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DESIGN OF NARROWBAND BANDPASS FILTER ON COPLANAR WAVEGUIDE USING SPIRAL SLOTS

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Abstract—A configuration for a miniaturized band-pass filter on a coplanar waveguide (CPW) is proposed in this communication. Parametric studies conducted for various geometrical parameters suggest that the frequency response of the filter is strongly related to that of the spiral slots. A a series gap on the center conductor of the CPW changes the overall response of the device. For validation of these concepts, a bandpass filter operating at about 3.5 GHz has been designed, fabricated and tested. Experimental results show good agreement with electromagnetic simulations. The design takes up an area of approximately $0.1\lambda_0 \times 0.1\lambda_0$.

1. INTRODUCTION

Monolithic microwave integrated circuit (MMIC) and radio frequency integrated circuit (RFIC) technologies enable the fabrication of RF systems that are not only compact, but also easily affordable. However to facilitate appropriate on-chip integration these components should have very small footprints and should be compatible to fabrication processes. Hence many bulky components including filters are often assembled off-chip although these are essential components to any RF/microwave system [1]. Therefore miniaturization of modern wireless and RF front ends requires band-pass filters which are compact and preferably with a topology that is easy to adapt for any new application.

Most of the current approaches to realize RF and microwave filters are based on using distributed elements or off-chip lumped elements [1].

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Filters have also been realized using technologies of high temperature super conducting (HTS) material [2], bulk acoustic wave (BAW) [3] or surface acoustic wave (SAW) devices. Many of these circuits are typically fabricated using microstrip line technology. However among the planar microwave transmission line topologies, the coplanar waveguide (CPW) has very good characteristics at high frequencies, and flexibility for assembling shunt as well as series components on a single plane.

Recently defected ground structures have been proposed for compact band reject filters with high quality factor. These incorporate slots, which are the defects, of various shapes in the ground plane of a microstrip line or a CPW. In one of the examples of band-pass filters using defected ground structures (DGS) such as a cascade of spiral shaped slots on CPW [4]. In this case the device has a large pass band making this suitable for wideband systems. A similar approach to realize narrowband frequency selective components uses coupled structures [5].

Reducing the overall size is has been a major emphasis in the design of microwave components such as filters. Several attempts have been reported to reduce the size of bandpass filters using miniaturized resonant structures [6–9]. DGS in a planar transmission line disturbs the current distribution in the wave guiding structure [10]. This disturbance will change the characteristics of a transmission line and has been suggested as a general approach to reduce the overall area of planar circuits.

In this paper, we propose a new topology for a band-pass filter that uses symmetrically placed spiral shaped slots on ground traces of a coplanar waveguide with a series gap discontinuity in the center conductor line [11]. As demonstrated previously, the proposed topology using spiral slots on the ground traces of the CPW is easily scalable for both board level and chip level designs. It has been shown that with a critical dimension of $25\,\mu\text{m}$ and an overall dimension of $0.7\,\text{mm} \times 0.7\,\text{mm}$ (corresponding to $0.03 \times 0.05\lambda_0$ where λ_0 is free space wavelength) a bandpass filter for on chip applications can be designed [12]. In the next section, we present a design for band pass filters along with the effects of various design parameters. The experimental validation of this design on a standard microwave laminate is provided in Section 3. A brief summary of this study is included as the last Section.

2. DESIGN AND PARAMETRIC STUDIES

The bandpass filter proposed in this letter consists of a minimum of two sets of spiral slots on the ground traces of a CPW transmission line. The device also has a series gap discontinuity located symmetrically about these. After presenting the basic design on a microwave laminate we present a set of parametric studies on various aspects of this design. These simulation and parametric studies were performed using IE3D.

