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MATERIAL-LOADED HIGH Q-FACTOR SLOT RESONATOR AND MEASUREMENT OF RELATIVE PERMITTIVITY

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Abstract—We introduce a new slot resonator in the ground plane of a microstrip that is loaded with a parallel plate capacitor. The loaded slot has a 73% reduced length. Its unloaded Q-factor is 98 which is 91% higher than that of an ordinary slot. It is suitable to reject the narrow band unwanted signal. The proposed high Q-factor compact slot resonator also suppresses the undesired spurious high frequency response of the unloaded slot resonator. The structure is further used to determine the unknown dielectric constant of a sheet material with 0.04 variation in ε_r.

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1. INTRODUCTION

The high Q-factor compact filters are needed in the cellular radio and mobile communication systems. The slots in the ground plane of a microstrip line, known as the defected ground structures (DGS) are used for the development of the compact filters [1–4]. The DGS resonator has also been made tunable [5].

However, the Q-factor of the DGS based resonator is low-around 10. The Q-factor of the DGS based resonators needs to be improved in order to improve the rejection performance of a filter. Several efforts are made in this direction [6, 8–10]. The Q-factor in the range of 200–700 has been obtained by using the substrate integrated cavity. Likewise, dielectric resonator is also used for this work. However, these structures are complicated and they occupy more space on the substrate.

Wang and Lin [6] have loaded the slot in the ground plane i.e. the DGS with a stub to reduce the resonance frequency and also to increase the Q-factor about 24. They have realized the capacitive stub by placing a metallic patch on another substrate behind the slot. It is a multilayer structure and its integration with usual microwave circuits is difficult. The V and U-slots are also reported to have the Q-factor in this range [1].

The high Q-factor resonators are also used to determine the relative permittivity of the sheet materials [11–16]. The microstrip patch resonators are popular for this work. However, we noted above that the Q-factor of the microstrip resonator is low. Therefore it is not very suitable for determination of the relative permittivity of the sheet material. Moreover, each time we have to take a portion of the substrate for designing the parch resonator.

We propose a new method to increase the Q-factor of a rectangular slot resonator in the ground plane by loading the substrate with a parallel plate capacitor. The parallel plate capacitor can accommodate material in the sheet form. The parallel plate capacitor loaded slot in the ground plane increases the Q-factor of the slot resonator from 9 to 98. The parallel plate loaded capacitor also reduces the size of the resonating slot significantly In the present design, the slot size is 74% smaller than the conventional rectangular slot for the identical resonance frequency. The proposed high Q-factor compact slot resonator also suppresses the undesired spurious high frequency response of the unloaded slot resonator. On using the low loss and high permittivity dielectric material in the parallel plate capacitor we can further reduce the size and increase the Q-factor of a slot resonator. The proposed high Q, capacitor loaded compact slot resonator can be used to develop filter and diplexer with improved performance.

We also propose to use the new high Q-resonator for measuring the dielectric constant of a dielectric sheet material. The proposed method is simple and inexpensive.

2. EQUIVALENT CIRCUIT MODEL OF THE SLOT

The geometric configuration of the proposed ground plane slot resonator is shown in Fig. 1. The structure consists of a 50 Ω microstrip line on the top layer and a rectangular slot is etched in the ground plane of substrate. Two metallic plates forming a parallel plate capacitor is soldered with the ground plane across the ground slot. The low loss dielectric material could be placed between two metallic plates to increase the loading capacitance. The maximum electric field in the slot is at the centre of the slot; where parallel plates are soldered.

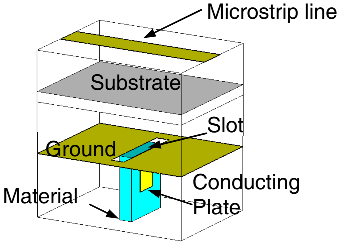


Figure 1. Three-dimensional view of the ground-plane slot with material.

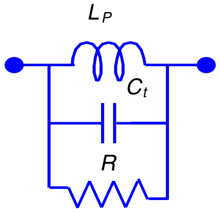


Figure 2. Equivalent circuit of the compact resonator.

