Accepted Manuscript of: Z. Shaterian and M. Mrozowski, "Crack Detection in Metallic Surfaces Based on Dumbbell-Shaped Defected Ground Structures in Microstrip Technology," 2022 24th International Microwave and Radar Conference (MIKON), Gdansk, Poland, 2022, pp. 1-4, doi: 10.23919/MIKON54314.2022.9924958.

Crack Detection in Metallic Surfaces Based on Dumbbell-Shaped Defected Ground Structures in Microstrip Technology

Zahra Shaterian*
Department of Electrical Engineering
Technical and Vocational University (TVU)
Tehran, Iran
z.shaterian@gmail.com

Michal Mrozowski
**Department of Microwave and Antenna Engineering*
Gdansk University of Technology
Gdansk, Poland
m.mrozowski@ieee.org

***Abstract*—In this paper, a novel crack detection sensor using a microstrip loaded with a Dumbbell-Shaped Defected Ground Structure (DS-DGS) is proposed. The sensing element is etched in the ground plane of a microstrip line and it is easy to fabricate. The electromagnetic (EM) field of the microstrip couples to the DS-DGS, thus demonstrating a bandstop behavior. It is shown that in the presence of a crack in a metallic surface underneath the sensor, the resonance frequency of the DS-DGS is shifted. This frequency shift can be used for crack sensing in metallic surfaces. The proposed sensor exhibits a good sensitivity above 260 MHz shift for a crack with a 200 μm width at the relatively low operating frequency of around 2 GHz.**

***Index Terms*—Crack detection, dumbbell-shaped defected ground structure, metallic surface, microstrip.**

I. Introduction

Detection of corrosion and cracks in metallic surfaces, for instance in aircraft structures, oil or gas vessels, steam generator turbines, and steel bridges is a critical step in their safety assessment and maintenance. An extreme environment or overload of these structures can produce cracks which can cause catastrophic disasters. Therefore, these structures need to be regularly monitored for the existence of sub-millimeter-size cracks that can be easily concealed by dirt and dust or may be covered by paint or a dielectric coating. Several non-destructive evaluation techniques such as acoustic, ultrasonic, and eddy current testing methods have been used for this purpose. However, these methods have some limitations. For instance, detecting cracks hidden under coatings or under the paint is not possible using these methods.

Nowadays, microwave sensors are widely used in different industrial applications, such as localization [1]–[4], gesture recognition [5], monitoring pipeline coating [6], [7] and metal crack characterization [8], [9]. The popularity of microwave sensors for these applications is due to some advantages such as compact size, good penetration, non-contact and nondestructive sensing capability, high sensitivity, and robustness [10].

In [11], an open-ended waveguide was used to detect cracks in metallic surfaces. The metal surface without a crack is a good short-circuit load, while the presence of a crack in the metal surface can change the magnitude of the reflection coefficient at the waveguide aperture. Based on this principle, a sensor operating at around 20 GHz could detect a crack of around 1 mm width. Operating at a relatively high frequency, which leads to increased fabrication cost, is one of the drawbacks of this sensor. To overcome this problem in [12], resonator filters were proposed to detect cracks in metallic surfaces. It was shown that the presence of a crack causes a 10 MHz shift in the resonance frequency which is originally at 10 GHz. This sensor suffers from low sensitivity. To increase the sensitivity and decrease the operating frequency a crack sensor based on a complementary split-ring resonator (CSRR) was proposed in [13]. The sensor was quite successful in detecting a crack width of 0.2 mm. It also has a relatively good sensitivity, demonstrating a resonance frequency shift of 260 MHz (compare to the case without the crack) at the operating frequency of around 5 GHz. To further decrease the operating frequency while maintaining the good sensitivity, in this paper a novel sensor for crack detection using Dumbbell-Shaped Defected Ground Structure (DS-DGS) is proposed.

DGS resonators are slot resonators that are etched in the ground plane of transmission lines such as microstrip lines to produce a stop band. There are many types of DGS resonators and they have been used in a wide variety of applications including the implementation of microwave filters [14], [15], and planar antennas [16]. Recently, DGS resonators are also used for the design of highly sensitive microwave sensors, especially for the characterization of material properties [17], [18]. The reason is that the resonance frequency of slot resonators is very sensitive to the surrounding dielectric material. In this work, a microstrip loaded with a DS-DGS is used to detect cracks in metallic surfaces.

