Minkowski Based Microwave Resonator for Material Detection over Sub-6 GHz 5G Spectrum

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***Abstract*— This paper describes the performance of a low-cost, high-sensitive microwave resonator for 5G modern wireless communication systems operating through sub-6GHz spectrum. Here, the proposed resonator is constructed from a Minkowski fractal open stub that is coupled to an interdigital capacitor. It is fetched to a circular spiral inductor structure with a back loop to increase the resonator quality and it operates at a frequency resonance of 524 MHz. Since the purpose of the study is to apply such technology to characterize liquid properties, the presented resonator is mounted on an FR4 substrate with a thickness of 1.6 mm and an area of 40×60 mm^2. Using CST MWS commercial software, the resulting design dimensions are optimized. The proposed design performance which is demonstrated in terms of S_{21} magnitude is found to vary significantly by the variations in the photo-resistor. Such a property motivated the authors to consider it for material detection as the frequency stability with a photo-resistor value change is relative to the light incidence. In such a manner, the achieved results are found to behave linearly without discrepancy due to the effects of diffraction from the resonator layers. This technology is frequently used as a strong contender for a variety of contemporary wireless technologies that may invoke optical-based interface systems.**

Keywords—Circular spiral inductor, fifth generation (5G) wireless communications interdigital capacitor, Minkowski, back loop, resonator, sub-6 GHz spectrum.

I. INTRODUCTION

Resonator technology has recently made an appearance in a variety of applications, including automobiles, aircraft, business equipment, and even home electronics. Quantifying the interaction of solid, liquid, and gaseous materials inside the fields of an electromagnetic wave is a typical method for measuring their dielectric characteristics [1]. Electrical properties of the materials like permittivity and conductivity can be measured without making contact [2]. There is a vast range of information about liquids, including relaxation processes and molecule orientation polarization, all of which contribute to the liquid's complicated dielectric function and frequency changes. Microwave methods, mostly used in the 1 GHz–10 GHz range, can be used to characterize liquids. The polar nature of liquids causes their molecules to interact with electric fields of the electromagnetic wave at microwave frequencies. This interaction is useful for the characterization of liquids by microwave resonators. In many applications, accuracy in measuring dielectric properties of the liquid remains a challenge. Even though there are variety of microwave resonators proposed to overcome this problem, there are still issues to be resolved. Accuracy, size, cost, simplicity, real-time measurements, and electromagnetic wave transmission efficiency are among the issues addressed. Previous research investigated a microwave-coupled ring resonator with a large dynamic range that might be used in sensing applications [3]. Without volume detection, electromagnetic energy is indicated in [4]. In [5], a microwave microfluidic resonator with a microstrip-line-coupled complementary resonator was investigated. The verification of the sensing principle is based on the computation of the complex permittivity and measurements [6]. The resonator structure used in [7] is a planar microwave resonator with an active feedback loop operating at 1.5 GHz. The flow rate within micro channels is measured in real time, non-contact and non-intrusive, using an innovative flow resonator . The microfluidic device in this case is constructed of a fluidic microchannel that is sealed by a thin polymer layer that connects the fluidics to the microwave electronics [8]. A different strategy is used in [9], with the goal of developing a unique wireless high-resolution resonant-based microwave resonator for chemical sensing applications.

In this paper, the design of a fractal-based resonator for material characterization at 524 MHz is proposed. The proposed resonator shows a significant change in S_{21} magnitude without a significant change in the resonance frequency. This is achieved by introducing an LDR switch to the proposed resonator design.