2.1. Design Approach of the Band-pass Filter

The topology used for the bandpass filter is shown in Figure 1. These studies have been performed on a microwave substrate with $\varepsilon_r = 2.2$, thickness = 0.787 mm and $\tan\delta = 0.0009$. The thickness of copper is 35 µm. The CPW has a center conductor of width 1.8 mm and ground traces of width 4 mm. The gap between them is 0.1 mm. The main component of this filter is the set of spiral slots on the ground traces of the CPW. It has recently been reported that such spiral shaped slots on the ground traces of a CPW can introduce an inductance in the series path at frequencies well below its self-resonant frequency and can lead to interesting characteristics near its self-resonant frequency [4]. Therefore these spiral slots provide an extra degree of freedom in microwave circuit design [13].

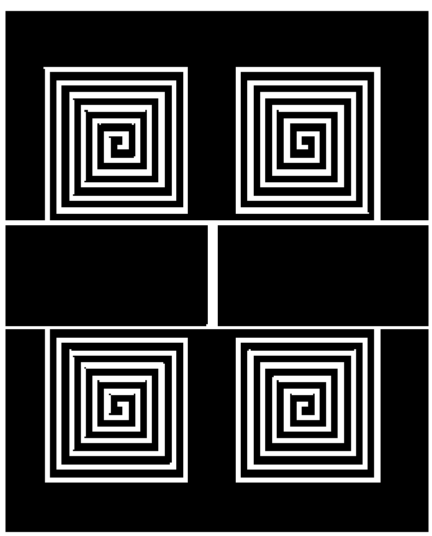

Figure 1. Geometry of the proposed bandpass filter.

With the introduction of the gap in the center conductor of the CPW, the EM response of this device resembles that of a band-pass filter whose pass-band is near the self-resonant frequency of this set of spiral slots. A comparison of responses of this device with and without a series gap of 0.2 mm is shown in Figure 2. The gap in the center conductor line blocks the propagation of the signal at resonant frequency, but the signal does propagate due to the strong coupling between the currents concentrated at the spirals. It has been observed that the resonant frequency of this geometry decreases as the overall size of the spiral slots is increased. In other words, by varying the number or turns, one can easily design the filter for the desired resonant frequency. The center frequency of spiral slots with different number of turns is given in Table 1. The resulting bandpass filter also has good out-of-band rejection characteristics.

Table 1. Center frequency of the spiral slot with different number of turns.

Number of turns	Spiral length (mm)	Center frequency (GHz)
2	4.4	13.6
3	9	7.4
4	15.2	4.6
5	22.2	3.75
6	30.8	2.65

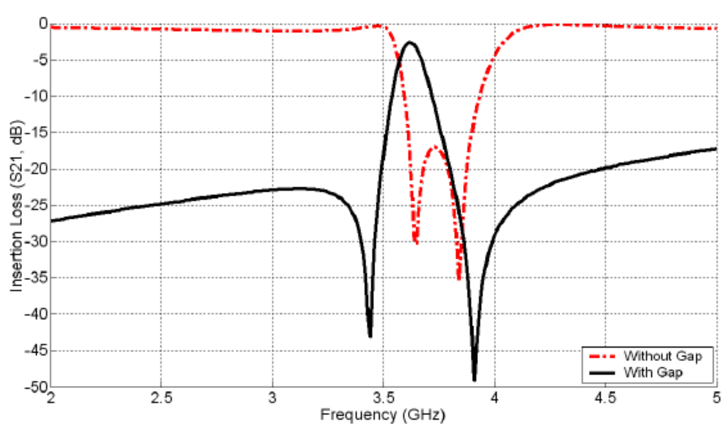

Figure 2. Transmission characteristics of the device with and without the series gap.

One of the equivalent circuit models suggested for a similar arrangement of spiral slots has a parallel combination of an inductance and a capacitance which leads to a rejection of the signal at a certain frequency, primarily decided by the size of these slots [12]. However, due to the strong electromagnetic coupling between the two adjacent spiral slots, the proposed bandpass filter configuration can not be studied by splitting this into such individual components. We have therefore conducted a parametric study on the effects of some of the critical geometric parameters of the combined device. These are discussed in the following sub-sections.