II. Sensor Design

Fig. 1 illustrates the top and side views of the proposed structure, which is located above an Aluminum block for crack sensing. As shown in the figure, the structure is composed of a microstrip line loaded with a folded DS-DGS resonator oriented normal to the microstrip line.

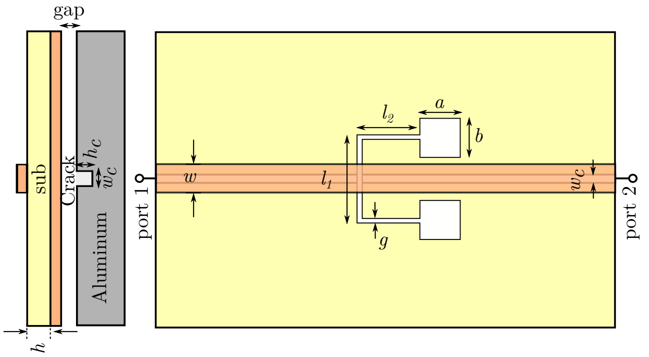

Fig. 1. Top and side views of the proposed structure, which is located above an Aluminum block for crack sensing. The microstrip line width is $w = 1.7$ mm, which corresponds to a 50 Ω characteristic impedance. The dimensions of the DS-DGS are: $a = 4$ mm, $b = 4$ mm, $g = 0.2$ mm, $l_1 = 2$ mm, $l_2 = 6$ mm. The dimensions of the crack are: $\omega_c = 0.2$ mm and $h_c = 0.2$ mm.

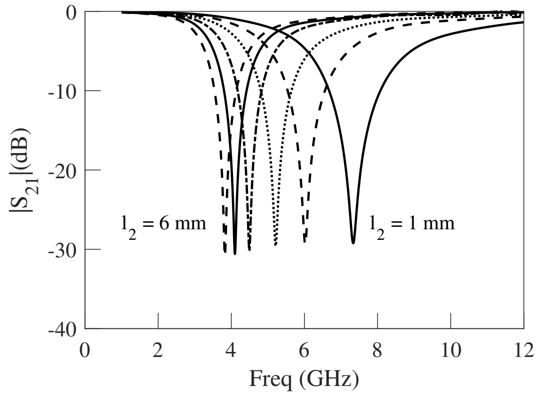

Fig. 2. Simulated magnitude of the transmission coefficients of the proposed sensor versus frequency for different values of l_2 from 1 mm to 6 mm in steps of 1 mm.

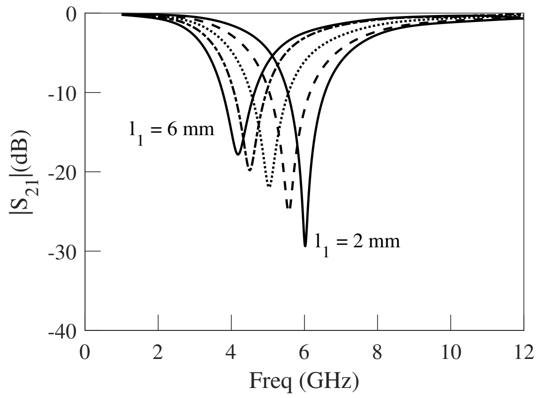

Fig. 3. Simulated magnitude of the transmission coefficients of the proposed sensor versus frequency for different values of l_1 from 2 mm to 6 mm in steps of 1 mm.

