Two-dimensional displacement and alignment sensor based on reflection coefficients of open microstrip lines loaded with split ring resonators

A.K. Horestani, J. Naqui, D. Abbott, C. Fumeaux and F. Martín

A two-dimensional displacement and alignment sensor is proposed based on two open-ended transmission lines, each loaded with a split ring resonator (SRR). In this arrangement, the depth of resonance-induced notches in the reflection coefficients can be used to sense a displacement of the loading SRRs in two orthogonal directions. Since the operation principle of the sensor is based on the symmetry properties of SRR-loaded transmission lines, the proposed sensor benefits from immunity to variations in ambient conditions. More importantly, it is shown that in contrast to previously published metamaterial-inspired two-dimensional displacement and alignment sensors, the proposed sensor can be operated at a single fixed frequency. The concept and simulation results are validated through measurement.

Introduction: In recent years, the application of metamaterial-inspired resonators such as split ring resonators (SRRs) to sensors has attracted increasing interest [1–4]. This has arisen because of the subwavelength dimensions, high-quality factor resonance and sensitivity of the resonance characteristics of these elements to their physical dimensions and constituent materials. Various types of displacement and rotation sensors based on variation of resonance frequency, quality factor and notch depth in the transmission spectrum of SRR-loaded transmission lines (TLs) have been proposed in the literature [1, 5–8]. The concept was also extended for the design of two-dimensional displacement sensors [9, 10].

This Letter proposes a two-dimensional displacement and alignment sensor based on variation in the depth of the resonant notch in the reflection coefficients of the two SRR-loaded microstrip lines. Since both SRRs and microstrip lines are inherently compact structures, the proposed sensor benefits from a small size. Furthermore, since the operation principle of the sensor is based on the symmetry properties of the SRRs, the sensor is robust to ambient conditions such as changes in temperature. It is also shown that because the excitation from microstrip lines imposes an almost constant loading effect on the SRRs, displacement is only manifested in the depth of the notch, leaving the resonance frequency intact. This is an important feature because it enables the sensor to work at a fixed frequency. This sensing mode allows operation based on two reflection coefficients rather than using the transmission coefficient of the structure, where at least two fixed frequencies are required for the operation of two-dimensional displacement sensors [9, 10].

Two-dimensional displacement and alignment sensor: Illustrations of the top and side views of the proposed sensor are depicted in Figs. 1*a* and *b*. The structure is composed of two substrates. On the bottom substrate, two open-ended microstrip lines along the *x*- and *y*-axis are excited at port 2 and port 1, respectively. Each TL is loaded with a SRR, which is patterned on the top substrate. As shown in the side view of the structure in Fig. 1*b*, the second substrate is separated from the first substrate by an air gap, and can be moved in *x*- and *y*-directions. At the initial position, the symmetry plane of each of the SRRs is aligned with the symmetry plane of the corresponding TLs. Thus, because the symmetry of the structure the SRRs are not excited by the TLs, and full reflection is observed at both the ports. However, if the alignment is broken by a displacement in the *x*- and/or *y*-direction(s), the SRR(s) will be excited and notch(es) will appear in the corresponding reflection coefficient(s). Further displacement in the *x*- and/or *y*-directions results in a stronger coupling between the TLs and the SRRs, in turn resulting in deeper notch(es) in the respective reflection coefficient(s) ($|S_{11}|$ and/or $|S_{22}|$) at the resonance frequency of the SRRs. Note that displacement in the *x*-direction has no effect on the depth of notch in $|S_{22}|$ and vice versa. Thus, misalignment in the *x* and *y* directions can be independently sensed from the depth of notches in $|S_{11}|$ and $|S_{22}|$, respectively. One advantage of this method is that both SRRs can be designed to operate at the same resonance frequency. This is in contrast to the previously proposed two-dimensional displacement sensors based on transmission characteristics of a through TL, where SRRs needed to have distinct resonance frequencies [9, 10].

