Progress In Electromagnetics Research M, Vol. 20, 73–80, 2011

COPLANAR METAMATERIAL MICRO-RESONATOR

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Abstract—We propose a metamaterial coplanar stop-band filter made of multi-turn rectangular spiral particles. Numerical and experimental results show the feasibility of devices with dimensions more than 10 times smaller than those in the literature and with good performances.

1. INTRODUCTION

Micro-resonators are microwave narrow band components that use capacitor-inductor coupling to perform the filtering function. The miniaturization of such circuits is important, but it is more important that they are easily integrated in other circuits. For this reason, coplanar structures are often preferred, but many structures described in the literature are based on microstrip lines. These structures generally have to be extended to obtain sufficient inductive effect while some other planar structures, e.g., [1, 2], require the insertion of a magnetic layer for right operation.

Falcone et al. [3] studied a microwave resonator with planar Split Ring Resonator (SRR). They have proposed wider slots to place the SRR. The size of this micro-resonator is $4.5\,\mathrm{cm} * 1.8\,\mathrm{cm}$ which allows it to function around 7 GHz. The calculation of the resonant frequency of the SRR was determined by Pendry et al. [4]. To achieve this micro resonator to operate in a lower band, between 1 and 2 GHz, it is not enough to reduce the width of the metallization strip forming the SRR, but one needs to increase the diameter of the SRR. The total size of the micro resonator becomes huge compared to the constraints of microelectronics. This is the main disadvantage of this structure for low frequency band.

Received 28 June 2011, Accepted 12 August 2011, Scheduled 17 August 2011

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In this paper, we propose to build a more compact coplanar micro resonator with spiral particles, in place of SRR, to create an artificial material [5]. These particles can be conveniently coupled with a coplanar line to create a stop band filter. Manufacturing is easier than the above mentioned magnetic left handed resonators.

2. CONCEPTION

The challenge for the proper functioning of coplanar micro-resonator [3] is to find a good place to put the resonant particles. In coplanar structures, the particles must be inserted in the slots where the electric field is high. Simultaneously, the access line at each port must be adapted. This requires large line and slots compared to the expected miniaturized circuit.

To resolve this problem, we use the tapered lines structure of Falcone et al. [3] and replace the SRR by more compact rectangular spirals (Figure 1) that were studied earlier by [5]. The surface area of these spirals is much smaller than that of the SRR at the same operating frequency, about 10 times. The size reduction is the main objective and the innovation of this study.

The first part of the work is to show the resonance of the proposed structure that can be used in filtering applications around 2 GHz. Then we improve this structure and manufacture it using 2 or 4 spiral particles.

The materials and geometric dimensions of the multi-turn spiral (Figure 1) were determined from a study presented earlier by Nemer et al. [5], for an operating frequency in the band [1–2 GHz] (Table 1). Two coplanar waveguides, with and without ground plane [6, 7], are studied (Figure 2). A large slot G_L (1300 µm) is necessary to insert the spirals particles, and the width of the transmission line W_l is optimized to obtain a good impedance matching. The metal layer is 6.5 µm thick for technical reasons (deposition process) and greater than the skin

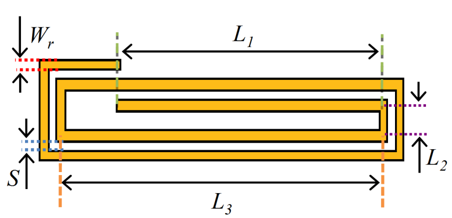
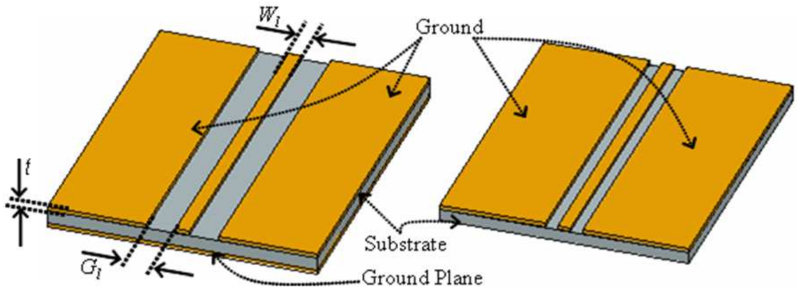


Figure 1. Particle structure with $N = 2$ turns, $W_r = 200$ µm, $S = 200$ µm, $L_1 = 6500$ µm, $L_2 = 600$ µm and $L_3 = 8000$ µm.