The loaded slot is modelled as a parallel LC resonant circuit with resistance R. It is shown in Fig. 2 [2]. The reactive circuit elements are given by [10]

$$C_t = \frac{5f_c}{\pi\left(f_p^2 - f_c^2\right)}\,\text{pF (a)} \qquad L_p = \frac{250}{C_p\left(\pi f_p\right)^2}\,\text{nH (b)} \tag{1}$$

where f_c is the 3 dB cut-off frequency and f_p is the pole resonance frequency of the loaded slot. All frequencies are in GHz. These frequencies are obtained from the simulated response of the structure using a commercial simulator [7]. The resistance R is computed from the following expression [10]

$$R = \frac{2Z_o}{\sqrt{\frac{1}{|S_{11}(\omega_p)|^2} - \left(2Z_o\left(\omega_p C_t - \frac{1}{\omega_p L_p}\right)\right)^2 - 1}}\,\Omega \tag{2}$$

where, S_{11} is the reflection co-efficient at the pole angular resonance frequency ω_p. The S_{11} and ω_p are obtained from the S-parameters of the structure simulated on the EM-simulator. Z is the characteristic impedance of the microstrip line.

We have investigated the structure on RO4003 circuit board with relative dielectric constant 3.38 and substrate thickness 0.813 mm. The $50\,\Omega$ microstrip line has width 1.9 mm. The rectangular slot resonator in the ground plane has a width of 0.813 mm and a length of 13 mm as shown in Fig. 3. The simulated transmission response S_{21} given in Fig. 4 shows that the structure has a resonance frequency of 9 GHz.

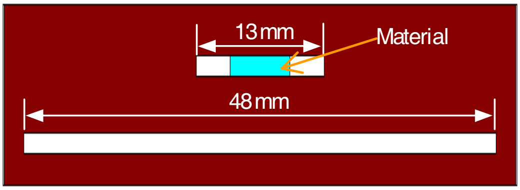


Figure 3. Rectangular slots: comparison of lengths.

3. PARALLEL PLATE LOADED SLOT RESONATOR

We consider the case of the parallel plate loaded slot resonator. The parallel plate with dielectric material inside lowers the resonance frequency significantly and also improves the Q-factor of the resonator.

3.1. Effect of Material on Compactness

In place of a simple rectangular slot in the ground plane, now we consider the parallel plate capacitor loaded slot. We maintain the slot dimension with length 13 mm and width 0.813 mm in the ground plane and solder a parallel plate capacitor of size $44\,\mathrm{mm}^2$. Inside the plate we have a dielectric sheet of relative permittivity 10. Fig. 4 shows that the resonance frequency shifts to 2.48 GHz. Thus the capacitance loading of the slot lowers the resonance frequency by 72.5%. It results in a compact resonating slot at 2.48 GHz.

In order to appreciate it further, we increased the length of the unloaded slot so that it resonates at 2.48 GHz. Fig. 3 shows that the new slot length is 48 mm. Thus loaded slot is 73% less in length as compared to the unloaded slot. Fig. 5 compares the transmission characteristics of our proposed capacitor load slot structure and the conventional rectangular long slot. The 3-dB bandwidth of the long

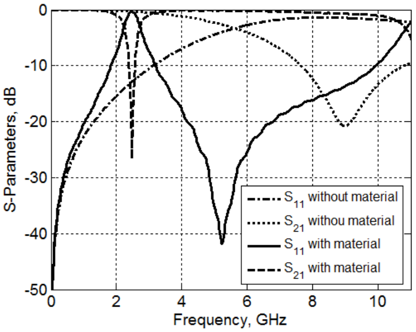


Figure 4. Simulated S-parameters of short slot with and without material.

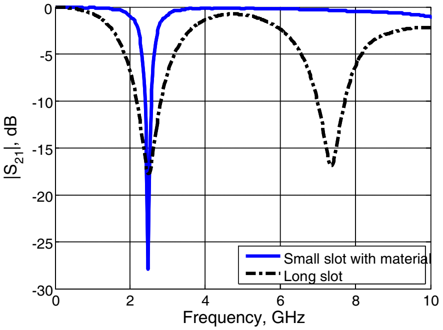


Figure 5. Simulated S_{12} of long slot without material and short slot with material.

slot is 3.1 GHz. The bandwidth of the loaded slot is 620 MHz. It is also worth noting that the proposed structure suppresses the unwanted spurious high frequency resonance of the long slot resonator.

