Planar Sensing Platform with Hexagonal Complimentary Split Ring Resonators Excited by Spoof Surface Plasmon Polaritons and Director Elements

Rishitej Chaparala[1], Y Vijay Kumar[2], Jyoti S[2], Ravisankar Ponnada[2] and Brahmaraju M[2]
[1]SR University, Hasanparthy, Warangal, Pin: 506371, Telangana, India
[2]Department of ECE, Pragati Engineering College, Surampalem, ADB Road, Andhra Pradesh, India

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Abstract: This work presents excitation of hexagonal complimentary split ring resonators (CSRRs), which function as sensor using SSPP and directors. This configuration removes the requirement for transmission lines (TLs) and minimizes the impact of external circuitry on sensing accuracy. A compact design was achieved by developing the complete sensing platform, which includes the CSRRs and director elements, for the C band and integrating them onto a single substrate with dimensions of 151 x 60 x 0.8 mm^3. Investigation results showed a resonant frequency to permittivity variations for Material Under Test (MUT). The measurements indicated that the sensor's $|S_{21}|$ (dB) parameters are influenced by the dielectric properties of the samples.

1 INTRODUCTION

Microwave resonant-based sensors have recently attracted widespread interest for a variety of applications, including biomedicine, chemistry (P. Vélez, J. 2019, M. C. Cebedio, M. Moradpour 2021), water quality control, and aviation (O. Malyuskin, I. Frau, S. R. Wylie, I. Frau, O. Korostynska 2018). These sensors demonstrate strong capabilities in detecting solid, gas, and liquid substances present in their environment (B. D. Wiltshire et al, A. Tricoli, N. Nasiri, B. D. Wiltshire, M. Alijani). Their ability to provide real-time, noncontact detection, combined with low-cost manufacturing, has facilitated their widespread use in industrial applications (M. H. Zarifi, H. Sadabadi, J. Kilpijärvi). Furthermore, microwave sensors can be designed in compact, low-profile configurations with reconfigurable features, making them compatible with CMOS technology and expanding their application range (A. Ebrahimi, W. Liu) A low-cost, low-profile microwave resonator sensor is the planar sensor, typically fabricated using PCB etching technology (A. Ebrahimi et al., O. Korostynska,). Split-ring resonator (SRR) sensors, in particular, have attracted significant attention for their compact design, flexibility, and potential to offer improved sensitivity and resolution (Z. Abbasi, M. H. Zarifi, M. Abdolrazzaghi, M. H. Zarifi). Various excitation methods have been investigated for SRRs, such as transmission lines (TL) and incident plane waves (D. Baena,2005). TL excitation is commonly used in SRR-based sensors due to its compatibility with planar platforms, providing a low-profile design and straightforward implementation. Nonetheless, in the TL-excitation technique, modifications in external circuitry, including the coupling gap, can influence crucial resonant parameters such as frequency, amplitude, and the loaded Q-factor (D. M. Pozar, 2012). Problems occur when a large material obscures the coupling gap between the SRR and TL (K. Luckasavitch) resulting in modified resonant responses and loaded quality factors (QL) that can interfere with the sensing process (M. H. Zarifi). While methods like positive feedback loops have been implemented to mitigate sensor losses and enhance resolution (M. H. Zarifi, J. B. Pendry), The reliance of sensing performance on variations in external coupling circuitry has not been entirely eliminated. To lessen this effect, resonators can be excited using incident plane waves emitted from an

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antenna instead (W. Wang). This approach is similar to the excitation of frequency selective structures (H. Torun, 2019) and effectively separates the resonators from the excitation probes (antennas), thus reducing the impact of external circuitry variations on the resonant characteristics.

Few studies have explored planar sensing platforms based on antenna-driven SRR excitation (S. Zahertar, C. A. Balanis), Recent studies have focused on similar structures that use printed monopoles and loop antennas for excitation. However, these designs place the resonators in the near-field zone of the antennas, resulting in heightened near-field coupling between the SRR and the excitation probes, which can exacerbate the loading effects of external circuitry on the resonators (W. Wang et al). Furthermore, this planar arrangement is analogous to detection methods that employ surface acoustic waves and eddy currents (W. Wang et al.,).