At the fundamental resonance, the folded DS-DGS resonator has an electric field orthogonal to its plane, and a magnetic field orthogonal to its symmetry plane. Since the microstrip line supports a quasi-TEM mode, the folded DS-DGS resonator shown in Fig. 1 can be excited by both vertical electric field, and in-plane (applied in the normal direction to the symmetry plane of the DS-DGS) magnetic field generated by the line. Thus, the microstrip line loaded with the DS-DGS structure exhibits a notch at the resonance frequency of the DS-DGS. It is important to note that EM field of the DS-DGS also exists below the ground plane. Therefore, its EM field and as a result its resonance frequency can be disturbed by nearby objects. For instance, the presence of a conductive material in the vicinity of the DS-DGS disturbs its EM field, and as a result increases its original resonance frequency. It will be shown in the next section that introducing a crack in the metallic surface results in a shift of resonance toward lower frequencies. Thus, monitoring the resonance frequency while moving the structure over the metallic surface can be used for detecting cracks.

III. Result and Discussion

To validate the proposed method, a crack detection sensor is designed and its performance is numerically simulated using HFSS full-wave EM simulation software. For simulation purposes, parameters of Rogers *RO4350* substrate with a thickness $h = 0.508$ mm, a relative permittivity $\epsilon_r = 3.66$, and dielectric loss tangent $\tan(\delta) = 0.004$ are used. Other dimensions as denoted in the caption of Fig. 1 are as follows. The microstrip line width is $w = 1.7$ mm, which corresponds to a 50 Ω characteristic impedance. The dimensions of the dumbbell-shaped defected ground structure are: $a = 4$ mm, $b = 4$ mm, $g = 0.2$ mm, $l_1 = 2$ mm, $l_2 = 6$ mm, and the dimensions of the crack are: $w_c = 0.2$ mm and $h_c = 0.2$ mm.

To gain insight into the behavior of the transmission notch by modifying the dimensions of the DS-DGS, the dimensions are initially set to $a = 2$ mm, $b = 2$ mm, $l_1 = 2$ mm, $l_2 = 2$ mm. In the first step, the variations in the length of the narrow slot of the DS-DGS (keeping the other dimensions unchanged) have been considered. This should mainly affect the capacitance of the resonant element. Fig. 2 depicts the simulation results that are obtained by varying the slot length l_2 from 1 mm to 6 mm in steps of 1mm. As expected, increasing of the slot length increases the capacitance that in turn decreases the resonance frequency. The simulated magnitude of the transmission coefficients of the proposed sensor for different values of vertical slot length l_1 from 2 mm to 6 mm in steps of 1 mm is shown in Fig. 3. By increasing l_1 the capacitance increases while the magnetic coupling of DS-DGS with the line decreases because they get further away from the line. Therefore, the resonance frequency decreases. The simulation results show that, increasing l_1 also results in a weaker resonance. Finally, the effect of changing the dimensions a and b of the rectangular defects are studies. The simulated magnitude of the transmission coefficients of the structure for different values of a and b from 1 mm to 4 mm in steps of 1mm are shown in Fig. 4. It can be seen from

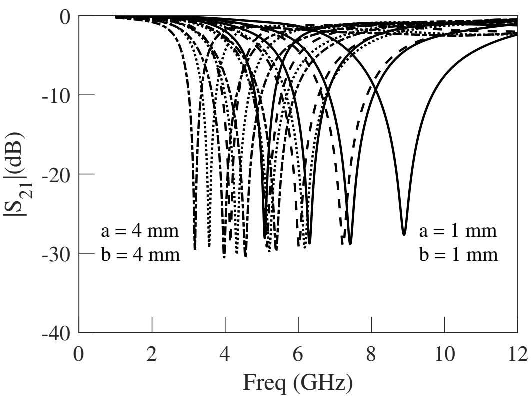

Fig. 4. Simulated magnitude of the transmission coefficients of the proposed sensor versus frequency for different values of a, b from 1 mm to 4 mm in steps of 1 mm.

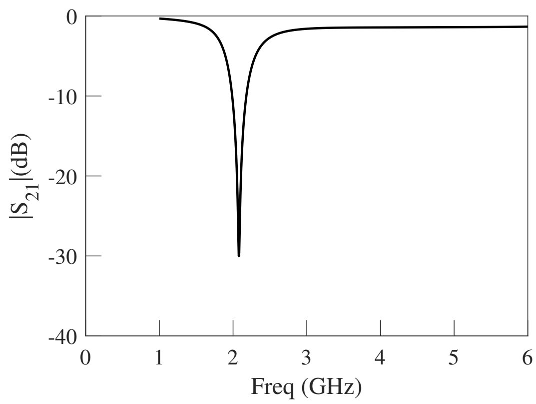

Fig. 5. Simulated magnitude of the transmission coefficient for the proposed sensor with dimensions as listed in the caption of Fig. 1 for working at frequency of $f \approx 2$ GHz.

this figure that increasing a and b decreases the resonance frequency while a resonance quality factor is increased. Note that for sensory applications a high quality factor resonance is desirable since it results in a high sensitivity.

