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Two-dimensional alignment and displacement sensor based on movable broadside-coupled split ring resonators

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ABSTRACT

This paper proposes a two-dimensional alignment and displacement sensor based on movable broadside-coupled split ring resonators (BC-SRRs). As a basis for this sensor, a one-dimensional displacement sensor based on a microstrip line loaded with BC-SRRs is presented firstly. It is shown that compared to previously published displacement sensors, based on SRR-loaded coplanar waveguides, the proposed one-dimensional sensor benefits from a much wider dynamic range. Secondly, it is shown that with modifications in the geometry of the BC-SRRs, the proposed one-dimensional sensor can be modified and extended by adding a second element to create a high-dynamic range two-dimensional displacement sensor. Since the proposed sensors operate based on a split in the resonance frequency, rather than the resonance depth, they benefit from a high immunity to environmental noise. Furthermore, since the sensors' principle of operation is based on the deviation from symmetry, they are more robust to ambient conditions such as changes in the temperature, and thus they can be used as alignment sensors as well. A prototype of the proposed two-dimensional sensor is fabricated and the concept and simulation results are validated through experiment.

1. Introduction

The concept of metamaterials was originally proposed for the realization of artificially engineered bulk materials with positive, near zero, or negative effective permittivity and/or permeability [1–3]. However, due to their sub-wavelength dimensions, metamaterial fundamental elements such as split ring resonators (SRRs), have also found applications in the design of compact one- and two-dimensional planar circuits such as filters [4–10], couplers [11–15], and antennas [16–18], or to improve the performance of these components [19,20]. It has been also shown that due to the high quality factor, subwavelength dimensions, and the localized sensitivity of the resonance to the constituent materials and physical dimensions, SRRs can be used in the design of high sensitivity and high resolution sensors [21–28], or to enhance the sensitivity of the conventional sensors [29].

Recently, one- and two-dimensional displacement sensors based on symmetry properties of SRR-loaded coplanar waveguide (CPW) have been proposed [21,24,27]. In these sensors a displacement was characterized by measuring the depth of the notch in the transmission coefficient of the loaded CPW. Other displacement sensors based on the shift of resonance frequency are reported in [30,31]. The main advantage of the sensors based on symmetry properties over those based on the shift of resonance frequency is that external (ambient) conditions may affect the resonators' resonance frequency but not the transparency of the loaded lines with perfectly aligned resonators. Thus, the sensors based on symmetry properties of SRR-loaded CPW are more robust and specially suited for alignment purposes. However, they have a fundamental dynamic range limitation, set by the width of the CPW signal strip.

This paper proposes a two-dimensional displacement sensor based on a microstrip line loaded with modified broadside-coupled SRRs (BC-SRRs). In contrast to the above-mentioned displacement sensors [21,24,27], in which a fundamental dynamic range limit was dictated by the CPW's lateral dimension, the proposed sensor has virtually no dynamic range limit. Moreover, since the operation principle is based on symmetry properties of the structure, it is more robust to ambient conditions and can be also used as a two-dimensional alignment sensor.

In contrast to other techniques for measuring displacement, such as laser-based displacement sensors, our proposed technique is especially suitable for measuring relative displacement between two two-dimensional surfaces, and of special interest for detecting any misalignment between such surfaces.

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2. One-dimensional displacement sensor based on broadside coupled split ring resonators

Fig. 1(a) and (b) illustrate the side and top view of the one-dimensional displacement sensor [31], which is composed of a microstrip line loaded with a pair of BC-SRRs. Each BC-SRR is composed of two U-shaped split-rings printed on different layers, on top of each other and open in opposite directions. Note that in this structure one of the rings is printed on the same layer as the microstrip line, so it is fixed, while the second ring is on the top layer of a second substrate, which can be displaced along the direction of the microstrip line, as shown by the red arrows in the figure. The aim of the sensor is to measure this displacement.

The BC-SRR can be modeled as a parallel LC resonator [32], in which the equivalent capacitance corresponds to the capacitance of the overlapping metallic area of the two U-shaped rings, and the equivalent inductance corresponds to the rectangular loop formed by the two U-shaped rings. The BC-SRR's resonance frequency is related to its equivalent capacitance and inductance by $f = 1/2\pi\sqrt{LC}$. In the configuration shown in the figure, an increase in the displacement Δx of the upper ring results in a decrease in the equivalent capacitance and an increase in the equivalent inductance of the BC-SRR. However, as shown in the simulation results of Fig. 1(c) and analyzed in Appendix, the change in the equivalent capacitance is dominant, which results in a shift of resonance frequency to higher frequencies. The shift in the resonance frequency can therefore be used to sense the amount of displacement in x direction. Note that the dynamic range of the sensor has virtually no intrinsic geometric limitation and can be increased by using longer BC-SRRs. Dimensions of the simulated structure are listed in the caption of Fig. 1.