In this study, a planar microwave sensing platform was introduced that employs the excitation of hexagonal CSRRs situated in the Fresnel zone of Yagi-Uda antennas, with all components consolidated onto a single substrate. This approach offers a different excitation mechanism for CSRRs, eliminating the need for transmission lines (TLs) to drive resonator elements in large platforms or arrays of adjacent resonators. By employing SSPP for excitation, the method reduces near-field effects from excitation probes (such as TLs) These factors influence the resonator's performance and field distribution, rendering it beneficial for sensing applications. The Yagi-Uda antenna topology was selected for its simplicity and endfire radiation characteristics (M. N. Abdallah), although other types of endfire radiating antennas could also be utilized. To address polarization mismatch, identical Yagi-Uda antennas were simulated and oriented toward the direction of maximum radiation. The SRR and director elements were strategically placed in the Fresnel zone to minimize near-field coupling with probing structures and transmission lines (TLs) (N. Katsarakis). To enhance intensity, the gaps between the SRR and director elements were aligned with the polarization of the antenna (Hosseini, Arezoo, et al, 2023). Hexagonal CSRRs were used instead of traditional circular SRRs and simulated using CST Microwave Studio software for optimal performance.

2 DESIGN AND PRINCIPLE OF OPERATION

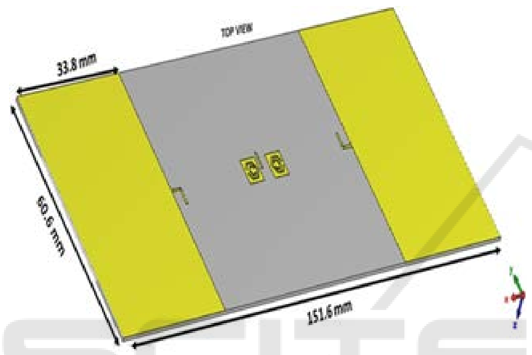
2.1 Designing Spoof Surface Plasmon Polariton (SSPP)

The SSPP feeder element was designed to excite the CSRR, replacing the conventional microstrip feeding technique. The proposed design's top and bottom views are illustrated in Fig. 1(a) and 1(b). It is composed of a single dielectric material, Rogers TMM3. Port 1 of the SSPP structure serves as the input, connecting to the director elements. This sensor operates across a frequency range of 18 GHz. SSPP feeding provides several benefits over microstrip feeding, such as enhanced field confinement, wideband operation, customizable dispersion characteristics, and compact integration. The SSPP structure, acting as the feeding element, features corrugated grooves with heights ranging from 0.5 mm to 3.5 mm on both sides as shown in fig. 1(b). These grooves are fed by a Yagi-Uda antenna, which includes director elements spaced 1.45 mm apart on both sides.

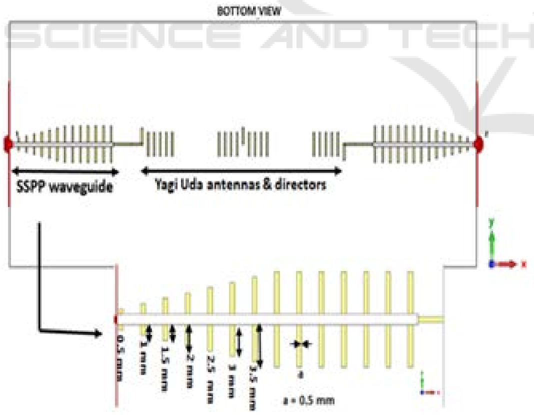
2.2 Excitation and Resonance Characteristics of CSRRs