Considering the results presented in Figs. 2 to 4, the dimensions of the DS-DGS can be chosen to have a high sensitivity sensor operating at preferably low frequency. With these aims in mind, the dimensions of the sensor are chosen as listed in the caption of Fig. 1. The simulated transmission coefficient of the proposed sensor with chosen dimensions is depicted in Fig. 5 and demonstrates an operating frequency of $f \approx 2$ GHz.

Once the DS-DGS is designed to operate in the frequency range of interest, the sensor is first placed directly above an Aluminum block without any cracks, and the resonance frequency of the structure is recorded as a reference. Then, a crack is presented in the Aluminum block and the new resonance frequency of the DS-DGS is monitored while the sensor is moved parallel to the metallic surface. Electromagnetic simulation results of the structure at these two states are depicted in Fig. 6. The figure shows that while the reference resonance frequency for a 0.1 mm air gap is at $f = 2.64$ GHz, the presence of a 200 μm crack results in a 264 MHz shift in the resonance frequency. In short, the simulation results show that the proposed sensor benefits from a relatively low operating frequency and high sensitivity for detecting cracks as narrow as 200 μm.

IV. Conclusion

A novel crack detection sensor using a microstrip line loaded with a dumbbell-shaped defected ground structure has been proposed. It has been shown that in this sensor the variation in the resonance frequency of the defected ground structure can be used to determine the presence of a crack in a metallic surface underneath the sensor. The proposed sensor benefits from a good sensitivity, and lower operating frequency compared to the state-of-the-art crack sensors.

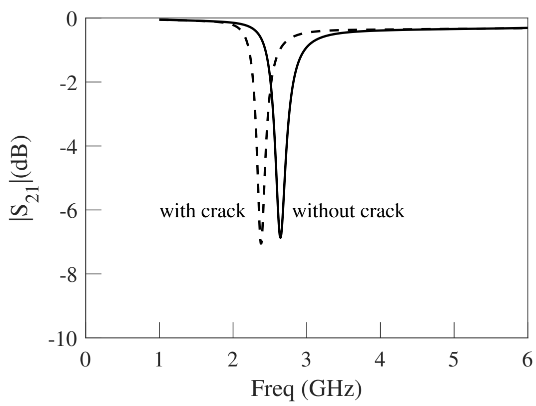

Fig. 6. Simulated magnitude of the transmission coefficients of the proposed sensor when the sensor is located above an Aluminum block with and without a crack.

References

[1] H. Guo, K.-S. Low, and H.-A. Nguyen, "Optimizing the localization of a wireless sensor network in real time based on a low-cost microcontroller," *IEEE Transactions on Industrial Electronics*, vol. 58, no. 3, pp. 741–749, Mar 2011.

[2] G. Han, C. Zhang, L. Shu, and J. J. P. C. Rodrigues, "Impacts of deployment strategies on localization performance in underwater acoustic sensor networks," *IEEE Transactions on Industrial Electronics*, vol. 62, no. 3, pp. 1725–1733, Mar 2015.

[3] Z. Shaterian, A. K. Horestani, and C. Fumeaux, "Rotation sensing based on the symmetry properties of an open-ended microstrip line loaded with a split ring resonator," in *2015 German Microwave Conference*. IEEE, Mar 2015.

[4] A. K. Horestani, Z. Shaterian, and F. Martin, "Detection modalities of displacement sensors based on split ring resonators: Pros and cons," in *2019 International Conference on Electromagnetics in Advanced Applications (ICEAA)*. IEEE, Sep 2019.

