Multi-band microwave sensor based on Hilbert’s fractal for dielectric solid material characterization

C. P. do N. Silva, J. A. I. Araujo, M. S. Coutinho, M. R. T. de Oliveira, I. Llamas-Garro and M. T. de Melo

ABSTRACT
A planar sensor designed using the fourth Hilbert fractal curve iteration for solid material characterization at multiple frequencies is reported in this paper. The fractal curve is self-similar with space-filling properties. The Hilbert fractal geometry is used to form a compact resonator, with a multiband frequency response where miniaturization is achieved since a large transmission line length is effectively confined in a limited area. The sensor provides five resonances in the frequency range from 0 to 5 GHz. The resonant frequencies are 0.56, 1.68, 2.72, 3.69 and 4.72 GHz, all used to measure the real permittivity of known samples with a sensitivity of 7, 20, 27, 43 and 50 MHz/permittivity, respectively. The sensor is used to measure dielectric samples with 20 × 20 mm² areas with several thicknesses. Simulations and measurements demonstrate that the Hilbert fractal geometry can be used to design a multiband planar sensor for solid dielectric material characterization.

ARTICLE HISTORY
Received 30 June 2020
Accepted 6 December 2020

KEYWORDS
Microwave sensor; fractal geometry; multiband sensing; resonator; dielectric substrates

Introduction

Nowadays it is possible to find several types of microwave-based sensors for diverse applications [1], such as liquid biological and chemical tests [2,3], food and agricultural products [4,5], and measurements of industrial materials [6].

Planar and hollow waveguides are commonly used for microwave sensor design, mainly in the range between 1 and 20 GHz. A broadly used planar structure is the microstrip line [7]. The microstrip structures are composed of a conductive strip, a dielectric substrate, and a ground plane. When employed in sensors, transmission and reflection techniques are used to characterize materials [8].

When microstrip transmission lines are designed for material characterization sensors, resonant or non-resonant structures can be applied. Resonant methods are preferable because they have greater precision and sensitivity [7]. One of these methods is known as resonant disturbance, based on detecting the frequency resonance shift of the microstrip resonator when measuring a sample [9]. The concept of planar...
microstrip sensors has been developed in the early 1970s, resulting in the first commercial sensors for food processing, as well as for measuring fruit maturation and moisture content [4].

The use of a fractal geometry results in a reduction of sensor dimensions with improved sensitivity, due to its intrinsic properties: self-similarity, infinite complexity, and small dimensions with space-filling properties. The term fractal characterizes objects whose parts resemble the whole structure, thus as the visualization scale increases or decreases, its shape is not altered, remaining identical or very similar to the original structure. Currently, fractal structures are used in several microwave applications such as the development of compact interferometers based on Hilbert’s fractal geometry [10], fractal phase shifters [11] or resonators for filter miniaturization [12].

In this paper, a planar sensor for real permittivity characterization is proposed and used to sense well-known dielectric substrates to demonstrate its multiband sensing properties with small dimensions. The sensor has five resonant frequencies at 0.56, 1.68, 2.72, 3.69 and 4.72 GHz, all of them suitable to measure the real permittivity with a sensibility of 7, 20, 27, 43 and 50 MHz/permittivity, respectively. To the best of the authors’ knowledge, there is no multiband sensor with 5 bands for dielectric material characterization in the literature. In Ref. [13], a multiband sensor with 4 bands is described; however, the design uses four different resonators, one per band, resulting in the need of large sample dimensions. The proposed sensor has just one resonator and requires smaller material samples with an area of 20 × 20 mm².

This paper is broken down into the following sections: The second section describes the Hilbert Fractal geometry. The third section describes the sensor implementation. The fourth section contains the experimental demonstration using the proposed sensor and the fifth section provides an overall conclusion to this work.