(a) (b)

Figure 2. Structure of the coplanar waveguide. (a) With a ground plane. (b) Without a ground plane.

Table 1. Materials characteristic and geometric dimensions of the multi-turn spiral.

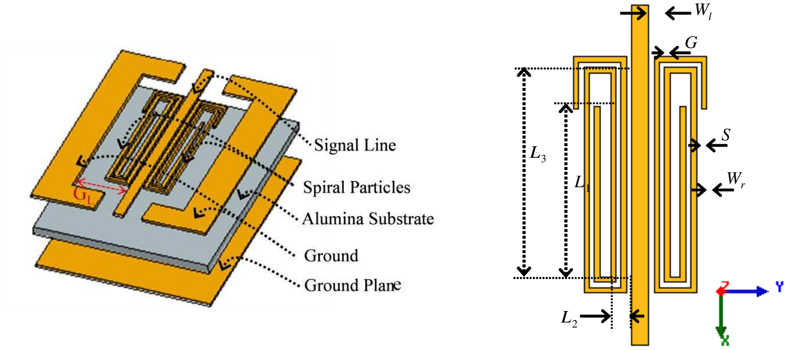
<table>
<tr><td colspan="6">Substrate (alumina 98%)</td><td colspan="4">G_l</td></tr>
<tr><td colspan="2">height</td><td>ε_r</td><td colspan="3">μ_r</td><td colspan="2">CPW</td><td colspan="2">CPWG</td></tr>
<tr><td colspan="2">635 µm</td><td>9.8</td><td colspan="3">1</td><td colspan="2">245 µm</td><td colspan="2">1300 µm</td></tr>
<tr><td colspan="10">Conductor (copper)</td></tr>
<tr><td>ρ ($\Omega \cdot$ m)</td><td>t</td><td>W_r</td><td>W_l</td><td>S</td><td>L_1</td><td>L_2</td><td>L_3</td><td>G</td><td>G_L</td></tr>
<tr><td>$17 \cdot 10^{-9}$</td><td>6.5 µm</td><td>200 µm</td><td>635 µm</td><td>200 µm</td><td>6500 µm</td><td>600 µm</td><td>8000 µm</td><td>200 µm</td><td>2200 µm</td></tr>
</table>

depth at the working frequency.

The difference between a coplanar waveguide with ground plane (CPWG) and a traditional one (CPW) is the mapping of the electromagnetic fields with two major consequences:

- An interaction with the spiral particles that differs for each structure. This will be discussed later.
- A different set of line dimensions to obtain a good impedance matching. These dimensions can be calculated from the equation of Wheeler and Owens that can be found in several references such as [8].

The width of the central line of the component (W_l) is set to 635 µm, and the corresponding slot width (G_l) must be set to 245 µm for CPW and to 1300 µm for CPWG to reach 50 ohms characteristic impedance. On the other hand, a large slot width (G_L) of about



(a) (b)

Figure 3. Structure of the proposed micro-resonator. (a) With the different stages. (b) Top view with the different geometrical parameters.

2200 µm is needed to place each particle (Figure 3(a)), which means that there is an impedance mismatch between the access port (G_l slot width) of the component and the resonant part (G_L slot width). The mismatch is stronger for CPW than for CPWG. The impedance matching becomes more complex with the presence of the particles.

3. NUMERICAL STUDY

A numerical study of the structures is performed using a finite element 3D electromagnetic simulator. As an example, the magnetic field has sufficient values in the whole slot to ensure an electromagnetic coupling between the transmission line and the spiral particles (Figure 4).

The transmission magnitudes (frequency sweep) of CPW and CPWG without particles are shown in Figure 5(a). CPWG presents low insertion losses ($|S_{12}| < 0.1$ dB) in the working band while those of CPW are higher because of impedance mismatch.

With two particles on both sides of the line, the simulations confirm the presence of a narrow stop band at 1.39 GHz (Figure 5(b)) for CPWG and CPW. This result is indicative of comparable coupling levels between spiral particles and CPWG or CPW. CPWG structure shows low insertion losses out of the resonance band and peak depth of about 8 dB. CPW structure shows higher insertion losses but, above all, a higher resonance peak as high as 13.4 dB that results from a better coupling with the particles. This better resonance leads us to keep the CPW structure despite the insertion losses.