II. GEOMETRICAL DETAILS

The geometrical features of the proposed resonator are presented in this section. Minkowski based microwave resonator is given in Fig. 1. Resonator consists of a transmission line coupled to an RLC branch network. It is printed on an FR4 substrate with a complete ground plane. The created RLC network is primarily made up of an interdigital capacitor (IDC) in series with a circular spiral inductor (CSI) and connected directly to a photo-resistor, also known as a light-dependent resistor (LDR). The LDR is positioned in the center of the resonator, between two LC branches, where the material under test (MUT) would reside. To eliminate the impact of field fringing from the inductor on the capacitor, two stubs are introduced on the digital capacitors [10]. Furthermore, the recommended stub is included to reduce distortion during the measuring process. This results in a distortion-free transmission line by minimizing the impact of electromotive forces on one port compared to the other [11]. As demonstrated in the latter sections, measurement consistency is maintained with this technique. The proposed resonator comprises an interdigital capacitor to eliminate the impact of the imaginary component generated by the inductor structure, which primarily stores the energy from propagation [12]. The spiral geometry of the inductor is invoked since it is a highly sensitive device that concentrates the current before it is transmitted to the MUT. An air gap is introduced under MUT to magnify the electrical field at this point [4]. Such increases in the electrical field could be very important to quantify the relative permittivity of MUT.

III. DESIGN METHODOLOGY

A. Transmission Line Design

A 50 Ω transmission line with 2.79 mm strip width is generated on FR4 substrate to assure smooth power flow from port 1 to port 2. Then, a single slot is introduced to the middle of the transmission line to leak electromagnetic fringing in a particular location [21]. The field penetration of the MUT was boosted by this fringing, as will be demonstrated later.

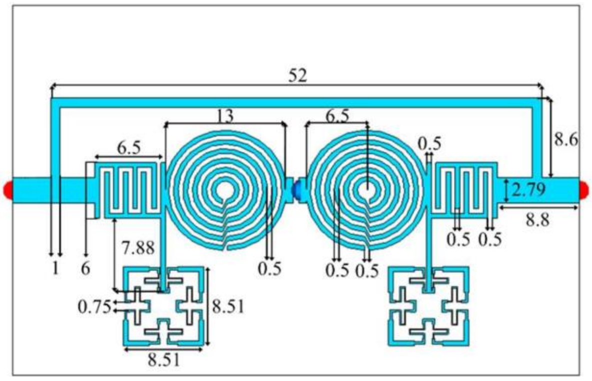

Fig. 1. Front view of the Minkowski based microwave resonator. Note that all dimensions are in millimeters scale.

S_{21} variation of the transmission line for the frequency band ranging from 0.1 GHz to 4 GHz obtained by CST MWS is given in Fig.2. As can be seen in Fig. 2, adding a single transversal slot to the transmission line decreased S_{21} dramatically across the whole frequency spectrum of interest. This reduction in the magnitude of the S_{21} value would be useful in the detection procedure. Nevertheless, the slot produces a capacitive coupling, which can store high-frequency electromagnetic energy. It is important to note that, as described in [21], the frequency resonances for microwave resonator design can be seen in the S_{21} spectrum.

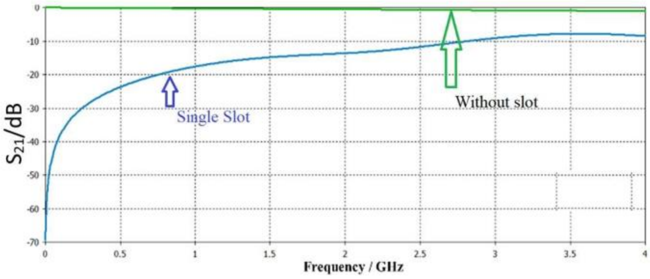

Fig. 2. Transmission coefficient variation of the transmission line with and without slot.

B. Effects of IDC

As seen from the previous section, there is no well-defined resonance that can be considered for sensing with fractions around 1GHz. Therefore, the authors introduced an IDC to their design to identify a frequency resonance [21]. Transmission coefficient variation of the proposed interdigital capacitor is shown in Fig. 3. The effects of changing the capacitor fingers from 2 to 4 with a step of 2 fingers in the IDC is observed in Fig. 3. It is found that the number of fingers on the IDC has a significant effect on S_{21} response.

