. Aggarwal, M. X. Yang, K. B. Parizi, X. Xu, D. Akin, A. S. Y. Poon, and H.-S.-P. Wong, “Micrometer-scale magnetic-resonance-coupled radio-frequency identification and transceivers for wireless sensors in cells,” Phys. Rev. A, vol. 86, no. 1, Jul. 2012, doi: 10.1103/PhysRevA.86.014031.

[17] P.-Y. Chen, D. C. Rodger, S. Saati, M. S. Humayun, and Y.-C. Tai, “Micro-fabricated implantable parylene-based wireless passive intraocular pressure sensors,” J. Microelectromech. Syst., vol. 17, no. 6, pp. 1342–1351, Dec. 2008, doi: 10.1109/JMEMS.2008.2004945.

[18] P.-Y. Chen, S. Saati, R. Varma, M. S. Humayun, and Y.-C. Tai, “Wireless intraocular pressure sensing using microfabricated minimally invasive flexible-coiled LC sensor implant,” J. Microelectromech. Syst., vol. 19, no. 4, pp. 721–734, Aug. 2010, doi: 10.1109/JMEMS.2010.2049825.

[19] J. Kim, M. Kim, M.-S. Lee, K. Kim, S. Ji, Y.-T. Kim, J. Park, K. Na, K.-H. Bae, H. K. Kim, F. Bien, C. Y. Lee, and J.-U. Park, “Wearable smart sensor systems integrated on soft contact lenses for wireless ocular diagnostics,” Nature Commun., vol. 8, no. 1, pp. 1–8, Apr. 2017, doi: 10.1038/s41467-017-00595-9.

[20] S. Sauer, U. Marschner, B. Adolph, B. Clasbrummel, and W.-J. Fischer, “Passive wireless resonant Galfenol sensor for osteosynthesis plate bending measurement,” IEEE Sensors J., vol. 12, no. 5, pp. 1226–1233, May 2012, doi: 10.1109/JSEN.2012.2167747.

[21] M. S. Mannoor, H. Tao, J. D. Clayton, A. Sengupta, D. L. Kaplan, R. R. Naik, N. Verma, F. G. Omenetto, and M. C. McAlpine, “Graphene-based wireless bacteria detection on tooth enamel,” Nature Commun., vol. 3, no. 1, pp. 1–9, Mar. 2012, doi: 10.1038/ncomms1767.

[22] L. Y. Chen, B.-C.-K. Lee, A. L. Chortos, G. Schwartz, V. Tes, D. J. Lipomi, H.-S. P. Wong, M. V. Mconnell, and Z. Bao, “Continuous wireless pressure monitoring and mapping with ultra-small passive sensors for health monitoring and critical care,” Nature Commun., vol. 5, no. 1, pp. 1–10, Oct. 2014, doi: 10.1038/ncomms6028.

[23] S. Niu, N. Matsuhiwa, L. Beker, J. Li, S. Wang, J. Wang, Y. Jiang, X. Yan, Y. Yun, W. Burnett, A. S. Y. Poon, J. B.-H. Tok, X. Chen, and Z. Bao, “A wireless body area sensor network based on stretchable passive tags,” Nature Electron., vol. 2, no. 8, pp. 361–368, Aug. 2019, doi: 10.1038/s41928-019-0286-2.

[24] R. Lin, H.-J. Kim, S. Achavanantadith, S. A. Kurt, S. C. C. Tan, H. Yao, B. C. K. Tee, J. K. W. Lee, and J. S. Ho, “Wireless battery-free body sensor networks using near-field-enabled clothing,” Nature Commun., vol. 11, no. 1, pp. 1–10, Jan. 2020, doi: 10.1038/s41467-020-14311-2.

[25] M. Dautta, M. Alshetaiwi, A. Escobar, F. Torres, N. Bernardo, and P. Tseng, “Multi-functional hydrogel-interlayer RF/NFC resonators as a versatile platform for passive and wireless biosensing,” Adv. Electron. Mater., vol. 6, no. 4, Apr. 2020, Art. no. 1901311, doi: 10.1002/aem.201901311.
HAOYAN XI was born in Linfen, Shanxi, China, in 1998. He received the B.S. degree in electronic information engineering from Shanxi Datong University, Datong, China, in 2020, where he is currently pursuing the master’s degree with the Institute of Solid State Physics. His current research interests include passive wireless sensing, wireless power transfer, and electromagnetic metamaterials.

YONG DONG was born in Lvliang, Shanxi, China, in 1998. He received the B.S. degree in theoretical physics from Shanxi Datong University, Datong, China, in 2020. He is currently pursuing the master’s degree with the Institute of Theoretical Physics and the State Key Laboratory of Quantum Optics and Quantum Optics Devices, Shanxi University. His current research interests include condensed matter physics and passive wireless sensing.

LEI ZHANG received the B.S. degree in geographic information system from the Henan University of Technology, Henan, China, in 2006, and the M.S. degree in geological engineering from Guizhou University, Guizhou, China, in 2009. He is currently the Associate Dean of College of Coal Engineering, Shanxi Datong University, Datong, China. His research interests include geological disaster and mine geological engineering.

YANHONG LIU received the M.S. degree in optics from Nankai University, Tianjin, China, in 2006, and the Ph.D. degree in condensed matter physics from Tongji University, Shanghai, China, in 2012. Her research interests include solid state physics and artificially structured materials.

XIAOQIANG SU received the M.S. degree in theoretical physics from Zhejiang Normal University, Zhejiang, China, in 2012, and the Ph.D. degree in optical engineering from Tianjin University, Tianjin, China, in 2016. His research interests include optical materials and artificial surface.

CAIXIA FENG received the Ph.D. degree in radio physics from Shanxi University, Shanxi, China, in 2015. Her research interests include microwave antenna and artificially structured materials.

FENG ZANG received the M.S. and Ph.D. degrees in theoretical physics from Shanxi University, Shanxi, China, in 2009 and 2020, respectively. His research interests include optical soliton theory and propagation characteristics of special beams and their applications.

LIUJIAN DONG received the M.S. degree in theoretical physics from Hebei University, Hebei, China, in 2003, and the Ph.D. degree in condensed matter physics from Tongji University, Shanghai, China, in 2009. Her research interests include condensed matter physics, passive wireless sensing, and artificially structured materials.

YUNLONG SHI received the Ph.D. degree in condensed matter physics from Tongji University, Shanghai, China. From June 2003 to June 2004, he was a Visiting Scholar at the Cavendish Laboratory, Cambridge University, U.K. Since 2004, he has been an Adjunct Professor and a Doctoral Supervisor at Tongji University. From 2000 to 2016, he was the Vice President of Shanxi Datong University. He is currently the Director of the Institute of Solid State Physics and the Honorary Director of the Shanxi Provincial Key Laboratory of Microstructure Electromagnetic Functional Materials.