The performance can still be improved by duplicating structure

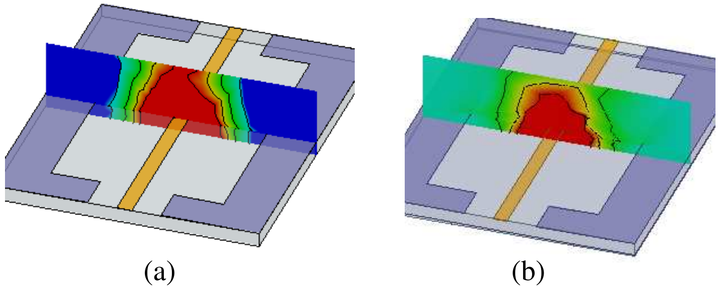


Figure 4. Magnitude of magnetic field around the transmission line in the large slot. (a) Without a ground plane (CPW). (b) With a ground plane (CPWG).

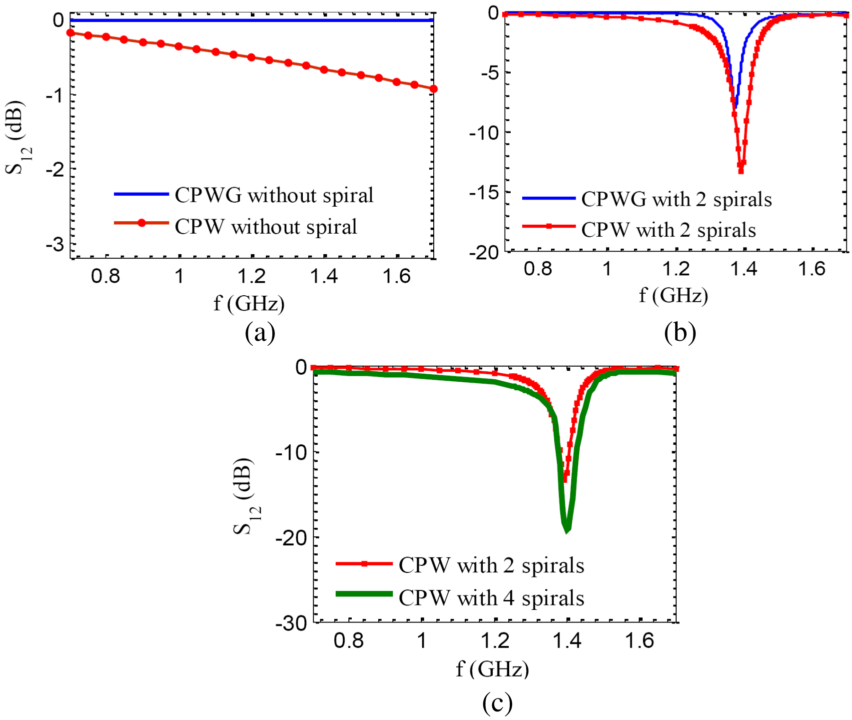


Figure 5. Simulated transmission coefficient of the micro-resonator. With $N = 2$ turns, $W_r = 635\,\mu\text{m}$, $W_l = 635\,\mu\text{m}$, $G_l = 1300\,\mu\text{m}$, $G = 200\,\mu\text{m}$, $S = 200\,\mu\text{m}$, $L_1 = 6500\,\mu\text{m}$, $L_2 = 600\,\mu\text{m}$, $L_3 = 8000\,\mu\text{m}$. (a) CPWG and CPW without spiral. (b) CPWG and CPW with 2 spirals. (c) CPW with 2 and 4 spirals.

along the propagation line with four particles. Then the peak depth reaches 19 dB (Figure 5(c)).

4. MEASUREMENTS RESULTS

To validate our study, we present experimental results of the CPW micro resonator structure. The materials used in the micro-resonator are an alumina substrate ($\varepsilon_r = 9.8$, thickness = 635 µm) and a copper metallic layer ($\rho = 17 \cdot 10^{-9}\,\Omega \cdot \mathrm{m}$, thickness = 6 µm). Two different prototypes are realized and measured, a CPW line with 2 spiral particles (Figure 6(a)) and 4 spiral particles (Figure 6(b)), in order

