Rotation Sensor Based on Horn-Shaped Split Ring Resonator

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***Abstract*— This paper presents a rotation sensor based on a modified split ring resonator (SRR) coupled to a coplanar waveguide. It is shown that compared with previous SRR-based rotation sensors, the proposed sensor benefits from a higher dynamic range and superior linearity. It is shown that the geometry of the SRR can be optimized to compensate for the non-uniformity of the magnetic flux through the SRR, in order to suppress the unwanted frequency shift in the resonance. This is a significant improvement because the sensor can be operated as an inexpensive single frequency system. The concept and simulation results are validated by experimental measurements.**

***Index Terms*— Microwave sensors, metamaterials, rotation sensor.**

I. Introduction

BEYOND the initial goals of creating artificially engineered materials with electromagnetic constitutive parameters not available in nature, such as double-negative materials, metamaterials have opened new perspectives for other novel applications such as high-quality resonators [1] and compact filters [2]. Also, it has been shown that metamaterial-inspired resonators such as split ring resonators (SRRs) are ideal structures for the design of high sensitivity and high resolution sensors because of their high quality factor resonance, subwavelength dimensions, as well as sensitivity to changes in surrounding materials and physical dimensions [3]–[8].

Recently, displacement and rotation sensors based on symmetry properties of SRRs have been published in [9], [10]. As explained in detail in [9], [10], a displacement or rotation of an SRR coupled to a coplanar waveguide (CPW) produces a notch in the transmission coefficient of the structure, when the SRR is displaced from the symmetry plane of the CPW. Since the depth of the notch is dependent on the displacement or rotation of the SRR, this spectral feature can be used to sense the amount of the displacement or rotation. Sensors of this type are more robust to changes in ambient conditions such as temperature and humidity, since they operate based on the change in the depth of notch rather than shift in the resonance frequency. However, one limitation of the sensors is that a change in displacement or a rotation not only changes the depth of resonance, but also causes a shift in the resonance frequency. Thus, their operation requires a frequency sweeping microwave source such as an expensive network analyzer. In a previous work [11] the authors showed that the shift in the resonance frequency in the displacement sensor based on uniform rectangular SRR is due to the non-uniformity of the magnetic flux passing through the SRR surface. Thus, the frequency shift can be suppressed by modifying the shape of the SRR to compensate the non-uniformity of the SRR's magnetic coupling by precisely adjusting its electric coupling.

In the present letter we show that a similar approach, based on the modification of the SRR shape, can be used to design a rotation sensor that not only operates at a single fixed frequency but also benefits from a higher dynamic range and superior linearity.

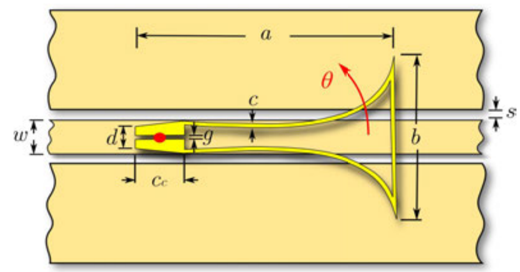

Fig. 1. Top view of the CPW loaded with a horn-shaped SRR. The angle and center of rotation are marked with a red arrow and a red dot, respectively. For electromagnetic simulation the parameters of a 0.127 mm thick RO3010 material with relative permittivity of 10.2 and copper metalization of 35 μm on both sides are used. The dimensions of the 50 Ω CPW and the horn-shaped SRR are as follows: $w = 1.67$ mm, $s = 0.2$ mm, $a = 12.6$ mm, $b = 7.8$ mm, $c = 0.2$ mm, $g = 0.2$ mm, $d = 1.1$ mm, and the optimized value of $c_c = 2.4$ mm.

II. Rotation Sensor Based on Horn-Shaped SRR

The proposed rotation sensor is composed of a CPW loaded with a horn-shaped SRR as illustrated in Fig. 1. The design starts by changing the rectangular SRR to a trapezoidal SRR, which increases the dynamic range [11]. Next, the SRR sides are curved (as a 3-point spline) and the curvature is optimized to achieve a linear response. Finally, the length of the SRR's split is adjusted to achieve a fixed operating frequency. The geometric dimensions of the optimized structure are listed in the caption of Fig. 1 and are scalable to achieve a desired operation frequency.

Figure 2 compares the simulated transmission coefficients of the proposed sensor (solid lines) with those of a rectangular rotation sensor similar to the rotation sensor in [9] (dashed lines) for a rotation of the SRRs from $\theta = 0°$ to $6°$ in steps of $2°$. The figure clearly shows that while there is an angle-dependent shift in the resonance frequencies for the rectangular SRR, in the case of the optimized horn-shaped SRR all notches are at a fixed frequency $f = 1.38$ GHz.