2.2. Effect of Variation of Series Gap on Filter Response

The variation of filter characteristics with the gap dimensions is shown in the Figure 3. As expected, the response of the device near the resonant frequency of the set of spiral slots is not changed; but the stop band attenuation of the bandpass filter is affected by changes in the dimensions of the series gap.

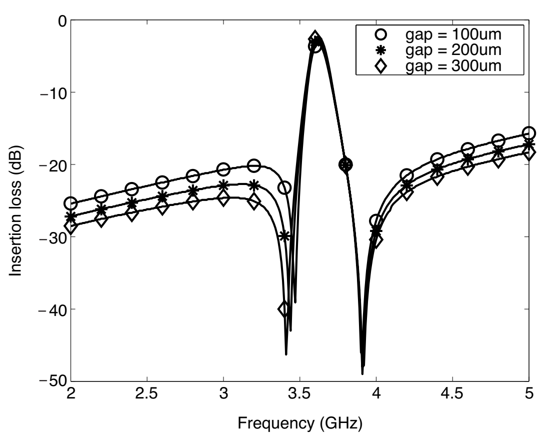

Figure 3. S_{21} of the filter as the gap width is varied from 0.1 to 0.3 mm. The separation between spiral slots is kept at 2 mm.

2.3. Effect of Variation of Separation between Spirals

As the propagation of the signal in pass-band is due to the coupling between the spirals, the pass band characteristics of the filter get altered with the variation of the separation between the spirals. Figure 4 shows the variation of filter characteristics with a variation of the separation between spirals. There appears to be an optimum

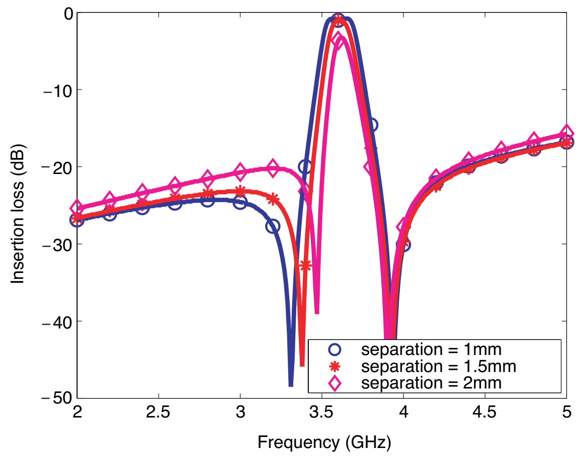

Figure 4. S_{21} of the filter as the separation between spiral slots is varied from 1 mm to 2 mm. The gap in the center conductor is kept at 0.1 m.

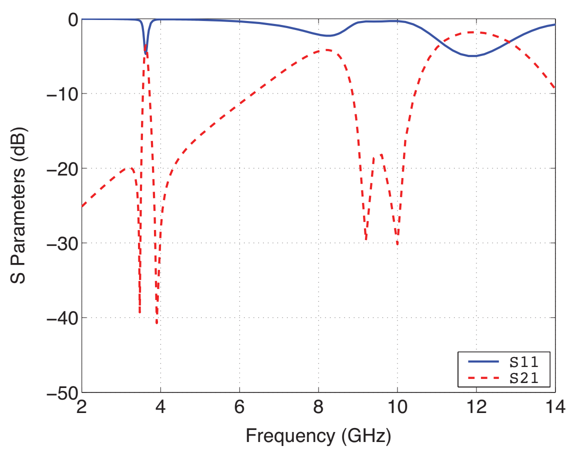

Figure 5. Simulated performance of the bandpass filter.

limit on the separation between the spirals if narrow bandwidth is the sole design objective. As these are brought closer than this limit, even though the insertion loss is improved, cross coupling between the spirals causes pole splitting which increases the bandwidth marginally.