The design of the sensor features two wide-band YagiUda antennas that act as radiators, in conjunction with planar CSRRs that serve as sensing elements. These components are excited via SSPPs. The structure is simulated using a single dielectric material, Rogers TMM3, and employs SSPP as the feeding element, featuring corrugated grooves with heights varying from 0.5 mm to 3.5 mm on both sides. Fig. 2 shows the hexagonal CSRR positioned at the center of the structure, with four director elements located beneath the resonator. Two planar, concentric CSRRs, composed of metal and having a thickness of 0.035 mm, are placed on the upper plane, accurately positioned at the center to create the sensing region. Furthermore, director elements are positioned on the lower plane, directly under the CSRR, to redirect extra electromagnetic energy for the optimal excitation of the CSRR. A planar configuration is established using an SSPP feed, with radiating elements arranged on both sides. Five director elements are incorporated to produce an end-fire radiation pattern. Additionally, the spacing of the director elements is optimized to improve the field intensity in the sensing region. As shown in Fig. 3, the optimized width of the CSRR gap (g) is 1 mm, along with the following dimensions: W_1 = 1 mm, W_2 = 0.5 mm, W_3 = W4 = 0.5 mm, L_1 = 33.8 mm, L_2 = 5.75 mm, and L_3 = 5.89 mm. The spacing (S_1) between the director elements is 1.45 mm. The outer (r_1) and inner radius (r_2) of the hexagonal CSRR measure 2.4 mm and 1.4 mm, respectively. The CSRR serves as the sensing elements and is expected to absorb the radiated electromagnetic power at the resonant frequency, creating a notch in the transmission coefficient.

3 SIMULATION RESULTS AND DISCUSSION



(a)



(b)

Figure 1: (a) Upper view displaying the CSRR and (b). Lower view of the director elements powered by SSPP feeding.

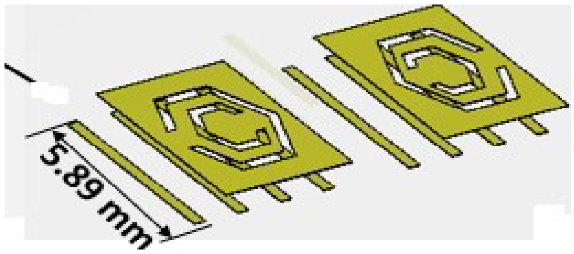


Figure 2: CSRR and below director elements.

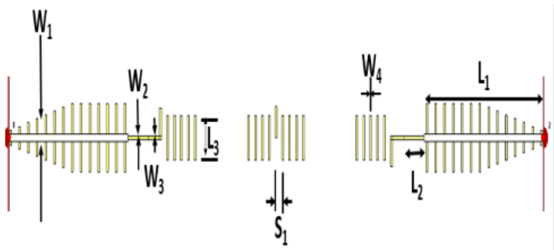


Figure 3: Measurement of director elements serving as radiating components

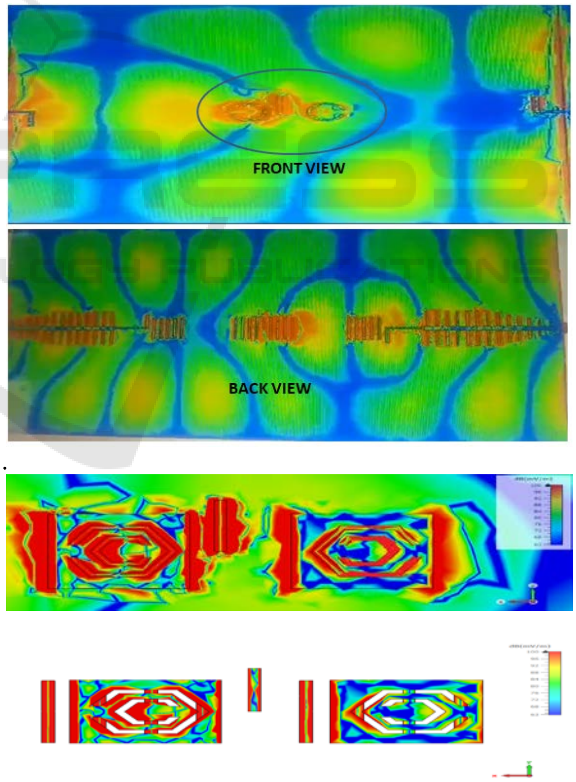


Figure 4: Front and back view showing radiation from director elements fed by SSPPs, with field confinement in hexagonal CSRRs observed in the top view.

