Microwave Alignment and Displacement Sensors in Groove Gap Waveguide Technology

Ali K. Horestani[*][†][1], Zahra Shaterian[*][‡][2], Michal Mrozowski[*]
[*]Department of Microwave and Antenna Engineering,
Faculty of Electronics, Telecommunications, and Informatics, Gdansk University of Technology, Gdansk, Poland
[†]Wireless Telecommunication Group, A&S Institute, Ministry of Science, Research and Technology, Tehran, Iran
[‡]Department of Electrical Engineering, Technical and Vocational University (TVU), Tehran, Iran
{[1]Alikaramih, [2]Z.Shaterian}@gmail.com

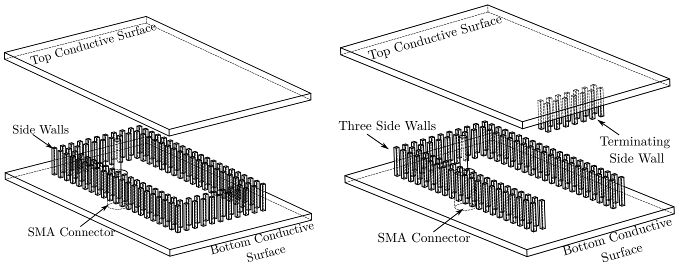
***Abstract*— This paper is aimed at presenting highly sensitive microwave displacement and alignment sensors. With this goal, the method of realizing mechanically tunable cavity resonators in groove gap waveguides technology is presented. The resonance frequency of the cavity is then used for displacement sensing. It is also demonstrated that the symmetry properties of a pair of groove gap waveguide cavities can be used to improve the robustness of the sensor to variations in ambient conditions. The proposed sensor also benefits from a reference zero, thus can be used as an alignment sensor. A very good sensitivity of $S = 1.25$ GHz/mm is achieved, which can be easily improved by scaling the operating frequency.**

***Keywords*— Alignment sensor, displacement sensor, gap waveguide, resonators.**

I. INTRODUCTION

During recent years, microwave sensors have received an increasing interest and found applications for sensing various parameters including mechanical parameters such as tilt, rotation [1], [2], and displacement [3], [4], [5], [6], [7], [8]. While sensors based on planar transmission lines (TLs) are low-cost and low-profile, they suffer from limited sensitivity and accuracy, which are mostly associated with dielectric and conductive losses, especially at higher frequencies. In contrast, despite being bulky, sensors realized in metallic waveguide technology benefit from very low loss and as a result high sensitivity and precision. Moreover, to achieve higher sensitivity, the sensors based on waveguide technology can be readily scaled to very high frequencies, an option that is very limited for planar TLs.

Nevertheless, since the parts of a conventional metallic hollow waveguide have to be seamlessly connected, their application for sensing mechanical parameters has been very limited [8], [9]. To address this issue, recently linear and angular displacement sensors based on the variation of phase in the transmission coefficient of a groove gap waveguide have been proposed by the authors [10]. This paper is aimed at presenting novel displacement and alignment sensors in groove gap waveguide technology. It is important to note that while the sensors presented in this work are realized in the same technology as those in our previous study [10], the principle of operation is completely different. The contribution of this research is twofold. First, it is shown that the resonance frequency (rather than transmission phase) can be used for sensing a displacement. Second and more importantly, it is demonstrated that the symmetry properties of a pair of groove gap waveguide cavities can be used to improve the robustness of the sensor to variations in ambient conditions such as changes in humidity or temperature. The proposed sensor also benefits from a reference zero, thus suits application for alignment monitoring.



(a) (b)

Fig. 1. Illustrations of (a) the conventional implementation of a groove gap waveguide cavity resonator, and (b) the proposed method for the implementation of a mechanically tunable groove gap waveguide cavity. (Adapted from [10])

II. TUNABLE GROOVE GAP WAVEGUIDE RESONATORS

This section is focused on presenting a tunable groove gap waveguide cavity resonator, which will be later used as the main building block of different displacement and alignment sensors. An illustration of a groove gap waveguide cavity resonator, composed of two parallel conductive plates which are separated by an air gap [11] is shown in Fig. 1(a). The sidewalls of the cavity are formed by arrays of conductive pins that are mounted (and thus short-circuited) on the bottom conductive surface. These conductive pins, which are about a quarter wavelength long, effectively produce an artificial perfect magnetic conductor (PMC) surface at their open ends. It has been shown that provided the distance between the produced PMC surface and the top conductive surface is less than a quarter wavelength, the EM wave is very well confined inside the cavity. In other words, despite having no electrical connection to the top conductive surface, the array of pins acts as the sidewalls that along with the top and bottom conductive surfaces form a gap waveguide cavity resonator.