3.2. Effect of Material on Q-factor

The unloaded Qfactor is an important parameter that determines the bandwidth of a rejection band. The unloaded Q-factor of a loaded slot resonator is obtained from the equivalent circuit parameters R, L_p and C_t shown in Fig. 2. It is given by $Q_u = 2\pi f_p R C_t$, where f_p is the pole resonant frequency. Using expression (1) and (2), and response on the EM-simulator, we can compute easily the unloaded Q-factor. It is 98 for our proposed loaded slot structure, whereas it is only 9 for the long rectangular slot. Thus the parallel plate with material loaded slot is a high Q compact resonator that also suppresses the spurious resonance of the unloaded slot resonator. It is a high Q-resonator with 91% increase in the unloaded Q-factor. The Q-factor can be further increase if we use low loss high permittivity dielectric material in side the parallel plate capacitor. It will further reduce the size of the structure. It is suitable for rejecting the undesired narrow band signal. The high Q-resonator is suitable to improve the band rejection performance of the filter and the diplexer.

4. DETERMINATION OF THE DIELECTRIC CONSTANT OF SHEET MATERIALS

The high-Q slot resonator is also a suitable device for measuring the dielectric constant of the sheet materials. In order to investigate the material loaded slot, we retained the size of the parallel plate connected with the slot and changed the dielectric constant of the sheet material. Fig. 6 shows the decrease in the resonance frequency with increase in the dielectric constant from 2 to 10. For the slot size and plate size considered, a curve-fitted empirical expression has been extracted to compute the dielectric constant of the material under test (MUT) as a function of the resonance frequency f_P.

$$\varepsilon_r = 0.18045 f_p^4 - 3.1372 f_p^3 + 21.014 f_p^2 - 65.807 f_p + 84.969 \tag{3}$$

The thickness of the unknown relative permittivity dielectric sheet must be 0.813 mm (same slot width). If we have to change the thickness, another calibration curve must be generated. However, this device, in principle, can be suitable to any other complex structure as long as it is fitted between the two metallic plates. Once the fabricated resonator is loaded with dielectric sheet, the resonance frequency is measured with the Network Analyzer. Using the measured resonance frequency in Equation (3), the dielectric constant of the MUT can be directly calculated.

The extracted value of the relative permittivity of the dielectric sheet must be independent of the length and width of the sheet that is why a complete examination of such parameters has been performed. For this purpose the sheet and plate dimensions are shown in Fig. 7. We consider the case of dielectric constant of 3.38 and sheet thickness 0.813 mm. The metallic plates have area $L_3 \times L_4 = 16\,\text{mm}^2$. The sensitivity of the device dimensions have been investigated as follows.

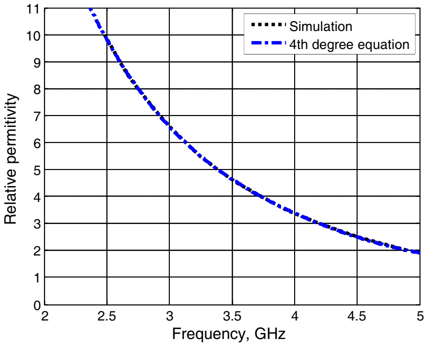


Figure 6. Dielectric constant values as a function of the slot resonant frequency.

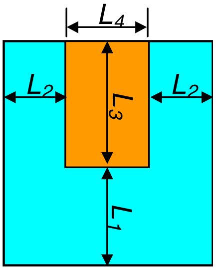


Figure 7. Material and metallic cover plates dimensions.

4.1. Case-I: L_1 Changeable, $L_2 = 1.5\,\text{mm}$

Figure 8 shows the variation in the resonance frequency with respect to L_1. The resonance frequency is decreased from 4.05 GHz to 4 GHz by increasing L_1 from 0 to 6 mm. For L_1 above 3 mm, the resonance frequency does not change.

4.2. Case-II: L_2 Changeable, $L_1 = 6\,\text{mm}$

Figure 9 shows the variation in the resonance frequency with respect to L_2. The resonance frequency is decreased from 4.15 GHz to 4 GHz by increasing L_2 from 0 to 4.5 mm. For L_2 above 2 mm, the resonance frequency does not change. Therefore, the dielectric sheet must be more than $10 \times 10\,\text{mm}^2$ in order to determine its relative permittivity accurately.

