Security of Infocommunication Systems and Internet of Things

2024 Vol 2, No 1

https://doi.org/10.31861/sisiot2024.1.01012

Received 23 July 2024; revised 24 August 2024; accepted 29 August 2024; published 30 August 2024

Access Control System Based on Ring Resonator's Sensitive Properties

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ABSTRACT The paper is dedicated to the development of a new type of electromagnetic (EM) devices to achieve unique output signal patterns for their potential applications in secure systems. The proposed device involves modification of a microstrip transmission line modification by ring resonators. The ring resonator is an EM component that is characterized by high sensitivity, impedance of which can be easily adjusted by its shape changing. It was performed with the ring resonator's microstrip lines lengthening from 1 to 13.5 mm that allows the resonance frequency changing from 1 to 1.6 GHz, demonstrating the tunability of the device. The modification of a microstrip transmission line with one or a few of such ring resonators by their strong near-field coupling leads to a deep minimum/minima appearance in the transmission line transfer function (S_{21}-parameters spectrum). This minimum can disappear under direct touching of the ring resonator by a human finger – changing of the total capacitance of the ring resonator. It means that the consequence touching/untouching of the ring resonator leads to a modulation of the input transmission line signal and producing unique output signal patterns. As the number of ring resonators increases, the complexity of these patterns also increases. The variety of the patterns can be unique and secure; thus, the output signals can serve as a key for creation of password for systems of access control. To ensure that the security level provided by the device meets the necessary standards, the keyspace – the total number of possible unique patterns – was estimated for various combinations of the developed ring resonators. The analysis revealed that with 14 available ring resonators, the keyspace can exceed 10^{15}, indicating a vast number of possible combinations and, therefore, a very high level of security.

KEYWORDS ring resonator, transmission line, security, keyspace, access control.

I. INTRODUCTION

The ring resonator is a fundamental structure typically composed of concentric/squared metallic ring/rings as described in several studies [1-4]. When ring resonators are arranged in a stack or as a two-dimensional array at the same plane, they form the artificial material known as a magnetic negative metamaterial [5-6]. This configuration enables the metamaterial to exhibit unique properties such as negative permeability, which is a characteristic also observed in a single ring resonator. In this case, the individual ring resonator, possessing negative permeability, is referred to a meta-atom.

There are numerous fabrication techniques available for creating ring resonators with varying dimensions, which allows these structures to be utilized across a broad spectrum of frequencies, including those at the nanoscale [7-9]. For applications at microwave frequencies, ring resonators are often fabricated by chemical etching on a dielectric substrate, as illustrated in Fig. 1a. The sensitivity of single ring resonators to their environment has made them the subject of extensive research and a valuable tool in a range of applications. For instance, ring resonators have been employed as microwave sensors for detecting small quantities of liquids [10-11], monitoring organic tissue [12-13], and measuring permittivity [14-15]. These devices typically consist of arrays of ring resonators or split square resonators, which form a metamaterial surface [16-17], or single ring resonators integrated into transmission lines to modify their characteristics [18].

The overall capacitance of such a meta-atom is a critical factor in these devices, as it serves as a sensitive element that influences the transmission or response characteristics of the system. This sensitivity to external conditions makes ring resonators highly effective for precise sensing and diagnostic applications across a variety of fields, from materials science to biomedical engineering. The versatility and adaptability of ring resonators ensure their continued relevance and utility in the development of advanced metamaterials and sensor technologies.

The high sensitivity and the ability to adjust electromagnetic (EM) properties of a single ring resonator by its shape variation, as well as an opportunity of its implementation as a metamaterial transmission line are a subject of the paper in order to develop a single transmission line device modified by a special ring resonator or set of ring resonators to achieve unique output signal patterns with a possibility of their exploiting in access control systems.

II. SINGLE ELEMENT DEVELOPMENT

Squared ring resonator was selected as a single element for the following study. The element is shown in Fig. 1a and is usually characterized by the following geometrical sizes: a = 20 mm – the width and length of a dielectric substrate; b = 15 mm – width and length of the metallic ring resonator placed over the dielectric substrate; c = 5 mm – distance between the outer and the inner microstrips of the ring resonator; e = 1 mm and d – the width and length of the microstrips; g = 1 mm – gap between two inner microstrips.