The Hilbert fractal geometry

The German mathematician David Hilbert introduced the Hilbert fractal curve in 1981. It is a space filling, self-similar continuous curve that fills space without intersecting itself. The first four iterations of the Hilbert fractal curve are shown in Figure 1. As one can see, as the total length increases, the total area occupied by the fractal structure remains the same. This characteristic is important for the proposed sensor design since a multiband behavior is obtained, where the coupling between adjacent lines increases the capacitance of the sensor, and consequently its sensibility.

In each subsequent iteration, the resonator length ideally doubles with respect to its previous iteration. In theory, the length of the resonator tends to infinity in a limited area for infinite iterations, however, in practice, narrow transmission lines become impractical for high order iterations.

The space-filling Hilbert fractal curve is used as a resonator to design a multiband sensor to measure the dielectric constant of dispersive materials. The multiband response is due to higher resonance frequencies of the resonator which are well defined. The long length required to achieve more resonances is confined in a constant area, thus resulting in a miniaturized sensor. Any fractal curve with space-filling properties, such as the Peano and Moore fractals, can be used. However, future studies must be done to evaluate how different types of fractal structures affect the sensor response.
Figure 1. The first four Hilbert fractal iterations occupying the same area.

Figure 2. Sensor layout design based on the fourth iteration of the Hilbert fractal curve.

Sensor design

Figure 2 shows the microstrip sensor layout using the fourth Hilbert fractal curve iteration as a resonator for its design. The shaded areas correspond to copper microstrip lines patterned on a substrate. The sensor is designed using an AD1000™ substrate with dielectric constant of 10.2, loss tangent of 0.0004 and thickness of 1.27 mm. The ports are designed to have a characteristic impedance of 50 Ohms. Here, the fourth iteration of the Hilbert fractal curve is utilized with an approximate length ($l_{ef}$) of 243 mm, occupying an area of 400 mm$^2$.2.
Table 1. Calculated and simulated first resonant frequency of the multiband sensor.

| Resonance (GHz) | Calculated | Simulated | Error  |
|-----------------|------------|-----------|--------|
| $f_1$           | 0.49       | 0.56      | 0.07   |

The fourth iteration is chosen because it provides a good trade-off between using a large resonator length, while obtaining an appropriate coupling between lines, all confined in a small area for multiband sensing.

The fundamental resonant frequency ($f_1$) of the proposed multiband sensor can be calculated using eq.1 [14].

$$f_1 \text{ (GHz)} = \frac{0.3}{l_{ef} \sqrt{\varepsilon_{reff}}}$$

The effective dielectric constant $\varepsilon_{reff}$ (AD1000™, $w = 0.3$ mm) = 6.35, and $l_{ef} \approx \lambda_{g1}$, where $\lambda_{g1}$ is the guided wavelength for $f_1$. The resonator also resonates at higher frequencies when $f_n \approx (2n - 1)f_1$. Table 1 shows the calculated and simulated fundamental resonance frequency of the multiband sensor. This also means that the resonant frequencies are separated from each other by $2f_1 \approx (f_n - f_{n-1})$.

The sensor principle of operation consists in the fact that although the electric field is more concentrated between the lines of the microstrip and the ground, there is a weaker field above the substrate. Therefore, the $\varepsilon_{reff}$ calculation considers the substrate and the material above the substrate (sample). When some sample is placed above the resonator, $\varepsilon_{reff}$ changes and hence the resonant frequencies changes. The sample not only causes a resonant frequency shift towards lower frequencies, but also a change in resonator quality factor towards lower Q-values [15]. Sensor strips are arranged to follow Hilbert’s fractal for device miniaturization and a multi-band response, resulting in perpendicular microstrips to form the resonator, thus, the proposed device is not suitable for anisotropy sample measurements [16].