The Yagi-Uda array, comprising half-wavelength dipoles and an SSPP feed, was designed to operate within a frequency range of roughly 5 to 8 GHz, enabling a compact physical footprint for the sensing platform. Fig. 4 shows the field confinement on the CSRR sensors at far field region when excited by the SSPP and the directors. At far field they are visualized with the radiating behavior characterized by planar wave fronts indicative of traveling plane waves. To lessen the near-field effects of the radiating and resonating components, the two director elements were adequately spaced apart. The design and simulation of the structure were conducted using CST Microwave studio. Simulation of the sensor was obtained at the frequency of 5.79 GHz, as depicted in Fig. 5. Initially, the design involving two Yagi antennas was simulated to analyze their impact on the transmission coefficient (S_{21}), with results presented in Fig. 5. The integrating CSRR featuring directors positioned at the centre created a stop band notch near its fundamental resonant frequency of 5.7 GHz, achieving amplitude of -38.14 dB. This highlights the crucial role played by the directors in exciting the CSRR by redirecting additional EM power towards them. As a result, the CSRR resonated, minimizing the transmission of power between the antennas and producing a unique band-stop resonance properties. The proposed hexagonal CSRR designed for the sensor application were simulated using the CST Microwave studio transient solver. As shown in Fig. 6 the material under test (MUT), a solid dielectric element, with a relative permittivity ranging from 1 to 5, is positioned on the surface of the two concentric CSRRs. When testing dielectric materials, CSRR can resonate at particular frequencies based on the material's dielectric characteristics, which may prove beneficial for sensing applications, potentially including RFID. Due to their unique electromagnetic properties, CSRR can be used for effective control of resonance, enabling more compact and efficient RFID system designs, especially at microwave and millimetre wave frequencies.

The CSRR sensor is modelled from metal that has a thickness of 0.035 mm. The size of the CSRR sensor is as follows: l × b × h= 5.75×6 ×0.035 mm. The measurement is performed with MUT 1&2 by successively changing the dielectric constant values from 1 to 5. Fig. 7 illustrates the simulated responses for dielectric constant values ranging from 1 to 5. It has been noted that as the dielectric constant rises, the curve moves towards lower frequencies. In RFIDbased sensing systems, CSRRs might be used to detect changes in environmental conditions (like humidity or pressure) by monitoring shifts in resonant frequency as a result of variations in the dielectric material properties. CSRRs with dielectric material testing may not be a typical RFID device, but could be employed in advanced RFID systems, particularly for specialized sensing or antenna miniaturization tasks. The improvements of this work over existing designs are summarized in Table 1. By incorporating SSPP feeding, the operating frequency is reduced compared to conventional design.

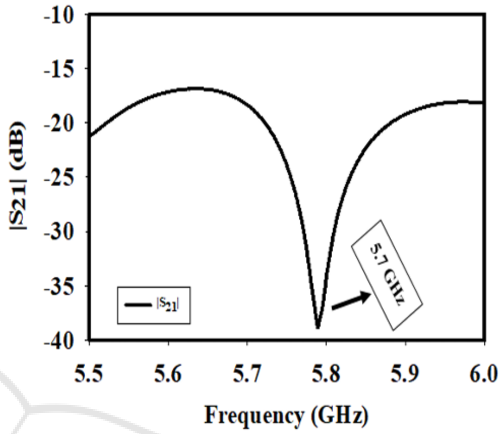


Figure 5: Simulated S_{21} response of the proposed CSRR.