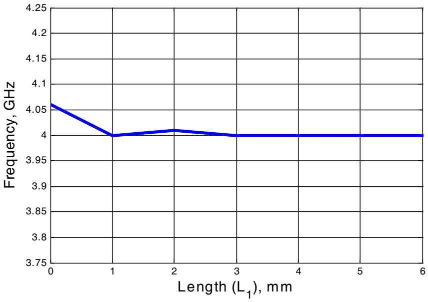


Figure 8. Effect of L_1 on the slot resonant frequency.

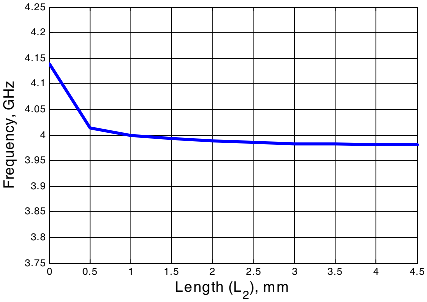
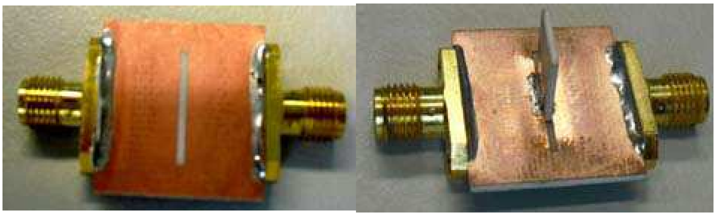


Figure 9. Effect of L_2 on the slot resonant frequency.

The proposed method to measure the dielectric constant of a sheet material is more convenient as compared to the patch resonator based methods mention in [15] and [16] and references given there in. The patch resonator has to be fabricated on each substrate separately. Whereas in the present case; a dielectric sheet can be easily mounted inside a parallel plate capacitor. The present method is less susceptible to errors as compared to the patch resonator based methods.

5. EXPERIMENTAL RESULTS

Figure 10 shows two photographs — unloaded and capacitor loaded slots, of the fabricated structures. The material is mounted at the center of the slot by soldering its metallic plates to the ground. Fig. 11 shows the measured and the simulated scattering parameters.



(a) (b)

Figure 10. Photograph of the fabricated resonator. (a) Unloaded slot. (b) Material loaded slot resonator.

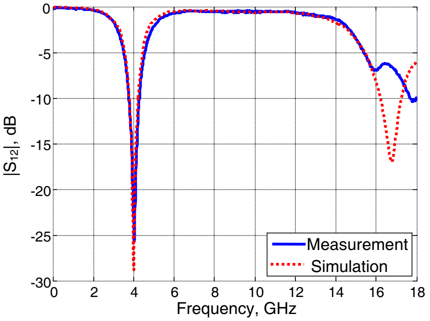


Figure 11. Measured and simulated S_{12} of a rectangular slot with material.

The simulated resonance frequency is 4 GHz; while the measured one is 4.016 GHz. The measured relative permittivity is calculated from Equation (3). The manufacturer's relative permittivity is 3.38; whereas the measured one is 3.34. The uncertainty of measurement of the dielectric constant is only 0.04 which gives an error of only 1.18%. It is in same range as provided by other complex measurement methods [11]. It is worth to mention that the resonator should be ready to characterize any other complex structure as long as it is embedded between the two metallic plates to form a simple capacitor. However, in order to improve the accuracy of the device, we have to fabricate the resonator carefully and the material inside the resonator has be placed carefully.

6. CONCLUSION

A new compact high Q-factor ground plane slot resonator loaded with a dielectric sheet material has been proposed. The resonator offers a reduced slot size of 73% of the conventional slot resonators. Its unloaded Q-factor is 98 which is much higher than the conventional structures as well (up to 91% increase). This resonator can be suitable for the narrow-band rejection of unwanted signals. The Q-factor can be further increased by placing low loss and high permittivity material inside the parallel plate capacitor. The high Q resonator has been further used as a sensor to measure the dielectric constant of a sheet material.