This is an important feature that has been the main motivation behind the invention of gap waveguides to overcome limitations of conventional hollow waveguides in terms of fabrication difficulties and power leak at mm-wave frequencies. Moreover, in contrast to conventional waveguides, since the top and bottom sections of a gap waveguide are not connected, they can have relative movements. However, note that provided the top conductive surface of the cavity resonator of Fig. 1(a) is wide enough, a horizontal displacement of the top surface with respect to the bottom surface does not have any effect on the resonance frequency of the cavity. Therefore, the structure, in its current shape, cannot be used as a mechanically tunable resonator.

This issue can be easily addressed, by a simple but elegant modification in the structure of the gap waveguide resonator. Fig. 1(b), shows an illustration of the proposed mechanically tunable gap waveguide cavity resonator. The structure is identical to the gap waveguide cavity resonator of Fig. 1(a) except that the array of pins forming the terminating wall of the cavity is realized on the top conductive surface (rather than the lower conductive surface). Note that, despite being implemented on the top conductive surface, the surface at the open end of the pin array still acts as a PMC surface that in parallel to the lower conductive surface provides the required cut-off condition. In short, the three sidewalls implemented on the bottom surface and the terminating wall implemented on the top surface along with the top and bottom conductive surfaces form a cavity resonator. However, in this new configuration, the length and as a result, the resonance frequency of the resonator can be easily tuned by a longitudinal displacement of the top conductive surface with respect to the bottom one. Therefore, the proposed structure can be used as a tunable resonator required in voltage-controlled oscillators, tunable filters, etc.

III. DISPLACEMENT SENSOR BASED ON THE RESONANCE FREQUENCY

In an earlier study [10], the potential of groove gap waveguides for sensing linear and angular displacements based on the variations in the phase of a transmitted signal was demonstrated. Despite its advantages such as high accuracy and linear response, the sensors have some limitations. Here, we show that the mechanically tunable cavity resonator of the previous section can be also used for displacement sensing.

As known, the fundamental resonance frequency of a rectangular cavity resonator for TE$_{mnp}$ mode is given by

$$f_{mn\ell} = \frac{c}{2\pi\sqrt{\mu_r\epsilon_r}}\sqrt{\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2 + \left(\frac{p\pi}{\ell}\right)^2} \quad (1)$$

where a and b are the cross-sectional dimensions of the waveguide and ℓ is the length of the cavity. Therefore, knowing the fundamental resonance of the dominant mode, i.e., f_{101}, for an air-filled gap waveguide cavity, the length of the cavity can be determined by

$$\ell = \pi/\sqrt{\left(\frac{2\pi f_{101}}{c}\right)^2 - \left(\frac{\pi}{w_{eff}}\right)^2} \quad (2)$$

where w_{eff} is the effective width of the gap waveguide that can be achieved based on the eigen-mode analysis of the waveguide unit cell [12]. In short, the equation shows that the resonance frequency of the cavity can be used to determine the displacement of an object attached to the top conductive surface of the cavity.

To validate the proposed concept the structure of a groove gap waveguide cavity resonator is simulated using HFSS full-wave EM simulator. Fig. 2 shows the top and side views of the simulated resonator. To operate at the Ku band (12 to 18 GHz), the waveguide width $w = 15.8$ mm, which corresponds to the width of a standard WR62 rectangular hollow waveguide is chosen. The dimensions of the array of pins forming the sidewalls of the cavity are determined following the guidelines provided in [13], [14] as: pin length $d = 6.25$ mm, pin width $a = 1$ mm, pins period $p = 2.7$ mm, and the air gap between the pins open end to the top conductive surface is $h = 1$ mm. A coaxial-to-waveguide transition with a 0.2 mm long prob is mounted on the bottom conductive surface. The feed is placed at a distance $s = 3.5$ mm to the corresponding terminating wall of the cavity.

The simulated reflection coefficients of the structure for different length ℓ of the cavity from 9 to 17 mm are depicted in Fig. 3. The results clearly show that altering the length (by longitudinal movement of the top conductive surface) results in changes in the resonance frequency of the resonator.

The EM simulated resonance frequency versus the length ℓ of the cavity is plotted in Fig. 4. The figure also shows the calculated (dashed line) values of the resonance frequency versus length of the cavity based on (2). Good agreement between the simulated and calculated values confirms that the equation can be used to accurately determine the amount of a displacement $\Delta\ell$ from a measured resonance frequency. Also, not that the one-to-one relation between the resonance frequency and the amount of displacement implies that the direction and the velocity of a displacement can be determined.

