Application of Metamaterial-Inspired Resonators in Compact Microwave Displacement Sensors

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***Abstract*—There is an emerging interest in the application of metamaterial-inspired resonators for the realization of smart sensors. This paper briefly describes two main categories of metamaterial-inspired displacement sensors, namely, the displacement sensors based on shift in the resonance frequency, and sensors based on changes in the depth of resonance. The paper also highlights the advantages and disadvantages of each category in terms of dynamic range, sensitivity, compactness, and robustness to noise and changes in ambient conditions.**

I. Introduction

Beyond the initial application of metamaterial-inspired resonators for the realization of artificially engineered bulk materials with negative effective permittivity and/or permeability, these resonators also have found applications in the design of compact planar microwave circuits such as different types of filters [1]–[4]. Due to the subwavelength dimensions and the sensitivity of the resonance of metamaterial-inspired resonators, such as split ring resonators (SRRs) and complementary split ring resonators (CSRRs), to the constituent materials and physical dimensions, these resonators also have been widely used in the design of various types of high sensitivity sensors [5]–[12]. In recent times, there has been an increasing interest in the application of metamaterial-inspired resonators to the design of high-resolution displacement sensors that are robust to environmental noise and ambient conditions [7], [12]–[16]. Thus, this paper describes and compares the two main methods of realization of metamaterial-inspired displacement sensors, namely, sensing based on shift in the resonance frequency and sensing based on changes in the depth of resonance.

II. Metamaterial-Inspired Displacement Sensors

A. Sensors Based on Shift in the Resonance Frequency

The resonance frequency of metamaterial resonators such as SRRs and CSRRs can be expressed as $f_0 = 1/2\pi\sqrt{LC}$, where L and C are the equivalent inductance and capacitance of the resonator, respectively. Thus, a change in the equivalent inductance or capacitance of the resonator results in a shift in the resonance frequency. This principle was used by Shaterian *et al.* [14] to design a high dynamic range displacement sensor based on a microstrip line loaded with a pair of broadside coupled SRRs (BC-SRRs). As shown in Fig. 1 each BC-SRR was formed by two overlapping U-shaped rings. In this configuration a displacement of the upper U-shaped rings results in a decrease in the equivalent capacitance, which results in shifting the resonance frequency to higher frequencies. The shift in the resonance frequency can therefore be used to sense the amount of displacement along the direction of the microstrip line. Similarly, a microstrip line loaded with a pair of triangular-shape CSRRs along with two ultra-wideband monopole antennas were used by Mandel *et al.* [17] to realize a wireless two-dimensional displacement sensor based on a shift in the resonance frequency.

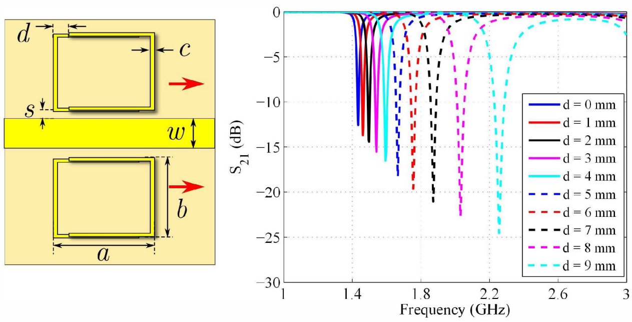

Fig. 1. The layout and simulation results of a displacement sensor based on a shift in the resonance frequency.

B. Sensors Based on Variations in the Depth of Notch Due to Break of Symmetry

Recently, Naqui *et al.* [5], [7] proposed displacement sensors based on symmetry properties of a SRR-loaded coplanar waveguide (CPW). In their sensors, at the initial position when the symmetry plane of the rectangular SRR is aligned with the symmetry plane of the loaded CPW, the SRR can not be excited. Thus, signal transmission between input and output ports are allowed. However, if the symmetry is broken by a lateral displacement of the SRR, a notch caused by the excitation of the SRR, appears in the transmission spectrum. Thus, the value of displacement can be sensed from the depth of the notch.

To improve the displacement sensors based on symmetry properties of SRRs, Horestani *et al.* [13] showed that, through an optimization process, a tapered diamond-shaped SRR can be designed, not only to reduce the physical size [18] and achieve a high dynamic range, but also to suppress the undesired shift in the resonance frequency. Thus, the sensor can be operated at one single frequency. Layouts and simulation results of the sensors based on rectangular, and

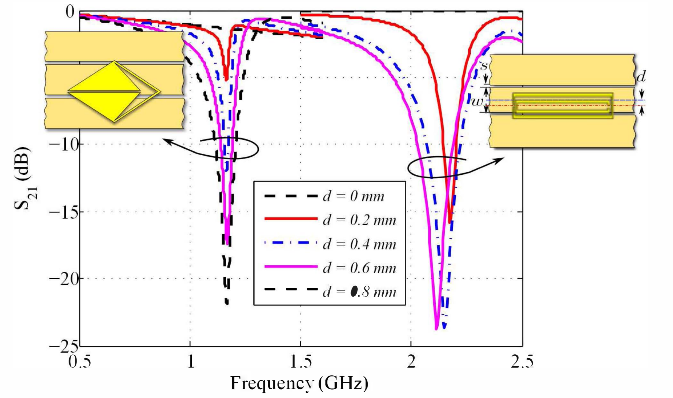

Fig. 2. The layouts and comparison between simulation results of displacement sensors based on rectangular SRRs (with notches above 2 GHz) and tapered diamond-shaped SRRs (with notches at 1.17 GHz).

tapered diamond-shaped SRRs are depicted in Fig. 2.

The symmetry properties of SRR-loaded microstrip lines were also used for the realization of one- and two-dimensional displacement sensors based on the depth of the resonant notch(es) in the reflection coefficient(s) of the structure [16].

III. Comparison Between the Two Categories of Displacement Sensors

Since, in comparison to the amplitude, the frequency of a signal is less susceptible to noise, the sensors based on a shift in the resonance frequency, benefit from a high immunity to environmental noise, whereas depth of notch in the sensors based on symmetry properties of SRRs can be affected by environmental noise. On the other hand, since the resonance frequency of a resonator is sensitive to changes in the physical dimensions of the resonator or changes in the permittivity of the surrounding material, the sensors based on a shift in the resonance frequency are more vulnerable to environmental variations such as changes in temperature. In contrary, operation based on the symmetry properties of SRRs makes the second type of sensors to be more robust to environmental changes, which usually apply to the whole structure and don't affect its symmetry. To combine the advantages of both types of sensors, recently one- and two-dimensional displacement sensors based on separation of resonance frequencies resulting from a break of symmetry, were proposed by Horestani *et al.* [15].

Regarding the dynamic range and sensitivity, both types of displacement sensors can be tailored to achieve a high sensitivity at the cost of a smaller dynamic range, or vice versa. However, as a general observation, achieving a high dynamic range is easier in the sensors based on a shift in the resonance frequency, for instance by using a BC-SRR with longer U-shaped rings. In contrast, the sensors based on symmetry properties of SRRs are more sensitive to small values of displacement, however they generally have a smaller dynamic range.

IV. Conclusion

The advantages and disadvantages of the two main categories of metamaterial-inspired displacement sensors, i.e. sensors operating based on shift of resonance frequency and those based on changes in the depth of transmission or reflection notch, have been reviewed. On that basis, it has been highlighted that, depending on the priority of system specifications such as dynamic range, sensitivity, frequency of operation, compactness, or robustness to noise and changes in ambient conditions, one or the other type of sensor will be preferred.

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