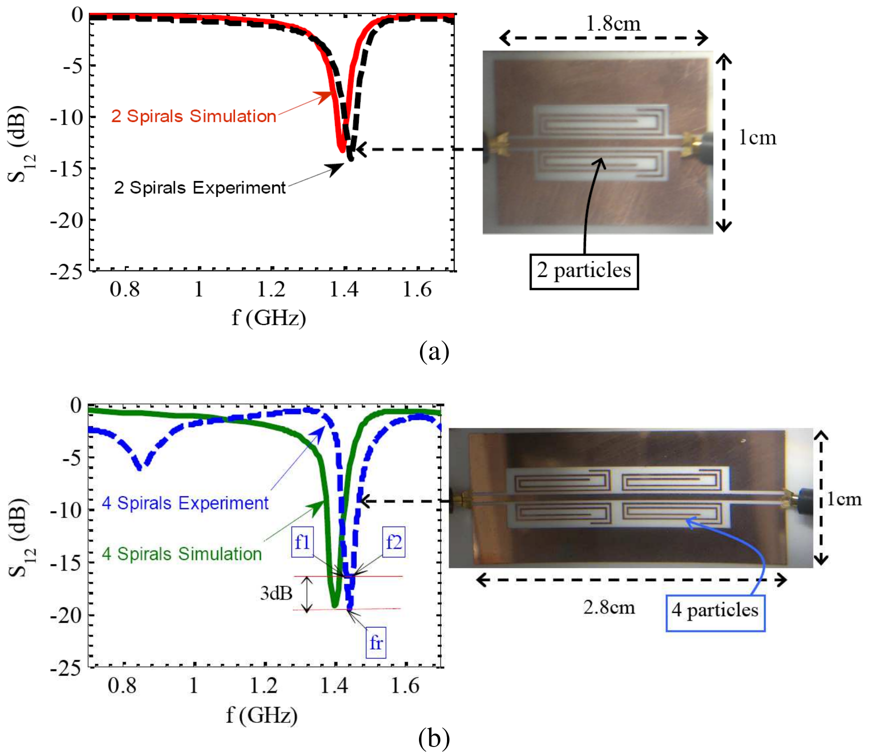


Figure 6. Experimental result of the insertion loss S_{12} (dB) for 2 and 4 particles. Such as: $N = 2$ turns, $W_r = 200$ µm, $W_l = 635$ µm, $G_l = 1300$ µm, $G = 200$ µm, $S = 200$ µm, $L_1 = 6500$ µm, $L_2 = 600$ µm, $L_3 = 8000$ µm. (a) Two particles placed on both sides of the transmission line. (b) Four particles placed on both sides of the transmission line.

to increase the rejection magnitude. The transmission characteristic of the micro-resonators is measured using a vector network analyzer (VNA) associated with a coplanar probe station.

The measurements show the resonance phenomenon near 1.4 GHz, and a very good agreement is observed between simulated and experimental results (Figure 6). A small frequency shift ($\Delta_f \approx 2.7\%$) can be noticed between the measured resonant frequency (Figure 5(d)) and simulated one (Figure (6)). The peak depths are high. We obtained peak depths of 14.25 dB for two particles and 19.40 dB for four particles. Insertion losses slightly increase from 0.47 dB to 1.30 dB, respectively, at 1.6 GHz, above the resonance. The 3 dB bandwidth is about 120 MHz in the case of 4 particles, and the quality factor is about 85 (Eq. (1))

$$Q = \frac{fr}{f_2 - f_1} = \frac{1.444}{1.451 - 1.434} \approx 85 \tag{1}$$

The structure with four particles shows secondary resonances (near 0.8 GHz). These effects are due to the increased length of the mismatched line. This length was however necessary to insert the four particles.

The experimental results show that our proposed micro resonator has a mean quality factor $Q = 85$ and a resonance peak over 19 dB. This is a good result since the size of the device is really compact. Thus, this micro resonator (CPW) with spiral particles is much better than that with SRR particles [3] according to those criterions. The dimensions of the equivalent SRR structure would be 15 times greater to operate in the same frequency band.

5. CONCLUSION

A coplanar micro resonator has been designed and realized. The device is based on the Falcone's structure [3], by replacing wide SRR with compact rectangular spiral particles. The most interesting advantages of the proposed micro resonator are its small dimensions ($10\,\mathrm{mm} * 28\,\mathrm{mm} * 0.639\,\mathrm{mm}$) for operation in the band of 1 to 2 GHz. The numeric and experimental studies have demonstrated efficient rejection (-19 dB) in the rejection band, low insertion losses ($<$ 1.30 dB) in the pass band, and very sharp cutoff. In conclusion, this device and its characteristics are very interesting, considering that the structure is fully compatible with low cost industrial processes (simple manufacturing, one print).

These results allow us to draw some perspectives. This study can be the baseline for studying other micro resonators operating at other frequencies (especially between 1 & 10 GHz).

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