IV. ALIGNMENT SENSOR IN GAP WAVEGUIDE TECHNOLOGY

In the previous section, a displacement sensor based on the shift in the resonance frequency of a gap waveguide cavity resonator was presented. It can be shown that since the frequency of a signal is more immune to noise compared to its amplitude, the proposed sensor benefits from a relatively good immunity to noise compared to sensors based on variations in the amplitude of a transmitted or reflected signal [15]. It must be noted however that the sensors based on a shift in the resonance frequency are generally more sensitive to environmental changes [16], [17]. For instance, in the case of the displacement sensor proposed in the previous section, variations in the temperature may change the physical size and

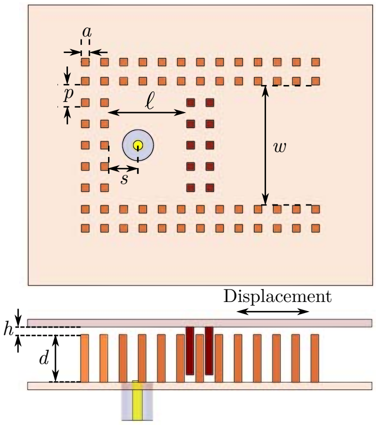


Fig. 2. Top and side views of the proposed groove gap waveguide structure for linear displacement sensing.

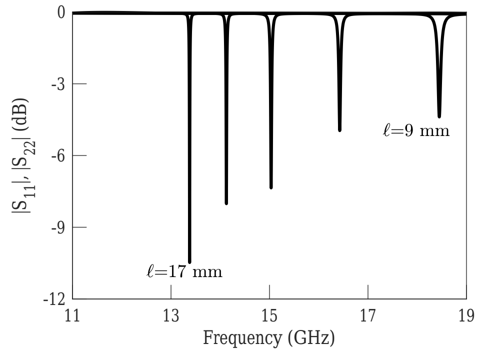


Fig. 3. The simulated reflection coefficients for different values of displacements Δx from 0 to 8 mm in steps of 2mm.

consequently the resonance frequency of the cavity, which in turn leads to errors in displacement measurement.

In a previous study, [18] some of the authors have shown that this issue can be significantly alleviated by taking advantage of the symmetry properties of microwave structures. It is shown in this section that a similar approach can be used to improve the robustness of the proposed displacement sensor to variations in ambient conditions. Moreover, the proposed sensor will benefit from an absolute zero reference, thus may act as an alignment sensor.

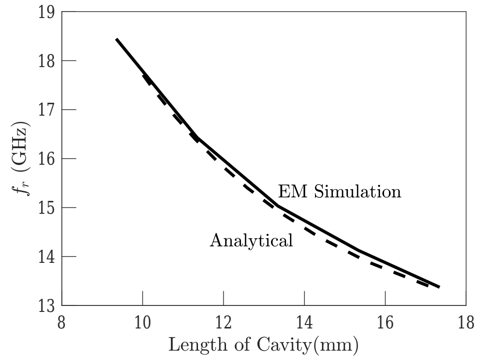


Fig. 4. EM simulated (solid line) and theoretical (dashed line) resonance frequency versus the length of the cavity ℓ.

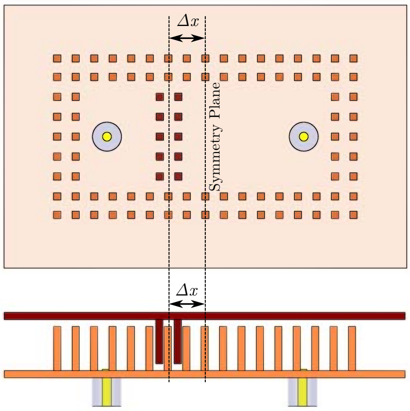


Fig. 5. Illustration of the top and side views of the proposed groove gap waveguide alignment sensor.

The top and side views of the proposed alignment sensor are illustrated in Fig. 5. The structure is composed of a gap waveguide cavity that is formed by four pin-array sidewalls. All four sidewalls are implemented on the bottom conductive surface of the waveguide. Thus, the size of the cavity is fixed. The cavity is further divided into two cavities by an array of pins that are mounted on the top conductive surface of the structure. The cavities can be connected to a measurement system through coaxial-to-waveguide transitions that are devised in each cavity.