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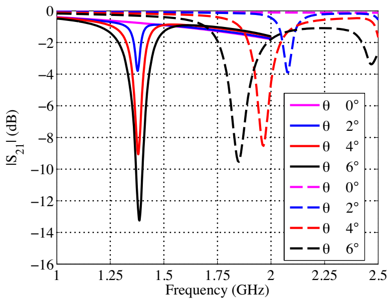

Fig. 2. Simulated transmission coefficients of the horn-shaped rotation sensor sensor (solid lines), and those of a rectangular-shaped rotation sensor (dashed lines) for the rotation of the SRRs from $\theta = 0°$ to $6°$ in steps of $2°$.

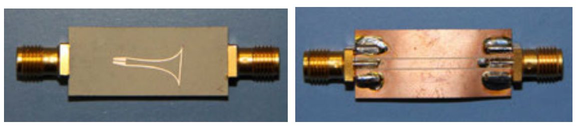

Fig. 3. Top and bottom view of one of the fabricated samples with $\theta = 5°$.

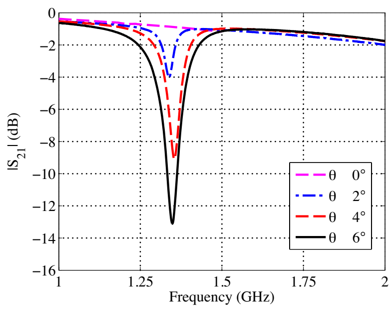

Fig. 4. Measured transmission coefficients of the horn-shaped sensor for the rotation of the SRR from $\theta = 0°$ to $6°$ in steps of $2°$.

For proof-of-principle experimental validation of the concept, several versions of the rotation sensors were fabricated on a single substrate with different fixed angles of rotation ranging from 0° to 8°. Fig. 3 shows the top and bottom view of one of the samples with $\theta = 5°$. The samples are fabricated on a 0.127 mm thick RO3010 material with relative permittivity of 10.2 and 35 μm thick copper metalization. The dimensions of the prototypes are as given in the caption of Fig. 1. Figure 4 depicts the measured transmission coefficients of the sensor for different values of rotation angle $\theta = 0°, 2°, 4°$, and $6°$. The figure shows a fixed resonance frequency at $f = 1.36$ GHz, which is in good agreement with the simulation results shown in Fig. 2. The slight frequency shifts can be attributed to the small discrepancy between different fabricated samples.

Figure 5 compares the rotation angle dependence of the response for the rectangular and horn-shaped SRR sensors. For the rectangular sensor, the simulated depth of the notch, i.e. $\min(|S21|)$, is shown as a function of the angle. For the proposed horn-shaped sensor, the simulated transmission coefficients at a fixed frequency ($f = 1.38$ GHz) is plotted versus the rotation of the SRR. Additionally in the figure, the horn-shaped sensor simulations are successfully validated with the corresponding experimental data measured at $f = 1.36$ GHz. It is worth emphasizing that, for the rectangular sensor the center frequency of the notches varies with the angle of rotation. In contrast, the horn-shaped sensor operates at a fixed frequency, and thus does not need a frequency sweeping system. The comparison also shows that, the proposed sensor

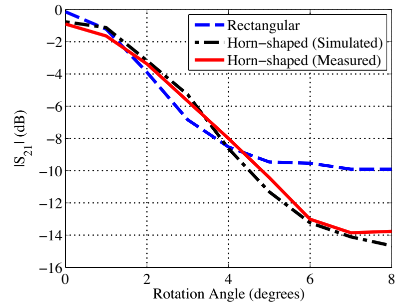

Fig. 5. Simulated depth of notch versus rotation angle for the sensor based on rectangular SRR (blue dashed line), and the simulated and measured transmission coefficients versus rotation angle for the horn-shaped sensor at a fixed frequency (black dash-dot line at 1.38 GHz and red solid line at 1.36 GHz, respectively).

benefits from a higher dynamic range which extends to about 7° compared to 5° for the rectangular sensor, and that it has a superior linearity in its dynamic range.

III. Conclusion

A rotation sensor based on a horn-shaped SRR has been presented. Compared to previous SRR-based rotation sensors, the proposed sensor benefits from superior linearity and around 40% higher dynamic range. More importantly, it has been shown that the unwanted frequency shift in the characteristic of the previous rotation sensor can be suppressed by precisely adjusting the length of the SRR's split. This is a significant improvement since the sensor does not require a frequency sweeping microwave source, but can be operated as an inexpensive single frequency system. The proposed sensor is possibly of greater interest in a scaled down structure using MEMS technology.

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