For the simulations and experimental investigations all the above-mentioned parameters were fixed except the value of *d* as shown in Fig. 1b. The variation for the value of d was performed from 1 to 13 mm with the step 1 mm and one more value of 13.5 mm considered as the maximum possible value of *d* for the considered ring resonator.

The test board that consists of a microstrip transmission line over the top of a dielectric substrate (FR-4 material of the substrate was selected in this investigation, ε = 4.2, $tan(\delta)$ = 0.02, 0.6 mm of thickness) and metallic ground on the back side of the dielectric substrate (Fig. 1c) was developed for simulations in CST Microwave Studio and fabricated for experimental measurements. The input and output of the transmission line are connected to the 50 Ohms SMA-connectors intended to interaction with the Vector Network Analyser (NanoVNA V2).

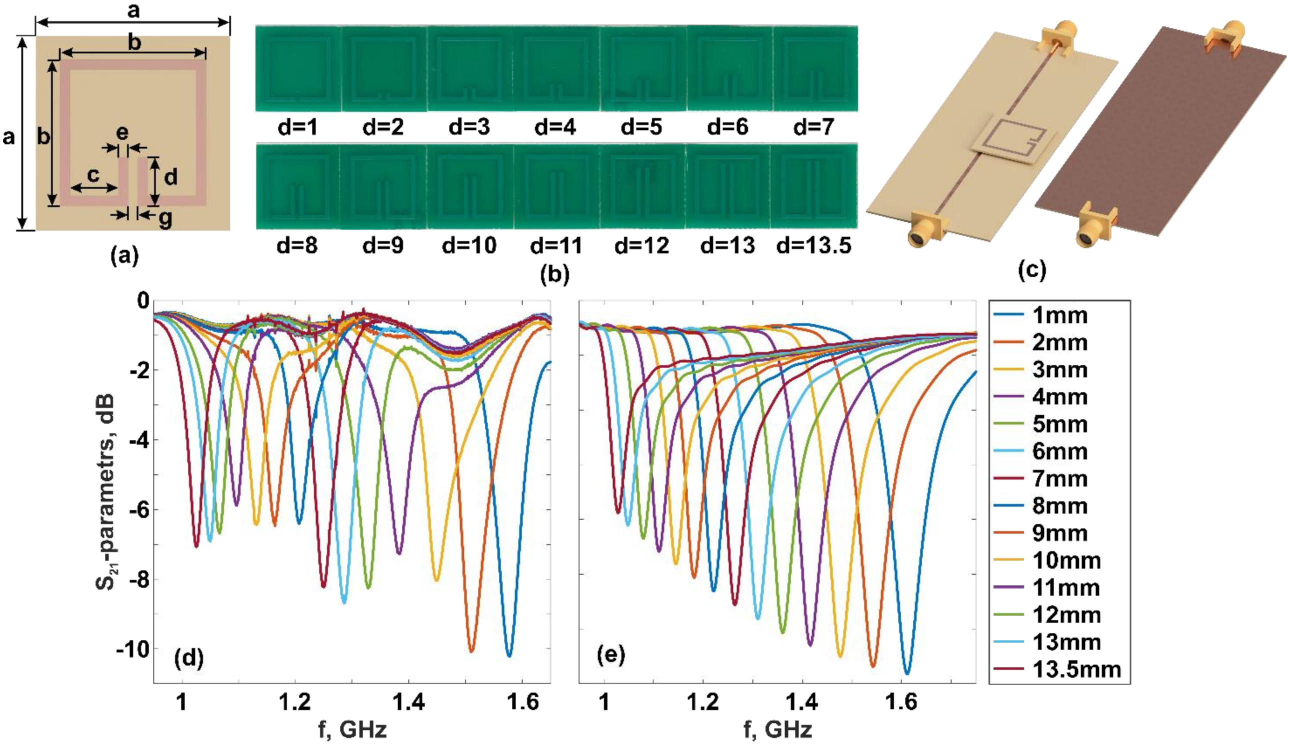

FIG. 1. The suggested design of a ring resonator which is geometrically characterized with parameters *a, b c, e, d, g* (a) and its experimental implementation with variation of *d* value from 1 to 13.5 mm (b). Test board for S_{21}-parameters analysis of the considered ring resonators (c). Simulation (d) and experimental (e) results represented via S_{21}-parameters.