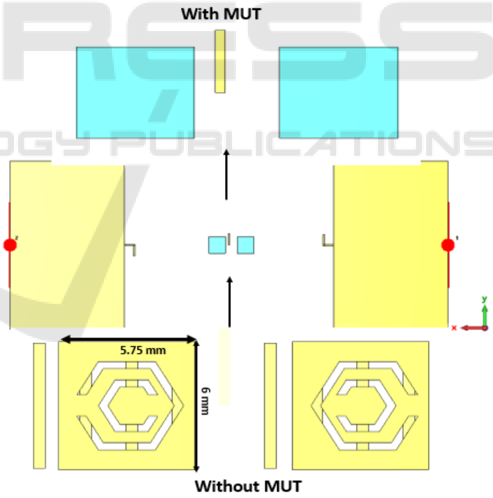


Figure 6: Placement of solid dielectric samples 5.75 × 6 mm on the surface of the two hexagonal CSRR.

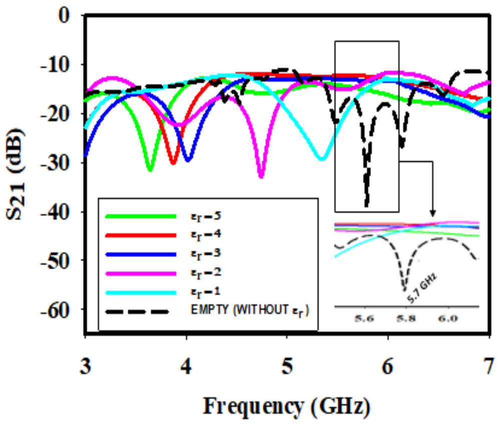


Figure 7: Measured transmission coefficient S_{21} for solid dielectric samples with different relative permittivity values from 1 to 5.

Table 1: Comparison with existing literature works.

Ref	Frequency	Feeding	Sensor	fo (GHz)	$\|S_{21}\|$ (dB)
[27]	1-3 GHz	microstrip	SRRs	1.8	-25 dB
[31]	5-25 GHz	microstrip	MIMO	16	-35 dB
[26]	5-8 GHz	microstrip	Loop sensor	6.6	-25 dB
[34]	14-16 GHz	microstrip	SRRs	15.4	-34 dB
This work	5-8 GHz	SSPP	CSRRs	5.79	-38 dB

4 CONCLUSIONS

A planar configuration combining Complimentary Split Ring Resonators (CSRRs) with Yagi-Uda antennas fed by SSPP was developed and studied for material sensing applications, targeting solid materials. By incorporating the CSRRs and director elements onto a single substrate, the need for transmission lines (TLs) was eliminated. The introduction of CSRRs shared by the director elements created a band-stop notch in the transmission coefficient. Various materials were placed over the sensitive region of CSRRs and the $|S_{21}|$ response in decibels was analyzed to distinguish between them. The results showed a correlation between changes in resonant frequency and the attributes of the solid samples evaluated particularly their dielectric constants and sample sizes. This excitation using director element for CSRR on a planar platform using incident plane waves not only extends the potential for microwave sensors in planar configurations without the need for wiring but also represents a significant advancement in reducing the reliance on external coupling circuitry, such as transmission lines. This sensor is highly appropriate for the application owing to its excellent sensitivity, cost-effectiveness, and ability to provide realtime sensing.

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REFERENCES

P. Vélez, J. Muñoz-Enano, K. Grenier, J. Mata-Contreras, D. Dubuc, and F. Martín, “Split ring resonator-based microwave fluidic sensors for electrolyte concentration measurements,” IEEE Sensors J., vol. 19, no. 7, pp. 2562–2569, Apr. 2019.

M. C. Cebedio, L. A. Rabioglio, I. E. Gelosi, R. A. Ribas,A. J. Uriz, and J. C. Moreira, “Analysis and design of a microwave coplanar sensor for non-invasive blood glucose measurements,” IEEE Sensors J., vol. 20, no. 18, pp. 10572–10581, Sep. 2020

M. Moradpour, E. Hosseini, M. C. Jain, R. Narang, N. Tanguy, and M. H. Zarifi, “Patterned PEDOT: PSS-enabled organic planar microwave resonator sensors,” Appl. Mater. Today, vol. 24, Sep. 2021, Art. no. 101106

O. Malyuskin, “Microplastic detection in soil and water using resonance microwave spectroscopy: A feasibility study,” IEEE Sensors J., vol. 20, no. 24, pp. 14817–14826, Dec. 2020.