Simulated and measured results

The Hilbert’s fractal sensor is simulated using a 3D electromagnetic software, the structure used for simulations is shown in Figure 3. Simulated and measured results are presented in Figure 4, and consist of $|S_{21}|$ (dB) in the frequency range from 0.1 to 5 GHz, according to a sensor with no sample on top of it. The sensor without sample presents five resonance frequencies at 0.56, 1.68, 2.72, 3.69 and 4.72 GHz. Table 2 summarizes the resonance frequency, quality factor and bandwidth (in relation to $-10$ dB values) for the sensor without sample. It is apparent from Figure 4 and Table 2 that the resonance frequencies have similar characteristics such as high-quality factors, bandwidths in the range from 210 to 290 MHz and return losses over 30 dB.

The sensor operation is based on the premise that all existing materials have a specific dielectric permittivity at RF and microwave frequencies. The electric field is mainly concentrated in the substrate, but there is still an electric field component above the substrate. Thus, when a material is placed on top of the resonator, the effective permittivity will vary and thus the resonance frequency of the sensor will shift.
Figure 3. Sensor schematic used for simulations, including a dielectric sample on top of the sensor.

Figure 4. Simulated frequency response of the fractal sensor with no sample.

Table 2. Simulated resonance frequency characteristics of the sensor without sample.

| Resonance (GHz) | Calculated | Simulated | Measured |
|-----------------|------------|-----------|----------|
| $f_1$           | 0.49       | 0.56      | 0.58     |
| $f_2$           | 1.68       | 1.68      | 1.73     |
| $f_3$           | 2.80       | 2.72      | 2.84     |
| $f_4$           | 3.92       | 3.69      | 3.88     |
| $f_5$           | 5.04       | 4.72      | 4.92     |

Sample thickness is an important parameter, taken into account in the measurement and simulation technique to find the dielectric constant. This technique is described in [9]. Simulation results showed that even a thin 100 µm thick sample can be detected. Frequency shifts on the five resonant frequencies happen for low-loss sample materials with high dielectric constants up to 100. In this paper, dielectric loss is not measured, however using perturbation theory techniques; the proposed sensor can be used to measure dielectric losses, by measuring the quality factor.

To simulate the sensor with the sample, a parallelepiped piece of material measuring $20 \times 20 \times t \text{ mm}^3$ is placed over the area containing the fractal resonator, where the highest concentration of electric field is found, $t$ is the thickness of the simulated samples, in specific
Figure 5. Fractal sensor simulated results for real permittivity variation from 1 to 10.8.

Thus, the relative permittivity sample values are varied between 1 (bare sensor, without sample) and 10.8. Figure 5 contains the simulated insertion loss results for the sensor with samples on top. The resonant frequency shift is apparent and according to sample relative permittivity variation.

Figure 6 analyzes dielectric permittivity variation as a function of sensor resonance frequency for the device five frequencies of operation. The curves obtained show a high degree of linearity. Through a linear fit of simulated data, equations show that the sensitivity obtained is 10, 35, 54, 86 and 97 MHz/permittivity, according to resonant frequencies one to five, respectively.

The higher frequencies are proportional to the fundamental one by the factor $2n - 1$. So, considering the simplest case, where $\varepsilon_r$ is constant, a shift in $f_1$, $\Delta f_{1r}$, causes a shift in $f_n$, $\Delta f_{nr} \approx (2n - 1) \Delta f_{1r}$. The sensitivity ($S_{f_1}$) of $f_1$ can also be calculated by solving $S_{f_1} = \Delta f_{1r} / \Delta f_{1r}$, where $\Delta \varepsilon_{r_1}$ is the difference between the lowest (i) and highest (k) dielectric constant value that the sensor can detect, and $\Delta f_{1r}$ is the first resonance shift according to the sample measured. That is, knowing the sensitivity of the fundamental resonant frequency, the sensitivity of the following resonances are well defined ($S_{f_n} = (2n - 1)S_{f_1}$) and always higher than the fundamental one.