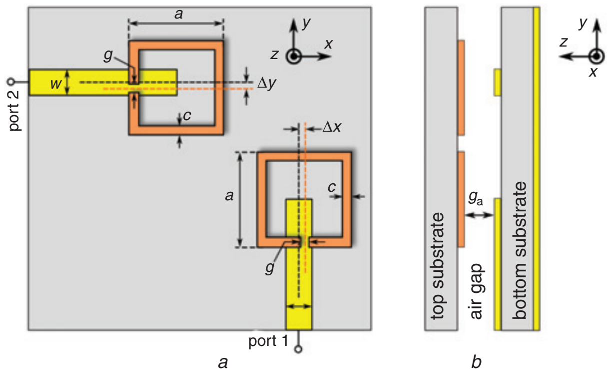

Fig. 1 *Proposed two-dimensional displacement and alignment sensor*
a Top view
b Side view

For electromagnetic simulations, two 0.81 mm-thick Rogers RO4003 substrates ($\varepsilon_r = 3.38$ and $\tan\delta = 0.0022$) with 35 µm-thick copper metallisation are used. The dimensions of the 50 Ω microstrip lines and the square SRRs are as follows: $w = 1.84$ mm, $a = 7$ mm, $g = 0.5$ mm, $c = 0.5$ mm and $g_a = 0.76$ mm. Fig. 2 shows the simulated reflection coefficient of the proposed sensor at port 1 for different values of Δx from 0.1 to 0.8 mm in steps of 0.1 mm. Since both the SRRs have identical dimensions, the simulated $|S_{22}|$ against Δy has an identical behaviour. The Figure clearly shows the variation of notch depth in $|S_{11}|$ (or $|S_{22}|$) with displacement in the *x*- (or *y*-) direction. An important feature of the proposed sensor is that since the excitation from the TLs imposes an almost constant – predominantly electrical – loading effect on the SRRs, a displacement only affects the depth of the notch, without altering the resonance frequency. This is in contrast to the previously proposed displacement sensors, in which due to cross-polarised coupling and loading effects, a displacement affected both the depth of the notch and the resonance frequency [5, 6, 8, 11].

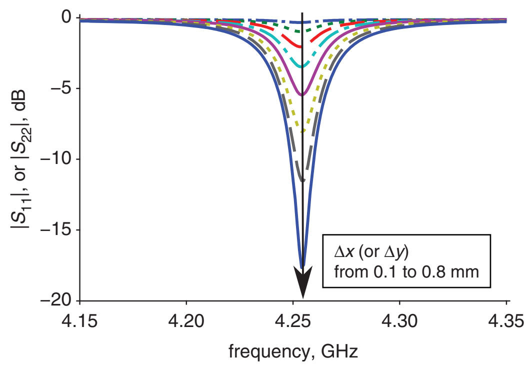

Fig. 2 *Simulated $|S_{11}|$ (or $|S_{22}|$) of structure for different values of displacement Δx (or Δy) from 0.1 to 0.8 mm in steps of 0.1 mm*
Note that due to symmetry of structure, behaviour of $|S_{22}|$ with respect to Δy is identical to that of $|S_{11}|$ with respect to Δx

To investigate the mutual effect of displacement in the *x*- and *y*-directions on the functionality of the sensor, Fig. 3 shows the simulated $|S_{11}|$ against displacement in the *x*-direction, at a fixed frequency $f = 4.253$ GHz, whereas displacement in the *y*-direction is changed from 0 to 0.8 mm in steps of 0.2 mm. Obviously, due to the symmetry of the structure, an identical behaviour is expected for the effect of Δx on $|S_{22}|$ against Δy. The Figure shows that sensing relatively large values of Δx is slightly affected by displacement in the *y*–direction; however, Δy has almost no effect on sensing smaller values of Δx ($\lesssim$0.4 mm). This is a crucial feature of the proposed structure for application as a two-dimensional alignment sensor.

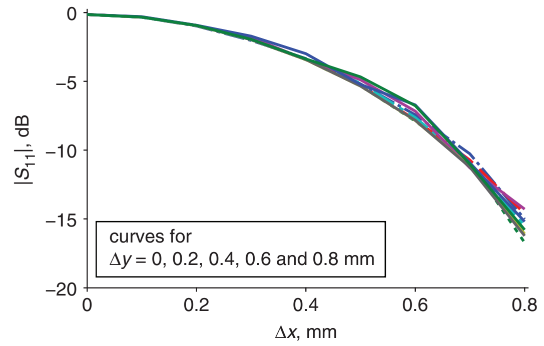

Fig. 3 *Simulated depth of notch against Δx, at fixed frequency f = 4.253 GHz, for different values of Δy from 0 to 0.8 mm in steps of 0.2 mm*