The suggested approach for the test is that the spectrum of S_{21}-parameters for the mentioned microstrip transmission line is the even plot as shown in Fig. 1d. It means that the entire power which is generated by port 1 is delivered to port 2 in the frequency range from 0.95 to 1.75 GHz. However, once a ring resonator is placed onto the microstrip line as shown in Fig. 1c the local minimum appears along the S_{21}-parameters plot. The position of the minimum depends on the resonance response of a ring resonator. Therefore, Figs. 1d-e represent the responses for all variety of the ring resonator from Fig. 1b. One can see that for the smallest value of d the resonance value is the maximum and vice versa. It is caused by the total value of the ring resonator's capacitance – two parallel inner metallic microstrips with length *d* and separation distance between them *g* is a planar capacitor [20].

III. SENSITIVE PROPERTIES OF RING RESONATOR DEVICE

It is well known that a ring resonator is highly sensitive element [14-19]. This fact is used as an approach to change the ring resonator electromagnetic properties in the considering device (Fig. 2a-b). While the spectrum of S_{21}-parametars for the ring resonator with d = 5 mm placed over the microstrip transmission line has the minimum at the frequency 1.35 GHz (the red plots in Fig. 2c – simulations and Fig. 2d – experiment), the plot becomes even when the ring is touched by a finger (the blue plots in Fig. 2c – simulations and Fig. 2d – experiment). It is caused by the dielectric properties of the finger and its interaction with the ring resonator in the reactive near-field zone.

The considered approach of control of the transmission line's output signals can correspond to modulation/coding concept of high frequency carrier signal. Each of the shown in Fig. 1b ring resonators is characterized by a specific resonance frequency that can be used as a secret key element. It can allow obtaining unique output time patterns by touching/untouching the element (as an example, the 1-key element set is shown in Fig. 2a-b). Then, a combination of an arbitrary number of such key elements with different resonance frequencies can complicate the output signal patterns. These patterns can be considered as passwords for different systems of access control. The security level of such a system is a combinatorics question that can be assessed as following.

As was above considered we have n = 14 key elements with different resonance frequencies (Fig. 1b). One can pick up $k \leq n$ different key elements that allow $\binom{n}{k}$ different approaches to form personal tags for individual users. Let's assume that the user can simultaneously touch not more than $m \leq k$ key elements, taking into account that at least one key element must be touched, and the whole password is entered in p steps. Therefore, the password can be expressed as

$$Password = (f_{1,1}, f_{1,2}, \dots f_{1,v})(f_{2,1}, f_{2,2}, \dots f_{1,u}) \dots$$
$$\dots (f_{p,1}, f_{p,2}, \dots f_{p,s}), v, u, s \le m,$$

where $f_{i,j}$ – the one of k key elements/frequencies.

Thus, a number of possible variants for the password creation based on k key elements is

$$\left(\sum_{r=0}^{m}\binom{k}{r} - 1\right)^{p} = \left(\sum_{r=1}^{m}\binom{k}{r}\right)^{p},$$

where r is a number of the simultaneously touched key elements while m is the maximum value of the simultaneously touched key elements; and p is a number of steps of k-elements entering in-row.