[5] S. Jiang, L. Li, H. Xu, J. Xu, G. Gu, and P. B. Shull, "Stretchable e-skin patch for gesture recognition on the back of the hand," *IEEE Transactions on Industrial Electronics*, vol. 67, no. 1, pp. 647–657, Jan 2020.

[6] M. H. Zarifi, S. Deif, M. Abdolrazzaghi, B. Chen, D. Ramsawak, M. Amyotte, N. Vahabisani, Z. Hashisho, W. Chen, and M. Daneshmand, "A microwave ring resonator sensor for early detection of breaches in pipeline coatings," *IEEE Transactions on Industrial Electronics*, vol. 65, no. 2, pp. 1626–1635, Feb 2018.

[7] S. Deif and M. Daneshmand, “Multiresonant chipless RFID array system for coating defect detection and corrosion prediction,” *IEEE Transactions on Industrial Electronics*, vol. 67, no. 10, pp. 8868–8877, Oct 2020.
[8] A. M. J. Marindra and G. Y. Tian, “Chipless RFID sensor tag for metal crack detection and characterization,” *IEEE Transactions on Microwave Theory and Techniques*, vol. 66, no. 5, pp. 2452–2462, May 2018.
[9] F. Mazlumi, S. H. H. Sadeghi, and R. Moini, “Interaction of rectangular open-ended waveguides with surface tilted long cracks in metals,” *IEEE Transactions on Instrumentation and Measurement*, vol. 55, no. 6, pp. 2191–2197, Dec 2006.
[10] Z. Chen, X. Q. Lin, Y. H. Yan, F. Xiao, M. T. Khan, and S. Zhang, “Noncontact group-delay-based sensor for metal deformation and crack detection,” *IEEE Transactions on Industrial Electronics*, vol. 68, no. 8, pp. 7613–7619, Aug 2021.
[11] C. Y. Yeh and R. Zoughi, “A novel microwave method for detection of long surface cracks in metals,” *IEEE Transactions on Instrumentation and Measurement*, vol. 43, no. 5, pp. 719–725, 1994.
[12] J. Kerouedan, P. Quéffélec, P. Talbot, C. Quendo, S. D. Blasi, and A. L. Brun, “Detection of micro-cracks on metal surfaces using near-field microwave dual-behavior resonator filters,” *Measurement Science and Technology*, vol. 19, no. 10, p. 105701, Aug 2008.
[13] A. M. Albishi, M. S. Boybay, and O. M. Ramahi, “Complementary split-ring resonator for crack detection in metallic surfaces,” *IEEE Microwave and Wireless Components Letters*, vol. 22, no. 6, pp. 330–332, Jun 2012.
[14] A. K. Horestani, Z. Shaterian, S. Al-Sarawi, D. Abbott, and C. Fumeaux, “Miniaturized bandpass filter with wide stopband using complementary spiral resonator,” in *2012 Asia Pacific Microwave Conference Proceedings*. IEEE, Dec 2012.
[15] A. K. Horestani, Z. Shaterian, W. Withayachumnankul, C. Fumeaux, S. Al-Sarawi, and D. Abbott, “Compact wideband filter element-based on complementary split-ring resonators,” in *SPIE Proceedings*, S. Juodkazis and M. Gu, Eds. SPIE, Dec 2011.
[16] A. K. Horestani, Z. Shaterian, T. Kaufmann, and C. Fumeaux, “Single and dual band-notched ultra-wideband antenna based on dumbbell-shaped defects and complementary split ring resonators,” in *2015 German Microwave Conference*. IEEE, Mar 2015.
[17] L. Su, P. Vélez, J. Muñoz-enano, and F. Martín, “Discussion and analysis of dumbbell defect-ground-structure (DB-DGS) resonators for sensing applications from a circuit theory perspective,” *Sensors*, vol. 21, no. 24, p. 8334, Dec 2021.
[18] L. Su, J. Munoz-Enano, P. Velez, J. Martel, F. Medina, and F. Martin, “On the modeling of microstrip lines loaded with dumbbell defect-ground-structure (DB-DGS) and folded DB-DGS resonators,” *IEEE Access*, vol. 9, pp. 150 878–150 888, 2021.