Owing to symmetry of proposed sensor, identical plot also describes dependency to displacement in *x*-direction for $|S_{22}|$ against Δ*y*

Experimental results: To validate the concept and the simulation results, a prototype of the sensor has been fabricated and measured. Fig. 4 depicts the photograph of the fabricated prototype, which includes two microstrip lines fabricated on the first substrate, whereas the SRRs are etched on the movable top substrate. As in the simulations, Rogers RO4003 material is used for both the substrates. The dimensions of the fabricated microstrip lines and SRRs correspond to the dimensions of the simulated structure.

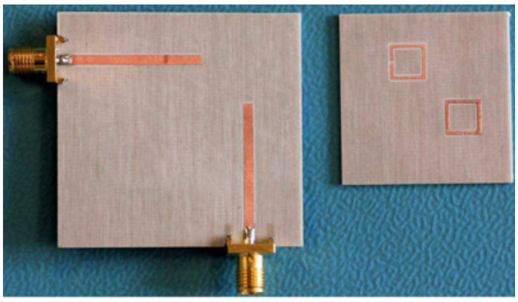

Fig. 4 *Photograph of fabricated prototype of sensor*

Two microstrip lines are printed on fixed substrate (left), and SRRs are fabricated on movable substrate (right). Rogers RO4003 material is used for both substrates

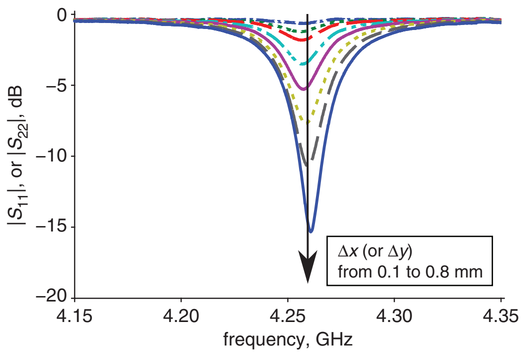

Fig. 5 *Measured $|S_{11}|$ (or $|S_{22}|$) of structure for different values of displacement Δx (or Δy) from 0.1 to 0.8 mm in steps of 0.1 mm*

The experimental setup is composed of three pairs of micrometre actuators, which allows the top substrate to move in three directions. The first pair of micrometre actuators are used to precisely adjust the air gap between the two substrates to $g_a = 0.76$ mm. The other two pairs of micrometre actuators are used to control displacements in the *x*- and *y*-directions from 0 to 0.8 mm in steps of 0.1 mm, whereas the reflection coefficients at port 1 and port 2 are measured. Fig. 5 depicts the measured reflection coefficient of the sensor at port 1 for different values of displacement in the *x*-direction. Owing to the symmetry of the structure, the reflection coefficient at port 2 has the same behaviour with respect to displacement in the *y*-direction. Thus, the experimental results clearly show that the notch depth in the reflection coefficients at port 1 and port 2 of the structure can be used to sense a displacement in *x*- and *y*-directions, respectively.

As mentioned earlier, one important advantage of the proposed sensor is that due to the almost constant loading effect of the TLs on the SRRs, displacement only affects the depth of the notch, and leaves the resonance frequency intact. This is an important feature that enables the proposed sensor to operate at a fixed frequency, bypassing the need for a frequency sweeping source and measurement system. To validate this important feature, Fig. 6 depicts the simulated (dashed lines) and measured (solid lines) $|S_{11}|$ and $|S_{22}|$ at a fixed frequency of 4.253 GHz against Δ*x*, while Δ*y* is 0 mm. The Figure clearly shows that the movement in the *x*-direction can be sensed from $|S_{11}|$, whereas $|S_{22}|$ remains unaffected and shows the alignment in the *y*-direction. The good agreement between the curves validates the simulation results, and confirms the operation of the sensor at a fixed frequency.