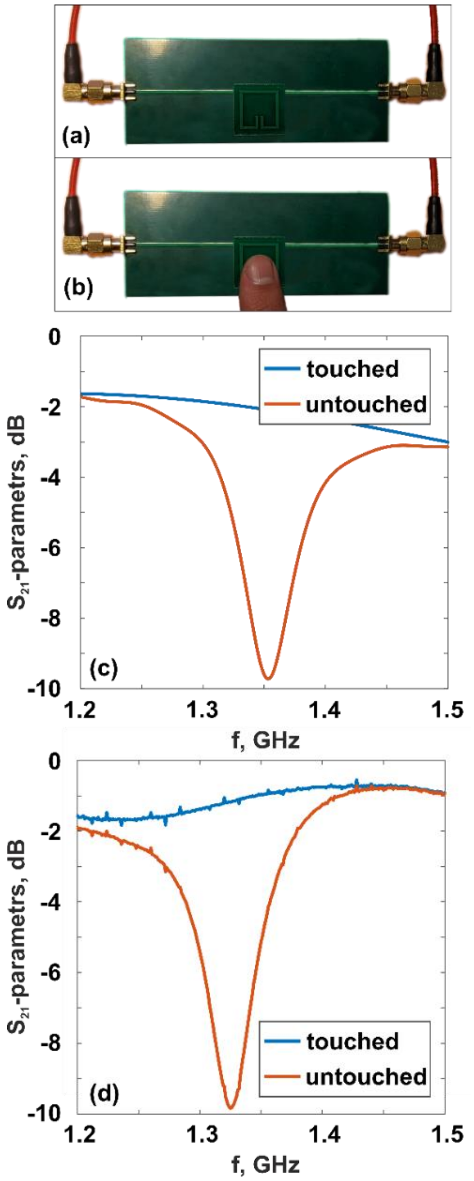

FIG. 2. Experimental setup for measurements of sensitive properties of the suggested device (a-b) as well as simulations (c) and experimental (d) results for the touched and untouched cases for the ring resonator with d = 5 mm – demonstration of changing of the output signal patterns.

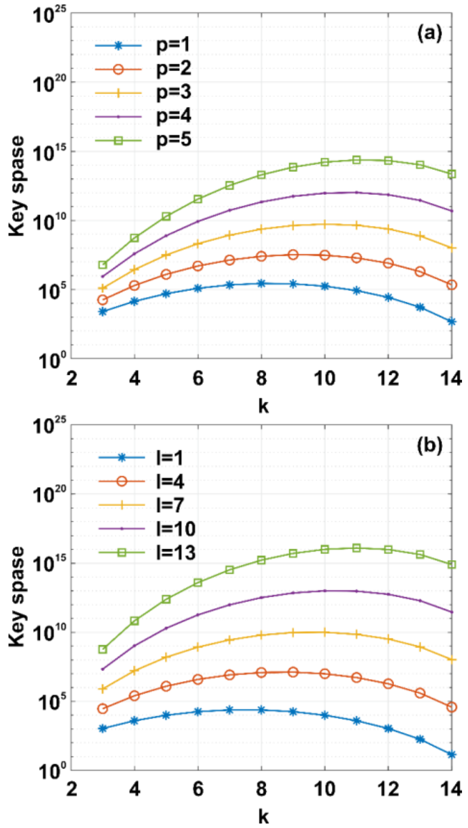

FIG. 3. The possible keyspace vs the number of picked up key elements k and steps of password entering p, taking into account that maximum m = 3 key elements can be touched simultaneously (a), as well as the possible keyspace vs a number of the number of picked up key elements k and password length l (b).

The whole keyspace for the system can be found as

$$KeySpace = \binom{n}{k}\left(\sum_{r=1}^{m}\binom{k}{r}\right)^{p}.$$

The appropriate dependence of the keyspace for different values of p = 1:5 is shown in Fig. 6a. If there is k = 3 and possible steps p = 3, thus the keyspace is more than 10^5, while for p = 5 the keyspace increases to 10^7.

One more variant of a password entering is sequential touching of an arbitrary sequence of k number of key elements. Thus, for the password length l the keyspace can be found as:

$$KeySpace = \binom{n}{k} k^{l}.$$

This variant allows simplification of detection process and is more convenient because only one finger-to-use is required. However, it is necessary to use a long combination $l > 10$ for $k = 3$ to provide an appropriate security level (Fig. 3b).