C. Effects of CSI

To reduce the frequency resonance towards the lower frequency bands that realize excellent penetration in the human body compared to those at high frequencies [17], the authors introduced two inductors that are shaped in spiral geometry to their design. Such an introduction realizes a significant size reduction with the minimum field interfering due to the MUT introduction [18]. Nevertheless, the effects of smoothing the obtained results by enhancing the asymptotic tangent would be improved using the magnetic field stored in the proposed inductors [20]. Therefore, the authors conducted a parametric study for the number of CSI turns by changing the proposed CSI turns from 2 turns to 6 turns with a step of 2 turns. As shown in the S_{21} spectra of the circular spiral inductor that is presented in Fig. 5, a significant frequency shift is observed towards the lower frequency bands with the increase in the number of CSI turns.

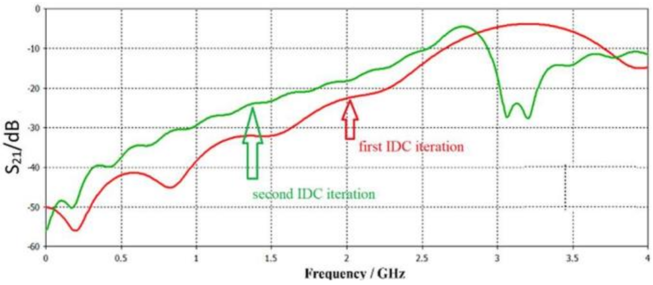

Fig. 3. Transmission coefficient variation of the interdigital capacitor.

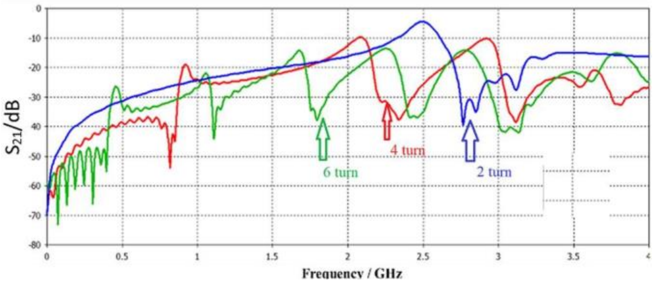

Fig. 4. Transmission coefficient variation of the circular spiral inductor.

D. *Effects of Fractal-Stub*

The effects of the proposed stub on the performance of resonator are parametrically assessed by varying the trace width and transmission line lengths. As a result of the parametric analysis, the fractal iteration order is modified from the first to the third iteration via the second iteration. Intersection of any conductor sections in the proposed resonator are prevented by restrictions in the alterations. It was discovered that the proposed fractal exhibits a frequency resonance around 0.8 GHz, which is extremely close to the resonance of our desired frequency resonance, which is shown in Fig. 5.

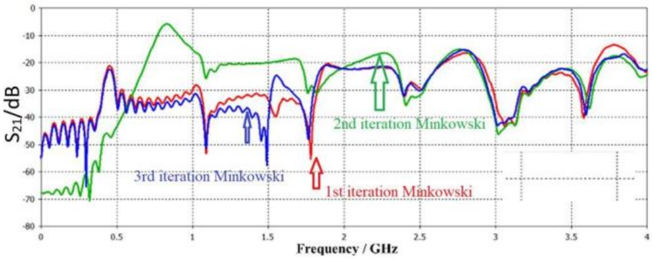

Fig. 5. Variation in the S_{21} spectrum regarding the Minkowski iteration.

E. *Effects of Introducing Back-Loop*

The proposed resonator design is conjugated with a back loop structure. The advantage of such an introduction is that it realizes a band-reject filter response instead of having a passband resonance. Such changes increase the accuracy of results during the measurements [19]. Therefore, the back loop design is parametrically studied by changing the trace width from 0.5 mm to 1.5 mm with a step of 0.5 mm. Such a study is applied to ensure that the total impedance influence on the proposed resonator is insignificant, which can be observed in Fig. 6.