I. Frau, S. R. Wylie, P. Byrne, J. D. Cullen, O. Korostynska, and A. Mason, “Functionalised microwave sensors for real-time monitoring of copper and zinc concentration in mining-impacted water,” Int. J. Environ. Sci. Technol., vol. 17, no. 4, pp. 1861–1876, Apr. 2020

I. Frau, O. Korostynska, A. Mason, and P. Byrne, “Comparison of electromagnetic wave sensors with optical and low-frequency spectroscopy methods for real-time monitoring of lead concentrations in mine water,” Mine Water Environ., vol. 37, no. 3, pp. 617–624, Sep. 2018.

B. D. Wiltshire et al., “Oleophobic textiles with embedded liquid and vapor hazard detection using differential planar microwave resonators,” J. Hazardous Mater., vol. 409, May 2021, Art. no. 124945.

A. Tricoli, N. Nasiri, and S. De, “Wearable and miniaturized sensor technologies for personalized and preventive medicine," Adv. Funct. Mater., vol. 27, no. 15, Apr. 2017, Art. no. 1605271

B. D. Wiltshire, M. Alijani, S. Mohammadi, A. Hosseini, J. M. Macak, and M. H. Zarifi, "High-frequency TiO2 nanotube-adapted microwave coplanar waveguide resonator for high-sensitivity ultraviolet detection," ACS Appl. Mater. Interface, vol. 14, no. 4, pp. 6203–6211, Feb. 2022.

M. H. Zarifi, H. Sadabadi, S. H. Hejazi, M. Daneshmand, and A. Sanati-Nezhad, "Noncontact and nonintrusive microwavemicrofluidic flow sensor for energy and biomedical engineering," Sci. Rep., vol. 8, no. 1, p. 139, Jan. 2018

J. Kilpijärvi, N. Halonen, J. Juuti, and J. Hannu, "Microfluidic microwave sensor for detecting saline in biological range," Sensors, vol. 19, no. 4, p. 819, Feb. 2019.

A. Ebrahimi, F. J. Tovar-Lopez, J. Scott, and K. Ghorbani, "Differential microwave sensor for characterization of glycerol– water solutions," Sens. Actuators B, Chem., vol. 321, Oct. 2020, Art. no. 128561.

W. Liu, J. Zhang, and L. Xu, "A transmission line sensor with sensitivity improved for detection of ionic concentration in microfluidic channel," IEEE Sensors J., vol. 21, no. 21, pp. 24066– 24074, Nov. 2021.

A. Ebrahimi et al., "Highly sensitive phase-variation dielectric constant sensor based on a capacitively-loaded slow-wave transmission line," IEEE Trans. Circuits Syst. I, Reg. Papers, vol. 68, no. 7, pp. 2787–2799, Jul. 2021.

O. Korostynska, A. Mason, and A. Al-Shamma'a, "Microwave sensors for the non-invasive monitoring of industrial and medical applications," Sensor Rev., vol. 34, no. 2, pp. 182–191, Mar. 2014.

Z. Abbasi, M. H. Zarifi, P. Shariati, Z. Hashisho, and M. Daneshmand, "Flexible coupled microwave ring resonators for contactless microbead assisted volatile organic compound detection," in IEEE MTT-S Int. Microw. Symp. Dig., Jun. 2017, pp. 1228–1231.

M. Abdolrazzaghi, M. H. Zarifi, and M. Daneshmand, "Wireless communication in feedback-assisted active sensors," IEEE Sensors J., vol. 16, no. 22, pp. 8151–8157, Nov. 2016.