The sensor prototype is manufactured using an Everprecision® EP2006H machine and has the overall dimensions provided in Figure 7. The $|S_{21}|$ (dB) experimental results are obtained using a Keysight® N9952A portable VNA.

The measurement setup consists of connecting the sensor through SMA connectors to the network analyzer and measuring the insertion loss values in the range from 0.1 to 5 GHz. The measurements are performed with samples made of substrates with known permittivity values, including the bare sensor with no sample. The measured samples are formed
Figure 6. Relation between the relative permittivity and resonant frequencies obtained through simulations. $f_1$ corresponds to the first resonance frequency and $f_5$ corresponds to the fifth resonance frequency, accordingly.

Figure 7. Photograph of the fabricated compact planar fractal sensor.

Table 3. Samples used for measurements.

| Substrates  | Permittivity | Substrate layer thickness (mm) | Samples thickness (mm) |
|-------------|--------------|-------------------------------|------------------------|
| RO6010      | 10.80        | 0.635                         | 2.540                  |
| AD1000      | 10.20        | 3.000                         | 3.000                  |
| FR-4        | 4.50         | 1.600                         | 3.200                  |
| RO6002      | 2.94         | 1.524                         | 3.048                  |
| Duroid 5880 | 2.20         | 0.750                         | 1.500                  |

using piled substrate layers with different thicknesses. The substrate layers are placed one above another to achieve the given sample thickness provided in Table 3.

The measurement setup is shown in Figure 8, for a sensor with a sample on top. Table 3 lists the samples used in the experiment and Figure 9 contains the experimental results obtained. Figure 4 shows a comparison between the simulated and measured insertion loss response for the sensor with no sample, where the results are in good agreement. The
measured results show five resonant frequencies. All the resonances present a small shift compared to the simulated results. The fifth resonance has a larger shift of 214 MHz.

It is apparent from Figure 9 that when a sample is deposited on top of the sensor, there is a resonance frequency shift according to the permittivity of the sample being measured, observed as different magnitudes of the transmission coefficient in $|S_{21}|$ (dB) at a given frequency. The resonance frequency variations are adequate to distinguish each sample, where the sensitivity increases as the frequency of operation increases.

Figure 10 shows the variation in dielectric permittivity as a function of resonance frequency for each of the five operating frequencies, obtained through linear regression of measurement data. The measured results present a high degree of linearity and a sensitivity of 7, 20, 27, 43 and 50 MHz, for the five resonance frequencies, respectively.

The sensitivities obtained from measurements differ from the simulated ones because there are air gaps formed between the substrate layers that compose the sample, and an air gap formed between the resonator and the sample. However, the expected resonant frequency shift behavior is observed according to each sample, making the proposed sensor adequate to characterize dielectric samples using the five different resonant frequencies with good sensitivity and small size.

A high dielectric constant substrate is used for this sensor design to achieve sensor miniaturization and allow small sensor samples to be measured, with the tradeoff of lower sensor sensitivity. Higher sensor sensitivity values can be achieved using a lower dielectric constant substrate to make the sensor or the use of coplanar transmission line.
Figure 9. Measured results for samples with different permittivity values and the bare sensor without sample.

Figure 10. Relation between the relative permittivity and resonant frequencies obtained through measurements. $f_1$ corresponds to the first resonance frequency and $f_5$ corresponds to the fifth resonance frequency.

Table 4 shows a comparison between the proposed sensor and other dielectric sensors available in the literature. In Ref. [13], the authors present a multiband sensor with four different resonances and good sensitivity. Four resonators are designed, one for each resonant frequency, which makes the sensor large compared to the proposed implementation. The required sample is large since it must cover all resonators for multiband sensing. In Ref.
Table 4. Comparison of dielectric material sensors available in the literature.