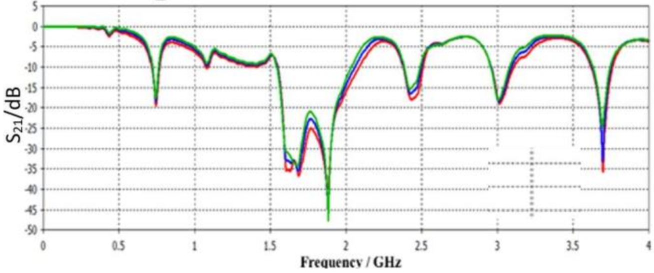

Fig. 6. S_{21} spectra for the proposed back loop; red line, blue line, and green line demonstrate to F.B width 0.5, F.B width 1, and F.B width 1.5, respectively.

IV. VALIDATION AND COMPARISON

This part reevaluates the suggested resonator's S-parameter spectrum performance using HFSS as validation. Transmission coefficient variation of the proposed microwave resonator is given in Fig. 7. It is discovered that the results obtained using the software packages for CST MWS and HFSS agree quite well. The proposed microwave resonator is compared with the other published resonators in Table I.

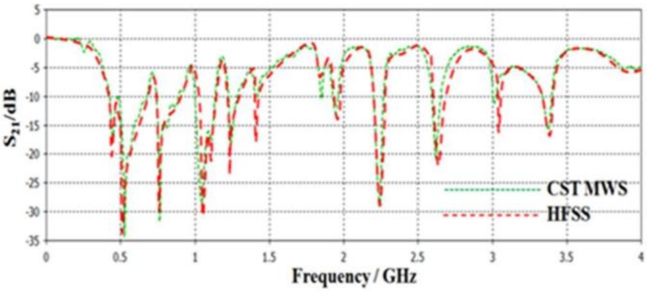

Fig. 7. Validation of S_{21} spectra.

TABLE I. COMPARISON OF THE MICROWAVE RESONATORS

Ref	**Type of Resonators**	**Fr (GHz)**	**Area of Sub(mm^2)**
[14]	CSRR	2.4	20 × 28
[15]	CSRR	2.4	30 × 25
[16]	MCSSR	2.45	35 × 25
[20]	IDC	2.98	29.5 × 29.5
[21]	SRR	1.9	28 × 28
This work	OS-CRLH	0.52	40 × 60

V. CONCLUSION

This paper proposes a microwave resonator design based on fractal geometry with an open stub structure. The microwave resonator bandwidth is achieved through coupling the electrostatic energy by a back loop structure. Therefore, the proposed resonator is found to behave linearly with sharp edges around the resonance frequency. The proposed design performance is tested numerically using CST MWS and validated with HFSS. The comparison between the achieved results reveals an excellent agreement between them. We found that the proposed resonator behaves linearly with very detectable edges with respect to the effects of the back loop introduction. Because of this, it is found that the proposed resonator is an excellent candidate for sub-6 GHz 5G applications.

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REFERENCES

[1] Ali Ismael Anwer, Zaid A. Abdul hassain, Taha A. Elwi, A Fractal Minkowski Design for Microwave Sensing Applications, Journal of Engineering and Sustainable Development (JEASD), 2022, Volume 26, Issue 5, Pages 78-83.

[2] al-Behadili, Amer Abbood, Iulia Andreea Mocanu, Teodor Mihai Petrescu, and Taha A. Elwi. 2021. "Differential Microstrip Sensor for Complex Permittivity Characterization of Organic Fluid Mixtures" Sensors 21, no. 23: 7865.

[3] Marwah Haleem and Taha A. Elwi, Circularly Polarized Metamaterial Patch Antenna Circuitry for Modern Applications, International Journal of Emerging Technology and Advanced Engineering, vol. 12, issu 12, pp. 44-50, Dec. 2022. https://doi.org/10.46338/ijetae1222_05.

[4] Abdulsattar, Russul Khalid, Taha A. Elwi, and Zaid A. Abdul Hassain. 2021. "A New Microwave Sensor Based on the Moore Fractal Structure to Detect Water Content in Crude Oil" Sensors 21, no. 21: 7143. https://doi.org/10.3390/s21217143.

[5] Russul K. Abdulsattar, Zaid A. Abdul hassain, Taha A. Elwi, A Theoretical Study To Design A Microwave Resonator For Sensing Applications, Journal of Engineering and Sustainable Development (JEASD) 2021, Volume 25, Issue Special_ Issue_2021, Pages 1-42-1-48.