REFERENCES

1. Ahn, D., J. S. Park, C. S. Kim, J. Kim, Y. Qian, and T. Itoh, "A design of the low-pass filter using the novel microstrip defected ground structure," *IEEE Trans. Microwave Theory Tech.*, Vol. 49, No. 1, 86–93, Jan. 2001.
2. Abdel-Rahman, A., A. K. Verma, A. Boutejdar, and A. Omar, "Control of band stop response of hi-low microstrip lowpass filter using slot in ground plane," *IEEE Trans. Microwave Theory Tech.*, Vol. 52, No. 3, 1008–1013, Mar. 2004.
3. Balalem, A., A. R. Ali, J. Machac, and A. Omar, "Quasi-elliptic microstrip low-pass filters using an interdigital DGS slot," *IEEE Microwave and Wireless Components Letters*, Vol. 17, No. 8, 586–588, Aug. 2007.
4. Ting, S. W., K. W. Tam, and R. P. Martins, "Miniaturized microstrip lowpass filter with wide stopband using double equilateral U-shaped defected ground structure," *IEEE Microwave and Wireless Components Letters*, Vol. 16, No. 5, 240–242, May 2006.
5. Wang, X. H., B. Z. Wang, H. Zhang, and K. J. Chen, "A tunable band-stop resonator based on a compact slotted ground structure," *IEEE Trans. Microwave Theory Tech.*, Vol. 55, No. 9, 1912–1918, 2007.
6. Wang, C. J. and C. S. Lin, "Compact DGS resonator with improvement of Q-factor," *Electronics Letters*, Vol. 44, No. 15, 908–909, 2008.
7. Computer Simulation Technology, Microwave Studio, Version-5.
8. Shen, G. and D. Budimir, "High-Q dielectric combline resonator with wide spurious free performance," *Proceedings of the International Microwave and Optoelectronics Conference IMOC*, 409–411, Nov. 2003.
9. Tavernier, A. C., R. M. Henderson, and J. Papapolymerou, "A reduced-size silicon micromachined high-Q resonator at 5.7 GHz," *IEEE Trans. Microwave Theory Tech.*, Vol. 50, No. 10, 2305–2314, Oct. 2002.

10. Woo, D. J., T. K. Lee, J. W. Lee, C. S. Pyo, and W. K. Choi, "Novel U-slot and V-slot DGSs for bandstop filter with improved Q factor," *IEEE Trans. Microwave Theory Tech.*, Vol. 54, No. 6, 2840–2847, Jun. 2006.
11. Baker-Jarvis, J., R. G. Geyer, J. H. Grosvenor, Jr., M. D. Janezic, C. A. Jones, B. Riddle, C. M. Weil, and J. Krupka, "Dielectric characterization of low-loss materials a comparison of techniques," *IEEE Transactions on Dielectrics and Electrical Insulation*, Vol. 5, No. 4, 571–577, Aug. 1998.
12. Williams, T. C., M. A. Stuchly, and P. Saville, "Modified transmission-reflection method for measuring constitutive parameters of thin flexible high-loss materials," *IEEE Trans. Microwave Theory Tech.*, Vol. 51, No. 5, 1560–1566, May 2003.
13. Kang, B., J. Cho, C. Cheon, and Y. Kwon, "Nondestructive measurement of complex permittivity and permeability using multilayered coplanar waveguide structures," *IEEE Microwave and Wireless Components Letters*, Vol. 15, No. 5, 381–383, May 2005.
14. Egorov, V. N., V. L. Masalov, Y. A. Nefyodov, A. F. Shevchun, M. R. Trunin, V. E. Zhitomirsky, and M. McLean, "Dielectric constant, loss tangent, and surface resistance of PCB materials at K-band frequencies," *IEEE Trans. Microwave Theory Tech.*, Vol. 53, No. 2, 627–635, Feb. 2005.
15. Verma, A. K. and Nasimuddin, "Nondestructive measurement of complex permittivity of sheet material," *Microwave and Optical Technology Letters*, Vol. 36, No. 6, 483–486, Mar. 2003.
16. Verma, A. K., Nasimuddin, and A. Omar, "Microstrip resonator sensors for determination of complex permittivity of materials in sheet, liquid and paste forms," *IEE Trans. Microwave, Antenna and Propagation*, 47–54, Feb. 2005.