In this configuration, when Δx (as denoted in Fig. 5) is zero, the two cavities are identical, thus resonating at the same frequency. Therefore, the difference in the resonance frequencies $\Delta f_r = f_{r1} - f_{r2}$ is zero. However, when the symmetry of the structure is broken by a longitudinal displacement, one resonator gets shorter while the other becomes longer. Therefore, the difference in the resonance frequencies Δf_r can be used to sense the amount of misalignment. Note that the frequency difference $\Delta f_r = 0$, corresponding to the initial position of the top surface, is a reference zero that can be used for accurate alignment monitoring. It is also worth highlighting that variations in ambient conditions such as changes in temperature or humidity identically affects the resonance frequencies of the two cavities. Thus, since the proposed sensor operates in a differential manner, a common-mode noise or error that may be caused due to variations in ambient conditions is suppressed. In short, the proposed sensor is robust to ambient conditions.

To validate the proposed concept, the performance of the proposed groove gap waveguide alignment sensor is simulated using HFSS EM simulator. Aiming to operate at the same frequency band (12 GHz to 18 GHz), the waveguide width and height, and the dimensions of the array of pins forming the sidewalls of the cavities are identical to those of the displacement sensor of the previous section. The plots of the simulated resonance frequencies versus misalignment Δx from -4 mm to 4 mm in steps of 2 mm for the two cavities are depicted in Fig. 6. The simulation results clearly show that while the resonance frequencies f_{r1} and f_{r2} of the two cavities

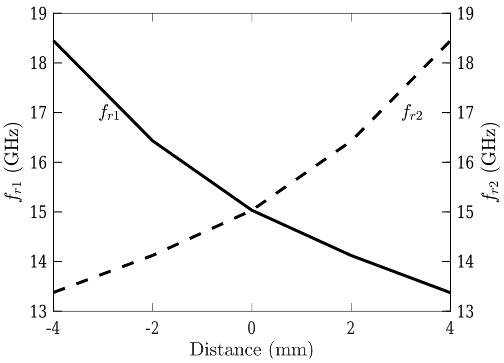


Fig. 6. Simulated resonance frequencies of the two cavities of the proposed alignment sensor versus misalignment Δx from -4 mm to 4 mm.

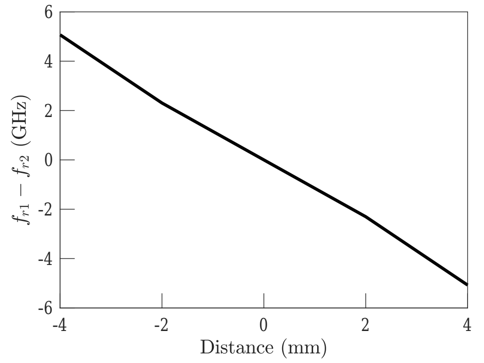


Fig. 7. The frequency difference $\Delta f_r = f_{r1} - f_{r2}$ of the proposed alignment sensor versus misalignment Δx.

are identical at $\Delta x = 0$ mm, introducing a misalignment results in shifts of f_{r1} and f_{r2} in opposite directions. The frequency difference Δf_r versus misalignment Δx is shown in Fig. 7. The results clearly show a linear, one-to-one relation between Δf_r and Δx that can be used for the accurate detection of misalignment and its direction. The sensor also benefits from a very good sensitivity $S = 1.25$ GHz/mm.

V. CONCLUSION

The method of realizing mechanically tunable cavity resonators in groove gap waveguide technology has been presented. It has been shown that the resonance frequency of the cavity can be used to precisely sense a displacement. The proposed concept has been further extended to develop a displacement/alignment sensor that benefits from robustness to ambient conditions such as changes in temperature or humidity. The proposed concept has been validated through EM simulation of displacement and alignment sensors with very good sensitivity of $S = 1.25$ GHz/mm, which can be easily improved by scaling the operating frequency.

ACKNOWLEDGMENT

This work was supported by Gdańsk University of Technology via research subsidy and NOBELIUM grant DEC-7/2020/IDUB/I.1 under the "Excellence Initiative – Research University" programme.

REFERENCES

[1] A. K. Horestani, D. Abbott, and C. Fumeaux, "Rotation sensor based on horn-shaped split ring resonator," IEEE Sensors J, vol. 13, no. 8, pp. 3014–3015, Aug. 2013.

[2] A. Ebrahimi, W. Withayachumnankul, S. F. Al-Sarawi, and D. Abbott, "Metamaterial-inspired rotation sensor with wide dynamic range," IEEE Sensors J, vol. 14, no. 8, pp. 2609–2614, Aug. 2014.