IV. CONCLUSION

This study successfully developed a novel type of EM device capable of generating unique output signal patterns, making it suitable for secure applications. The device relies on modifying a microstrip transmission line by incorporating ring resonators, which are highly sensitive EM components with impedance that can be easily adjusted by altering their shape. The research demonstrated that by extending the inner microstrip lines of the ring resonator from 1 to 13.5 mm, the resonance frequency can be shifted from 1 to 1.6 GHz. The integration of one or more ring resonators into the microstrip transmission line via strong near-field coupling, led to the appearance of deep minima in the transmission line's S_{21}-transfer function. These minima are the subject of control via direct contact with a human finger, which changes the resonator's total capacitance. This process of sequentially touching and untouching the ring resonator modulates the input signal and results the unique output signal patterns. As the number of ring resonators increased, the complexity of these patterns increases, offering a broad range of secure and distinctive patterns. These output signals can be effectively used as keys for creating passwords in access control systems. The security level of these passwords was evaluated by estimating the keyspace for different combinations of the developed ring resonators, revealing that the keyspace could exceed 10^{15} for the 14 key elements.

Therefore, this development has significant implications for the field of secure communications. The ability to generate a large number of unique and secure signal patterns using a relatively simple and compact device opens up new possibilities for protecting sensitive information. The combination of tunable resonance frequencies, the interaction of multiple ring resonators, and the modulating effect of human touch creates a versatile and powerful tool for enhancing security in a wide range of applications.

AUTHOR CONTRIBUTIONS

V.T. – conceptualization, methodology, investigation; writing (original draft preparation), writing (review and editing).

COMPETING INTERESTS

The author declare no competing interests.

REFERENCES

[1] J. García-García, F. Martín, J. D. Baena, R. Marqués, and L. Jelinek, "On the resonances and polarizabilities of split ring resonators," *J. Appl. Phys.*, vol. 98, no. 3, p. 033103, 2005.

[2] D. Dobrykh *et al.*, "3D genetic metamaterials for scattering maximization," *arXiv [physics.app-ph]*, 2024.

[3] 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 Tech.*, vol. 53, no. 4, pp. 1451–1461, 2005.

[4] L. J. Roglá, J. Carbonell, and V. E. Boria, "Study of equivalent circuits for open-ring and split-ring resonators in coplanar waveguide technology," *IET Microw. Antennas Propag.*, vol. 1, no. 1, p. 170, 2007.

[5] W. N. Hardy and L. A. Whitehead, "Split-ring resonator for use in magnetic resonance from 200–2000 MHz," *Rev. Sci. Instrum.*, vol. 52, no. 2, pp. 213–216, 1981.

[6] K. Aydin, I. Bulu, K. Guven, M. Kafesaki, C. M. Soukoulis, and E. Ozbay, "Investigation of magnetic resonances for different split-ring resonator parameters and designs," *New J. Phys.*, vol. 7, pp. 168–168, 2005.

[7] J. Zhou, T. Koschny, M. Kafesaki, E. N. Economou, J. B. Pendry, and C. M. Soukoulis, "Saturation of the magnetic response of split-ring resonators at optical frequencies," *Phys. Rev. Lett.*, vol. 95, no. 22, p. 223902, 2005.

[8] I. Al-Naib *et al.*, "Conductive coupling of split ring resonators: a path to THz metamaterials with ultrasharp resonances," *Phys. Rev. Lett.*, vol. 112, no. 18, p. 183903, 2014.

[9] F. Aznar, A. Vélez, M. Durán-Sindreu, J. Bonache, and F. Martín, "Open complementary split ring resonators: Physics, modelling, and analysis," *Microw. Opt. Technol. Lett.*, vol. 52, no. 7, pp. 1520–1526, 2010.

[10] C.-S. Lee, B. Bai, Q.-R. Song, Z.-Q. Wang, and G.-F. Li, "Open complementary split-ring resonator sensor for dropping-based liquid dielectric characterization," *IEEE Sens. J.*, vol. 19, no. 24, pp. 11880–11890, 2019.

[11] S.-Y. Jang and J.-R. Yang, "Double split-ring resonator for dielectric constant measurement of solids and liquids," *J Electromagn Eng Sci*, vol. 22, no. 2, pp. 122–128, 2022.