Fig. 2(a) and (b) illustrate the side and top views of a novel one-dimensional sensor, in which the BC-SRRs are rotated such that a lateral displacement increases the equivalent capacitance of one of the BC-SRRs, while it decreases the equivalent capacitance of the other BC-SRR. Also, the equivalent inductance of one of the resonators is decreased, while that of the other resonator is increased. Therefore, as shown with the blue solid line in Fig. 2(c), at the initial position, i.e. for $\Delta y = 0$ mm, when the symmetry plane of the top substrate is aligned with the symmetry plane of the microstrip line, both resonators are identical, and only one notch in the transmission coefficient of the loaded TL appears at f_{y0}. However, when the symmetry is broken by a lateral displacement of the upper substrate, one of the BC-SRRs becomes smaller than the other one, resulting in the splitting of the resonance in two notches f_{y0} and f_{y1} in the transmission spectrum of the TL. Thus, the frequency difference between the two notches $\Delta f_y \overset{\text{def}}{=} f_{y1} - f_{y0}$ can be used to sense the lateral displacement.

Simulation results show that compared to the previously published displacement sensors [27,33], where an intrinsic dynamic range limitation of about 1 mm was dictated by the CPW's lateral dimensions, the proposed sensor has a much larger dynamic range of 3 mm. Note that this work is a proof-of-concept, upon which the dynamic range in the proposed sensors can be enhanced by enlarging the resonant elements in the direction of displacement. By doing this, the variable capacitance between intersecting (i.e. face-to-face) metallic elements of the resonator can provide a wider dynamic range. Also, since the proposed sensor operates based on a split in the resonance frequency rather than the resonance depth, it benefits from a higher immunity to environmental noise [33]. Furthermore, since the operation principle of the sensor is based on the break in symmetry arising from the displacement, the sensor is robust to variable ambient conditions such as changes in the temperature, and can be also used as alignment sensor [24,27].

3. Two-dimensional displacement sensor

With some geometrical modifications, the proposed one-dimensional sensor can be extended to a dual-element configuration operating as a two-dimensional alignment and displacement sensor. To this end, as shown in Fig. 3, one possible strategy is to introduce a right angle bend in the microstrip line, and etch a pair of BC-SRRs with orthogonal orientation in each section. The pairs of BC-SRRs need to have different dimensions to resonate at sufficiently different frequencies such that a displacement in x direction can be distinguished from that in y direction. Furthermore, the geometry of the resonators needs to be modified so that the resonant frequency is altered by the displacement in one direction only. To this end, the upper rings are replaced with straight strips. In this configuration, provided the strips are long enough, the pair of the modified resonators that are coupled to the horizontal section of the microstrip line is only sensitive to a displacement in y direction, while the pair of the modified BC-SRRs coupled to the vertical section of the line is only responsive to a displacement in x direction. In a practical system, in order to avoid abrasion of metallic layers and substrates, and consequently to increase the

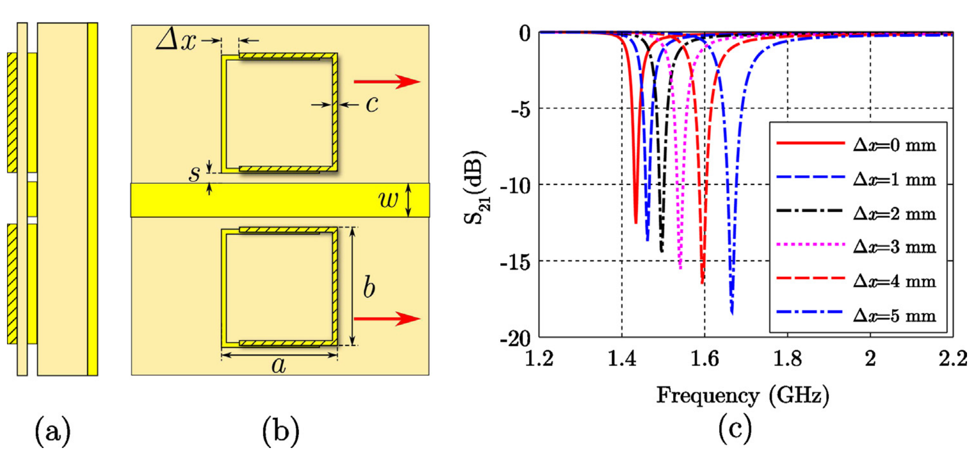

Fig. 1. (a) Side view and (b) top view of the displacement sensor based on BC-SRRs. Rogers *RO4003* substrates with relative permittivity of 3.38 and copper metallization with thickness of 35 μm are used. The thickness of the bottom and top substrates are 1.524 mm and 0.203 mm, respectively. The width of the microstrip line is w = 3.3 mm which corresponds to a 50 Ω characteristic impedance. Other dimensions of the structure are a = 10.2 mm, b = 12.4 mm, c = 0.4 mm, and s = 0.2 mm. (c) Simulated transmission coefficients of the structure for different values of displacement from Δx = 0 mm to Δx = 5 mm in steps of 1 mm. (For interpretation of the references to color in text, the reader is referred to the web version of the article.)