2.4. Brief Design Guidelines

As noted from the above parametric studies, the geometrical parameters of the device decide the center frequency, roll-off, insertion loss and bandwidth. The center frequency of the filter is decided by the dimensions of the spiral sections. It is widely known that the inductance of such spirals increase by increasing the number of turns and/or by reducing the spacing between conductors. The bandwidth may be controlled with the separation between spirals or by adding additional spiral sections on either side of the gap discontinuity on the center conductor of the CPW. However, these do affect the insertion loss in the passband. Furthermore, the depth of the rejection band may be controlled with the gap on the center conductor of the CPW.

Based on the above rules, a bandpass filter is designed for 3.6 GHz for experimental studies. This has 0.2 mm gap in the center conductor and has spiral slots with five turns each. The CPW signal line is 1.8 mm wide and is separated from the ground by 0.1 mm. The overall dimensions of the simulated device measures 1 cm $\times$ 1 cm. The performance of this filter is shown in Figure 5. Compared to a bandpass filter of similar behavior reported earlier [5], the current approach offers better insertion loss characteristics, and offers the possibility of further miniaturization without compromising the performance [12].

3. EXPERIMENTAL VALIDATION

For the purpose of experimental validation, a bandpass filter with 0.2mm gap in the center conductor and having five turns of spiral slots with 0.1 mm as the minimum dimension and 2 mm separation between them, have been fabricated on a microwave laminate. The CPW signal line is 1.8 mm wide and is separated from the ground by 0.1 mm. This design is fabricated using standard lithography techniques on a microwave substrate (NY 9220) from Neltec. The fabricated device is extended with 50Ω line on both sides. The width of ground traces is also increased. These have been done to facilitate assembly of SMA connectors. The fabricated device is tested using a microwave vector network analyzer. The measured results are presented in Figure 6. Due to fabrication inaccuracies and modifications mentioned above, the measured performance varied slightly from the simulated predictions in Figure 5. The pass band of this filter is from 3.475 GHz to 3.610 GHz. The insertion loss (S21) is better than -3 dB and return loss (S11) is better than -10 dB within this band. A summary of comparison between the simulated and experimental results is shown in Table 2.

Table 2. Comparison of simulation and measurements.

Parameter	Simulated (GHz)	Measured (GHz)
Center frequency	3.62	3.25
Pole on left side	3.47	3.52
Pole on right side	3.90	3.97

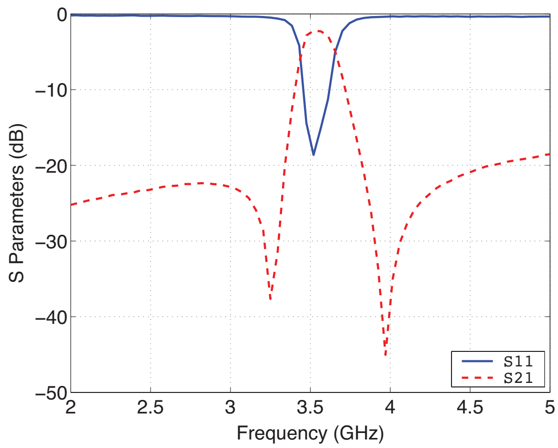

Figure 6. Measured scattering parameters for the fabricated device.

4. CONCLUSIONS

A new approach for designing narrowband band-pass filters for the RF, microwave frequency regime using spiral slots on the ground traces of a coplanar waveguide is presented here. The series gap on the center conductor of the CPW changes the overall response of the device, but has a marginal role in fine-tuning its passband characteristics. Parametric studies have been conducted for various geometrical parameters of the bandpass filter. The frequency response of the filter is strongly related to that of the spiral slots and the frequency selectivity of this design increases as the number of spiral slots on either side of the gap discontinuity is increased.

A bandpass filter operating at about 3.5 GHz has been designed, fabricated and tested. The measured results show good agreement with the simulated performance. The design for a microwave laminate shown here requires an area of approximately $0.1\lambda_0 \times 0.1\lambda_0$.

Components using this approach may be useful in designing a wide range of RF/microwave filters. An analytical model of this filter may require further analyses due to the strong coupling between closely spaced spiral slots used here.

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