[12] M. Puentes, M. Maasch, M. Schubler, and R. Jakoby, "Frequency multiplexed 2-dimensional sensor array based on split-ring resonators for organic tissue analysis," *IEEE Trans. Microw. Theory Tech.*, vol. 60, no. 6, pp. 1720–1727, 2012.

[13] C. Reimann *et al.*, "Planar microwave sensor for theranostic therapy of organic tissue based on oval Split Ring Resonators," *Sensors (Basel)*, vol. 16, no. 9, p. 1450, 2016.

[14] S. P. Chakyar, S. K. Simon, C. Bindu, J. Andrews, and V. P. Joseph, "Complex permittivity measurement using metamaterial split ring resonators," *J. Appl. Phys.*, vol. 121, no. 5, p. 054101, 2017.

[15] K. Xu *et al.*, "Novel microwave sensors based on split ring resonators for measuring permittivity," *IEEE Access*, vol. 6, pp. 26111–26120, 2018.

[16] K. Grotov, A. Mikhailovskaya, D. Vovchuk, D. Dobrykh, C. Rockstuhl, and P. Ginzburg, "Superradiant broadband magneto-electric arrays empowered by meta-learning," *arXiv [physics.app-ph]*, 2023.

[17] A. M. Albishi, S. A. Alshebeili, and O. M. Ramahi, "Three-dimensional split-ring resonators-based sensors for fluid detection," *IEEE Sens. J.*, vol. 21, no. 7, pp. 9138–9147, 2021.

[18] 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.

[19] D. Vovchuk, M. Khobzei, and M. Khavruniak, "Sensing properties of SRR: Influence of finger touching," in *2019 IEEE International Scientific-Practical Conference Problems of Infocommunications, Science and Technology (PIC S&T)*, 2019.

[20] X. Hu and W. Yang, "Planar capacitive sensors – designs and applications," *Sens. Rev.*, vol. 30, no. 1, pp. 24–39, 2010.

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Система контролю доступу на основі сенсорних властивостей кільцевого резонатора

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АНОТАЦІЯ Робота присвячена розробленню нового типу електромагнітних (ЕМ) пристроїв для досягнення унікальних вихідних сигналів, що мають потенційне застосування у системах безпеки. Запропонований пристрій передбачає модифікацію мікросмужкової лінії передавання за допомогою кільцевих резонаторів. Кільцевий резонатор – це ЕМ компонент, який характеризується високою чутливістю, а його імпеданс можна легко налаштувати шляхом зміни геометричної форми. Це було здійснено шляхом подовження мікросмужкових ліній кільцевого резонатора від 1 до 13,5 мм, що дозволяє змінювати резонансну частоту від 1 до 1,6 ГГц, демонструючи можливість налаштування резонансу пристрою. Модифікація мікросмужкової лінії передавання за допомогою одного або кількох таких кільцевих резонаторів, завдяки їх сильному ближньопольовому зв'язку, призводить до появи глибокого мінімуму/мінімумів у функції передачі лінії (спектр параметрів-S_{21}). Цей мінімум може зникнути при прямому дотику кільцевого резонатора пальцем людини – через зміну загальної ємності кільцевого резонатора. Це означає, що послідовне доторкання/не доторкання до кільцевого резонатора призводить до модуляції вхідного сигналу лінії передавання та створення унікальних вихідних сигналів. Зі збільшенням кількості кільцевих резонаторів зростає і складність вихідних сигналів. Різноманітність сигналів може бути унікальною; таким чином, вихідні сигнали можуть слугувати ключем для створення пароля для систем контролю доступу. Щоб забезпечити відповідність рівня безпеки, що забезпечується пристроєм, необхідним стандартам, був оцінений розмір простору ключів – загальна кількість можливих унікальних сигналів для різних комбінацій розроблених кільцевих резонаторів. Аналіз показав, що при наявності 14 кільцевих резонаторів розмір ключового простору може перевищувати 10^{15}, що свідчить про велику кількість можливих комбінацій і, отже, дуже високий рівень безпеки.

КЛЮЧОВІ СЛОВА кільцевий резонатор, лінія передачі, безпека, простір ключів, контроль доступу.