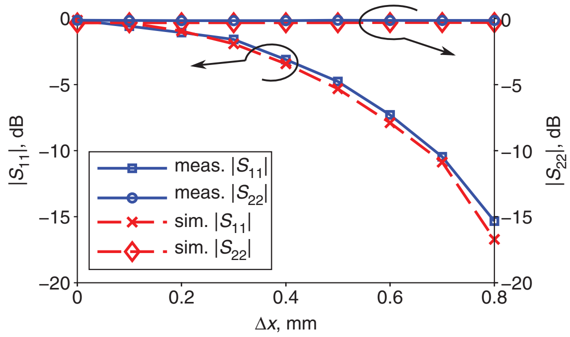

Fig. 6 *Comparison between measured and simulated $|S_{11}|$ and $|S_{22}|$ at fixed frequency f = 4.253 GHz against Δx, for Δy = 0 mm*

Owing to symmetry of proposed sensor, identical comparison is valid between measured and simulated $|S_{11}|$ and $|S_{22}|$ against Δ*y*

Conclusion: A two-dimensional displacement and alignment sensor based on the reflection characteristics of two open-ended microstrip lines loaded with two SRRs has been presented. The proposed sensor is compact and its operation is robust to ambient conditions such as changes in temperature, as it is operated based on a break of symmetry and only requires measurement at a single fixed frequency. This is an important feature that bypasses the need for a frequency sweeping measurement system such as a network analyser. The good agreement between the numerical and experimental results validates the design principle. The fact that the sensor radiates when a displacement is detected may be of benefit for future wireless sensors.

15 February 2014
doi: 10.1049/el.2014.0572
One or more of the Figures in this Letter are available in colour online.

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References

1 Schueler, M., Mandel, C., Puentes, M., and Jakoby, R.: 'Metamaterial inspired microwave sensors', *IEEE Microw. Mag.*, 2012, **13**, (2), pp. 57–68
2 Withayachumnankul, W., Jaruwongrungsee, K., Fumeaux, C., and Abbott, D.: 'Metamaterial-inspired multichannel thin-film sensor', *IEEE Sens. J.*, 2012, **12**, (5), pp. 1455–1458
3 Taya, S.A., and Shabat, M.M.: 'Sensitivity enhancement in optical waveguide sensors using metamaterials', *Appl. Phys. A*, 2011, **103**, (3), pp. 611–614
4 Ebrahimi, A., Withayachumnankul, W., Al-Sarawi, S., and Abbott, D.: 'High-sensitivity metamaterial-inspired sensor for microfluidic dielectric characterization', *IEEE Sens. J.*, 2014, **14**, (5), pp. 1–7
5 Naqui, J., Durán-Sindreu, M., and Martín, F.: 'Novel sensors based on the symmetry properties of split ring resonators (SRRs)', *Sensors*, 2011, **11**, (8), pp. 7545–7553

6 Horestani, A.K., Fumeaux, C., Al-Sarawi, S., and Abbott, D.: 'Displacement sensor based on diamond-shaped tapered split ring resonator', *IEEE Sens. J.*, 2013, **13**, (4), pp. 1153–1160

7 Shaterian, Z., Horestani, A.K., and Fumeaux, C.: 'Metamaterial-inspired displacement sensor with high dynamic range'. Proc. 4th Int. Conf. Metamaterials, Photonic Crystals and Plasmonics, META'13, Sharjah, United Arab Emirates, March 2013, Vol. 1, pp. 9–11

8 Horestani, A.K., Abbott, D., and Fumeaux, C.: 'Rotation sensor based on horn-shaped split ring resonator', *IEEE Sens. J.*, 2013, **13**, (8), pp. 3014–3015

9 Naqui, J., Durán-Sindreu, M., and Martín, F.: 'Alignment and position sensors based on split ring resonators', *Sensors*, 2012, **12**, (9), pp. 11790–11797

10 Horestani, A.K., Naqui, J., Shaterian, Z., Abbott, D., Fumeaux, C., and Martín, F.: 'Two-dimensional alignment and displacement sensor based on movable broadside-coupled split ring resonators', *J. Sens. Actuators A, Phys.*, 2014, **210**, pp. 18–24

11 Naqui, J., Duran-Sindreu, M., and Martin, F.: 'Modeling split-ring resonator (SRR) and complementary split-ring resonator (CSRR) loaded transmission lines exhibiting cross-polarization effects', *IEEE Antennas Wirel. Propag. Lett.*, 2013, **12**, pp. 178–181