| Ref.   | N° of resonant bands | $f_r$ (GHz) | Size (mm) | Sample size (mm) | Sensitivity (GHz/$\varepsilon_r$) | Q factor | Technology                                      |
|--------|----------------------|-------------|-----------|------------------|-----------------------------------|----------|-------------------------------------------------|
| [13]   | 4                    | 1.5, 2.45, 3.8 and 5.8 | Not presented Large sensor | Not presented (almost the size of the sensor) | 0.9 | Not presented | Microstrip (Ring resonator on ground plane) |
| [14]   | 1                    | 2.22        | 68.30 × 71.84 | 25 × 17 | 0.652 | 652.94 | Microstrip (split ring resonator) |
| [17]   | 2                    | 4.9, 9.30   | 20 × 20 | 20 × 20 | 0.44 | 417.8, 143.4, 160.2, 442.2, 375.5 | Not presented | Metamaterial structure |
| This work | 5                  | 0.56, 1.68, 2.72, 3.69 and 4.72 | 40 × 28 | 20 × 20 | 0.007, 0.022, 0.027, 0.043 and 0.05 | 143.4, 160.2, 442.2, 375.5 | Fractal resonator |
the authors present a microstrip ring resonator with high sensitivity but just with one resonant frequency. In Ref. [17], a metamaterial structure with two resonant frequencies is proposed, however, just one resonance is used to measure the real permittivity of a sample. In this work, a small sensor with five resonant bands is proposed. The sensor presents good quality factors and needs a small sample. All five resonances have good sensitivity for dielectric material characterization using multiband sensing. Ways to increase the sensitivity of the proposed sensor include using a lower dielectric constant substrate to make the sensor, or the use of coplanar transmission lines. In both cases, more electric field will penetrate the sample, resulting in increased sensor sensitivity.

Conclusions

The Hilbert fractal curve is used in the design and construction of a small size microwave planar sensor to characterize low loss materials with relative permittivity ranging from 1 to 10.8, and according to simulations, the sensor can be used to measure dielectric constants up to 100. The results show that the Hilbert fractal-based sensor presents a multiband response with an adequate quality factor and transmission loss for sensing. The sensor has been designed on a high dielectric constant substrate to achieve miniaturization with the trade-off of having a lower sensor sensitivity. Sensor sensitivity can be increased by using a lower dielectric constant material to make the sensor or by using coplanar interdigital transmission lines. When samples are placed on top of the sensor, the capacitance of the structure varies, and therefore, a resonance frequency shift is observed in the sensor response. The proposed sensor operates with five resonance frequencies in the range from 0.1 to 5 GHz, namely, 0.56, 1.68, 2.72, 3.69 and 4.72 GHz. The highest sensor resonance frequency of operation presented the highest sensitivity. The sensor has small dimensions with a multiband response and consequently requires small sample dimensions. The results obtained indicate that the proposed compact and low-cost fractal sensor is suitable for measuring dispersive low-loss samples using multiband sensing. Future work involves analysing the response and sensitivity of sensors using other fractal structures with self-filling properties.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This work is supported by the Spanish government under MICINN (Ministry of Science and Innovation) [grant number RTI2018-099841-B-I00]. Part of this work has been supported by the Generalitat de Catalunya [grant number 2017 SGR 891] and CAPES (Coordenação de Aperfeiçoamento de Pessoal de Nível Superior) PDSE 47/2017 from the Brazilian Government.

Notes on contributors

C. P. do N. Silva recently conclude her Ph.D. in electrical engineering at Federal University of Pernambuco (UFPE). In the Ph.D., she studied the design, manufacture and tests of active and passive microwave circuits for frequency identification and sensors devices. Obtained the Master’s Degree and her B.Sc. Degree in Electrical/Electronic Engineering at same institution. The Master’s Degree was
with emphasis on development of passive microwave devices. During her undergraduate studies, she
joined the Microwave Laboratory of UFPE, since then, she has been participated in research projects
and contributed to national and international publications in this laboratory. Hers interests include
active and passive microwave devices, filters, couplers, antennas and sensors.