J. D. Baena et al., "Equivalent-circuit models for split-ring resonators and complementary split-ring resonators coupled to planar transmission lines," IEEE Trans. Microw. Theory Techn., vol. 53, no. 4, pp. 1451–1460, Apr. 2005.

D. M. Pozar, Microwave Engineering, 4th ed. Hoboken, NJ, USA: Wiley, 2012.

K. Luckasavitch, R. Kozak, K. Golovin, and M. H. Zarifi, "Magnetically coupled planar microwave resonators for real-time saltwater ice detection," Sens. Actuators A, Phys., vol. 333, Jan. 2022, Art. no. 113245.

M. H. Zarifi, S. Farsinezhad, K. Shankar, and M. Daneshmand, "Liquid sensing using active feedback assisted planar microwave resonator," IEEE Microw. Wireless Compon. Lett., vol. 25, no. 9, pp. 621–623, Sep. 2015.

Mohammadi, K. K. Adhikari, M. C. Jain, and M. H. Zarifi, "Highresolution, sensitivity-enhanced active resonator sensor using substrateembedded channel for characterizing low-concentration liquid mixtures," IEEE Trans. Microw. Theory Techn., vol. 70, no. 1, pp. 576–586, Jan. 2022.

M. H. Zarifi, A. Gholidoust, M. Abdolrazzaghi, P. Shariaty, Z. Hashisho, and M. Daneshmand, "Sensitivity enhancement in planar microwave active-resonator using metal organic framework for CO2 detection," Sens. Actuators B, Chem., vol. 255, pp. 1561–1568, Feb. 2018.

J. B. Pendry, A. J. Holden, D. J. Robbins, and W. J. Stewart, "Magnetism from conductors and enhanced nonlinear phenomena," IEEE Trans. Microw. Theory Techn., vol. 47, no. 11, pp. 2075–2084, Nov. 1999.

W. Wang, Q. Cao, and Y. Zheng, "Bandstop frequency-selective structures based on stepped-impedance loop resonators: Design, analysis, and measurement," IEEE Trans. Antennas Propag., vol. 67, no. 2, pp. 1053–1064, Feb. 2019

H. Torun, F. Cagri Top, G. Dundar, and A. D. Yalcinkaya, "An antennacoupled split-ring resonator for biosensing," J. Appl. Phys., vol. 116, no. 12, Sep. 2014, Art. no. 124701.

S. Zahertar, Y. Wang, R. Tao, J. Xie, Y. Q. Fu, and H. Torun, "A fully integrated biosensing platform combining acoustofluidics and electromagnetic metamaterials," J. Phys. D, Appl. Phys., vol. 52, no. 48, Sep. 2019, Art. no. 485004

C. A. Balanis, Antenna Theroy: Analysis and Design. Hoboken, NJ, USA: Wiley, 2012.

W. Wang et al., "Novel coil transducer induced thermoacoustic detection of rail internal defects towards intelligent processing," IEEE Trans. Ind. Electron., vol. 71, no. 2, pp. 2100–2111, Feb. 2024

W. Wang et al., "Wideband gain enhancement of MIMO antenna and its application in FMCW radar sensor integrated with CMOSbased transceiver chip for human respiratory monitoring," IEEE Trans. Antennas Propag., vol. 71, no. 1, pp. 318–329, Jan. 2023.

M. N. Abdallah, T. K. Sarkar, M. Salazar-Palma, and V. Monebhurrun, "Where does the far field of an antenna start?" IEEE Antennas Propag. Mag., vol. 58, no. 5, pp. 115–124, Oct. 2016.

N. Katsarakis, T. Koschny, M. Kafesaki, E. N. Economou, and C. M. Soukoulis, "Electric coupling to the magnetic resonance of split ring resonators," Appl. Phys. Lett., vol. 84, no. 15, pp. 2943–2945, Apr. 2004.

Hosseini, Arezoo, et al. "Planar Sensing Platform Based on Split Ring Resonators and Microstrip Yagi-Uda Antennas." *IEEE Sensors Journal* (2023).