[3] J. Naqui and F. Martin, "Transmission lines loaded with bisymmetric resonators and their application to angular displacement and velocity sensors," IEEE Trans Microw Theory Techn, vol. 61, no. 12, pp. 4700–4713, Dec. 2013.

[4] A. Horestani, J. Naqui, D. Abbott, C. Fumeaux, and F. Martín, "Two-dimensional displacement and alignment sensor based on reflection coefficients of open microstrip lines loaded with split ring resonators," Electron Lett, vol. 50, no. 8, pp. 620–622, Apr. 2014.

[5] J. Naqui, J. Coromina, A. Karami-Horestani, C. Fumeaux, and F. Martín, "Angular displacement and velocity sensors based on coplanar waveguides (CPWs) loaded with S-shaped split ring resonators (S-SRR)," Sensors, vol. 15, no. 5, pp. 9628–9650, Apr. 2015.

[6] A. K. Horestani, N. Varmazyar, F. Sadeghikia, M. T. Noghani, Z. Shaterian, and F. Martín, "On the applications of S-shaped split ring resonators (s-srr) in sensors, filters, and antennas," in International Conference on Electromagnetics in Advanced Applications (ICEAA). IEEE, Sep. 2019, pp. 0485–0488.

[7] S. Fericean, A. Hiller-Brod, A. D. Dorneich, and M. Fritton, "Microwave displacement sensor for hydraulic devices," IEEE Sensors J, vol. 13, no. 12, pp. 4682–4689, Dec. 2013.

[8] A. Soltan, R. A. Sadeghzadeh, and S. Mohammad-Ali-Nezhad, "High sensitivity simple structured displacement sensor using corrugated substrate-integrated waveguide (CSIW)," IET Microwaves, Antennas & Propagation, vol. 14, no. 5, pp. 414–418, Feb. 2020.

[9] P. Sharma, L. Lao, and G. Falcone, "A microwave cavity resonator sensor for water-in-oil measurements," Sens. Actuators B Chem., vol. 262, pp. 200–210, Jun. 2018.

[10] A. K. Horestani, Z. Shaterian, and M. Mrozowski, "High dynamic range microwave displacement and rotation sensors based on the phase of transmission in groove gap waveguide technology," IEEE Sensors J., vol. 22, no. 1, pp. 182–189, 2022.

[11] E. Rajo-Iglesias and P.-S. Kildal, "Groove gap waveguide: A rectangular waveguide between contactless metal plates enabled by parallel-plate cut-off," in Proceedings of the Fourth European Conference on Antennas and Propagation, 2010, pp. 1–4.

[12] Z. Shaterian, A. K. Horestani, and J. Rashed-Mohassel, "Design of slot array antenna in groove gap waveguide technology," IET Microwaves, Antennas & Propagation, vol. 13, no. 8, pp. 1235–1239, Mar. 2019.

[13] Z. Shaterian, A. K. Horestani, and M. Mrozowski, "Design guidelines for microwave filters in gap waveguide technology," in 2021 IEEE MTT-S International Microwave Filter Workshop (IMFW), 2021, pp. 182–184.

[14] E. Rajo-Iglesias and P.-S. Kildal, "Numerical studies of bandwidth of parallel-plate cut-off realised by a bed of nails, corrugations and mushroom-type electromagnetic bandgap for use in gap waveguides," IET Microwaves, Antennas & Propagation, vol. 5, no. 3, p. 282, 2011.

[15] A. K. Horestani, J. Naqui, Z. Shaterian, D. Abbott, C. Fumeaux, and F. Martín, "Two-dimensional alignment and displacement sensor based on movable broadside-coupled split ring resonators," Sens. Actuators Phys., vol. 210, pp. 18–24, Apr. 2014.

[16] A. K. Horestani, Z. Shaterian, D. Abbott, and C. Fumeaux, "Application of metamaterial-inspired resonators in compact microwave displacement sensors," in 1^{st} Australian Microwave Symposium, 2014, pp. 19–20.

[17] A. K. Horestani, Z. Shaterian, and F. Martín, "Detection modalities of displacement sensors based on split ring resonators: Pros and cons," in 2019 International Conference on Electromagnetics in Advanced Applications (ICEAA). IEEE, 2019, pp. 0479–0484.

[18] A. K. Horestani, C. Fumeaux, S. F. Al-Sarawi, and D. Abbott, "Displacement sensor based on diamond-shaped tapered split ring resonator," IEEE Sensors J, vol. 13, no. 4, pp. 1153–1160, Apr. 2013.