**J. A. I. Araujo** received his B.Sc. in Electrical Engineering from Federal University of Piauí, Brazil in 2017,
and M.Sc. in Electrical Engineering from Federal University of Pernambuco, Brazil in 2019. He is cur-
currently a Ph.D. student with the Federal University of Pernambuco, Recife, Brazil. His research activities
focus on electromagnetic waveguides, antennas and resonators, microwave sensors and FSS.

**M. S. Coutinho** received the B.S. degree in Telecommunication Engineering from the Centro Universi-
tário Mauricio de Nassau, Recife, Brazil, in 2014. In this year, he started to work as a RF and cellular
engineer. Since 2015, he has been working toward the M.S. degree from the Universidade Federal de
Pernambuco. He received the M.S. degree in Electrical Engineering in 2017. The subject of the disserta-
tion was focused on microstrip sensor for materials characterization. He is currently pursuing his Ph.D.
in electrical engineering, at the same university. His present research interests include fault detection
in metal structures through microwave devices and the design and fabrication of coplanar structures
in microwave and RF frequencies, like antennas, filters, sensors, fractal structures and couplers.

**M. R. T. de Oliveira** completed her B.Sc. Degree in Electronic Engineering at the Federal University
of Pernambuco (UFPE) in 2013. She also completed her D.Sc. and Master’s Degree with emphasis on
Photonics, in the design and manufacture of Frequency Selective Surface, at the same institution in
2016 and 2018 respectively. Form 2010 to 2012, she joined the Microwave Laboratory of UFPE to par-
ticipate in a program of scientific initiation. She is professor at the Instituto Federal de Pernambuco,
Campus Garanhuns.

**Dr I. Llamas-Garro** is an expert in the field of device engineering and implementation from design to
fabrication and testing, applied to wireless communications and sensors, including RF and microwave
circuits, reconfigurable designs using microelectromechanical systems and semiconductor diode-
based components. Micromachined devices, 3D printing of microwave passive components, inkjet
printing of planar circuits and sensors, and micro/nano fabricated optical sensors for the detection
of hazardous liquids and gases. Ignacio Llamas-Garro obtained his Ph.D. from the University of
Birmingham, United Kingdom in 2003, and has been with the CTTC since 2010.

**Prof. M. T. de Melo**, has completed undergraduate degree in Physics from the Federal University of
Pernambuco-UFPE, Brazil, in 1983. Continuing his studies at the same University he received the
M.Sc. degree also in Physics in 1992, where his dissertation focused on Microwave Absorption on
Superconducting Samples. In 1997, he received the Ph.D. in Electrical Engineering from Birmingham
University, England, where his thesis focused on High Temperature Superconducting Devices. In 1999,
he joined the Department of Electronic and Systems, UFPE. During 2012–2013 he also had the posi-
tion of Visiting Professor at Imperial College London, Electrical and Electronic Engineer Dep. He is
now Visiting Professor at CTTC (Centre Tecnològic de Telecomunicacions de Catalunya)-Barcelona-
Spain. He became full Professor of the UFPE in 2019. He was able to contribute to attracting more
than 9 million dollars in research and development projects, involving government funding agen-
cies and also (mainly) national and international companies. He has 180 published works, among
Journal papers, Conference papers, books, book chapters and patents. He was the General Chair
of the 2015 SBMO/IEEE MTT-S International Microwave and Optoelectronic Conference. He is IEEE
senior member since 2020 and IEEE MTT-S Chapter Chair - Bahia Section. He will be Co-Chair of 2023
SBMO/IEEE MTT-S International Microwave and Optoelectronic Conference which will take place in
Barcelona (already approved by SBMO). His present research interests include the design and fabrica-
tion of coplanar structures in microwave frequencies, like resonator, power divider, filter, delay line,
instantaneous frequency 80 measurement systems, microsatellites, neural network, measurement
of dielectric properties of novel materials for microwave applications, frequency selective surface,
micromachined technique and also terahertz device applications.
References