[6] Taha Ahmed Elwi Wisam J. Khudhayer , "A Passive Wireless Gas Sensor Based on Microstrip Antenna with Copper Nanorods," Progress In Electromagnetics Research B, Vol. 55, 347-364, 2013. doi:10.2528/PIERB13082002.

[7] Taha A. Elwi, On the Percentage Quantization of the Moisture Content in the Iraqi Petroleum Productions Using Microwave Sensing, Al-Ma'mon College Journal, vol. 28, pp. 262-277, Dec. 2016.

[8] Elwi, TA. Metamaterial based a printed monopole antenna for sensing applications. Int J RF Microw Comput Aided Eng. 2018; 28:e21470. https://doi.org/10.1002/mmce.21470.

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

[10] J. G. D. Oliveira, E. N. M. G. Pinto, V. P. Silva Neto, and A. G. D'Assunção, "CSRR-based microwave sensor for dielectric materials characterization applied to soil water content determination," *Sensors*, vol. 20, no. 1, p. 255, 2020.

[11] M. G. Mayani, F. J. Herraiz-Martínez, J. M. Domingo, and R. Giannetti, "Resonator-based microwave metamaterial sensors for instrumentation: Survey, classification, and performance comparison," *IEEE Trans. Instrum. Meas.*, vol. 70, pp. 1–14, 2020.

[12] A. L. McKenzie and L. E. Armstrong, "Monitoring body water balance in pregnant and nursing women: The validity of urine color," *Ann. Nutr. Metab.*, vol. 70, no. Suppl. 1, pp. 18–22, 2017.

[13] L. E. Armstrong, M. S. Ganio, J. F. Klau, E. C. Johnson, D. J. Casa, and C. M. Maresh, "Novel hydration assessment techniques employing thirst and a water intake challenge in healthy men," *Appl. Physiol. Nutr. Metab.*, vol. 39, no. 2, pp. 138–144, 2014.

[14] A. Ebrahimi, J. Scott, and K. Ghorbani, "Differential sensors using microstrip lines loaded with two split-ring resonators," *IEEE Sens. J.*, vol. 18, no. 14, pp. 5786–5793, 2018.

[15] L. Su, J. Naqui, J. Mata-Contreras, and F. Martín, "Modeling and applications of metamaterial transmission lines loaded with pairs of coupled complementary split-ring resonators (CSRRs)," *IEEE Antennas Wirel. Propag. Lett.*, vol. 15, pp. 154–157, 2015.

[16] H.-Y. Gan *et al.*, "Differential microwave microfluidic sensor based on microstrip complementary split-ring resonator (MCSRR) structure," *IEEE Sens. J.*, vol. 20, no. 11, pp. 5876–5884, 2020.

[17] Abdulkarim, Y.I.; Deng, L.; Karaaslan, M.; Dalgaç, ¸S.; Mahmud, R.H.; Ozkan Alkurt, F.; Muhammadsharif, F.F.; Awl, H.N.;Huang, S.; Luo, H. The Detection of Chemical Materials with a Metamaterial-Based Sensor Incorporating Oval Wing Resonators.Electronics 2020, 9, 825.

[18] Zhang, X.; Ruan, C.; Haq, T.U.; Chen, K. High-sensitivity microwave sensor for liquid characterization using a complementary circular spiral resonator. Sensors **2019**, 19, 787.

[19] Alibakhshikenari, M.; Virdee, B.S.; Limiti, E. Compact Single Layer Travelling-Wave Antenna Design Using Metamaterial Transmission Lines. Radio Sci. 2017, 52, 1510–1521.

[20] 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, 2019.

[21] Javed, A.; Arif, A.; Zubair, M.; Mehmood, M.Q.; Riaz, K. A Low-Cost Multiple Complementary Split-Ring Resonator-Based Microwave Sensor for Contactless Dielectric Characterization of Liquids. IEEE Sens. J. 2020, 20, 11326–113