[1] Skulski J, Galwas BA. Planar resonator sensor for moisture measurements. 12th International Conference on Microwaves and Radar, Kraków, Poland, May 1998, p. 692–695.
[2] Galwas BA, Piotrowski JK, Skulski J. Dielectric measurements using a coaxial resonator opened to a waveguide below cut-off. IEEE Trans Instrum Meas. 1997;46(2):511–514.
[3] Galwas BA, Piotrowski JK, Skulski J. New type of microwave resonator sensors with waveguide below cut-off. Conference on Precision Electromagnetic Measurements Digest, Braunschweig, Germany, Aug 1996, p. 76–77.
[4] Yeow YK, Jalani SNA, Abbas Z, et al. Application of bandpass filter as a sensor for rice characterization. International Conference on Computer Applications and Industrial Electronics (ICCAIE), Kuala Lumpur, Malaysia. Dec 2010. p. 570–573.
[5] El Sabbagh AM, Ramahi MO, Trabelsi S, et al. Use of microstrip patch antennas in grain permittivity measurement. Instrumentation and measurement technology conference (IMTC), Vail, CO, May 2003, p. 640–644.
[6] Fericean S, Dorneich A, Droxler D, et al. Development of a microwave proximity sensor for industrial applications. IEEE Sens J. 2009;9(7):870–876.
[7] Bogner A, Steiner C, Stefanie W, et al. Planar microstrip ring resonators for microwave-based gas sensing: design aspects and initial transducers for humidity and ammonia sensing. Sens J. 2017;17(10):2422.
[8] Coutinho MS, Silva CPN, Oliveira MRT, et al. Planar sensor for powder grain characterization. IET Microw Antennas Propag. 2018;12(10):1666–1670.
[9] Chen L-F, Ong CK, Neo CP, et al. Microwave electronics: measurement and materials characterization. Chichester: John Wiley & Sons; 2004.
[10] Silva CPN, de Oliveira EMF, de Oliveira MRT, et al. New compact interferometer based on fractal concept, 2015 SBMO/IEEE MTT-S International Microwave and Optoelectronics Conference (IMOC), Porto de Galinhas, 2015, p. 1–3.
[11] de Oliveira EMF, Pontes LP, Silva CPN, et al. Microstrip fractal-based phase shifter an UHF phase shifter based on with Hilbert’s fractal delay lines. 2017 47th European Microwave Conference (EuMC), 2017, p. 1148–1150.
[12] Jarry P, Beneat J, Kerherve E. Fractal microwave filters, 2010 IEEE 11th Annual Wireless and Microwave Technology Conference (WAMICON), Melbourne, FL, 2010, p. 1–5.
[13] Ansari MAH, Jha AK, Akhter Z, et al. Multi-band RF planar sensor using complementary split ring resonator for testing of dielectric materials. IEEE Sens J. 2018;18(16):6596–6606.
[14] Neto AG, Goncalves da Costa A, da Silva Moreira C. A new planar sensor based on the Matryoshka microstrip resonator. 2017 SBMO/IEEE MTT-S International Microwave and Optoelectronics Conference (IMOC); 2017.
[15] Alahnomi RA, Zakaria Z, Ruslan E, et al. High-Q sensor based on symmetrical split ring resonator with spurlines for solids material detection. IEEE Sens J. 2017;17(9):2766–2775.
[16] Morales-Lovera H-N, Olvera-Cervantes J-L, Corona-Chavez A, et al. Dielectric anisotropy sensor using coupled resonators. IEEE Trans Microw Theory Tech. 2019;68(4):1–7. DOI:10.1109/tmtt.2019.2958265
[17] Islam MT, Rahman MN, Mahmud MZ, et al. Investigation of a resonator-based metamaterial for sensor applications. Appl Phys A. 2018;124(2):1–7.