2009 IEEE MTT-S International Microwave Workshop Series on
Signal Integrity and High-Speed Interconnects (IMWS2009-R9)

Miniaturized Metamaterial Filters Using Ring Resonators

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Abstract — **In this paper extremely compact metamaterial closed loop resonators are demonstrated and implemented in a 3 pole Chebyshev filter and a 4 pole quasi elliptic filter at 800MHz for mobile communications. Simulated and experimental results are shown.**

I. Introduction

Metamaterials (MTM) were envisioned by Veselago's investigations in which materials displaying negative permittivity (ε) and permeability (μ) simultaneously were reported giving rise to waves with antiparallel group velocity (v_g) and phase velocity (v_p), and hence having a negative refractive index [1]. Experimental demonstrations of such properties were not achieved until 30 years later when an effectively homogenous structure, able to propagate MTM waves was proposed [2]. In 2002, a new engineering approach to Left Handed (LH) structures was shown by arranging lumped inductors and capacitors [3]. The unique electromagnetic properties of MTM allow breakthrough improvements in microwave subsystems performance [4]. In particular, for filter applications, metamaterials offer circuit miniaturization and no harmonic generation [5]-[9]. In modern mobile phone systems such as B3G/4G, frequencies in the range of 400MHZ, 700MHz and 800MHz have been allocated [10]. Since these bands are relatively low to avoid atmospheric attenuation, filter miniaturization is essential. Moreover, to achieve ultra high speed data transfer rates, these systems will also require parallel processing of higher frequency bands (2.3-2.4GHZ and 3.4-3.6GHz [10]) for which filters with no harmonic generation will be key components to avoid interference between the lower and higher bands.

Circular ring resonators have been well studied in the literature for mono and dual band filters [11]-[18]. These consist of a 360° looped transmission line. However, one of their main drawbacks is their large size. By using MTM structures miniaturization can be achieved [9]. In a MTM ring resonator a LH MTM transmission line is cascaded with a conventional (RH) transmission line, both having the same phase-shift magnitude but with opposite signs therefore giving rise to a zeroth order resonance at the center frequency [7].

To date, no high performance filters have been reported in the literature using MTM ring resonators. In this paper a 3 pole Chebyshev and a 4 pole quasi elliptic filters are demonstrated at 800MHz achieving a 90% miniaturization compared to conventional structures. Simulation and experimental results will be exhibited showing good agreement.

II. CRLH Ring Resonator Desing

The first step was to design a Composite Right Left Hand (CRLH) balanced transmission line using Rogers DUROID 5880, ε_r = 2.2, and h = 1.575 mm. The structure was designed at 50 Ω, with two cells N = 2, and a phase of 0° at the center frequency f_0 = 860MHz. The phase shift of the LH is +111°. The values for the LH line are calculated following the procedure shown in [3] and are: C_L = 3.96854pF, and L_L = 9.921nH. Then this structure is cascaded with a conventional RH transmission line with a phase shift -111° and looped together as shown in Fig. 1. Each LH cell is implemented in a "T" type configuration with two series capacitors of value $2C_L$ and a shunt inductor of value L_L. The lumped elements were realized with standard Surface Mounted Devices (SMDs). This resonator is 80% smaller than a conventional ring resonator.

To measure the unloaded quality factor this resonator was weakly coupled to the input transmission lines and simulated in a metallic enclosure using [19]. Then it was implemented and measured using a Vector Network Analyser (Wiltron model 360B). Fig. 1a shows a picture of the final resonator. Fig. 1b exhibits the experimental and simulated results. The simulated center frequency is f_0 = 886MHz, whereas the experimental is f_0 = 820MHz. Since the length of the SMDs is not considered in the simulator this frequency shift is expected. Moreover manufacturing and material tolerances exist. The simulated unloaded Q_0 is 65.09. And the experimental is Q_0 = 40.

At around 2.8GHz the length of the looped resonator is equivalent to 360° in terms of electrical length, hence generating the first spurious resonance as shown in Fig. 1c.

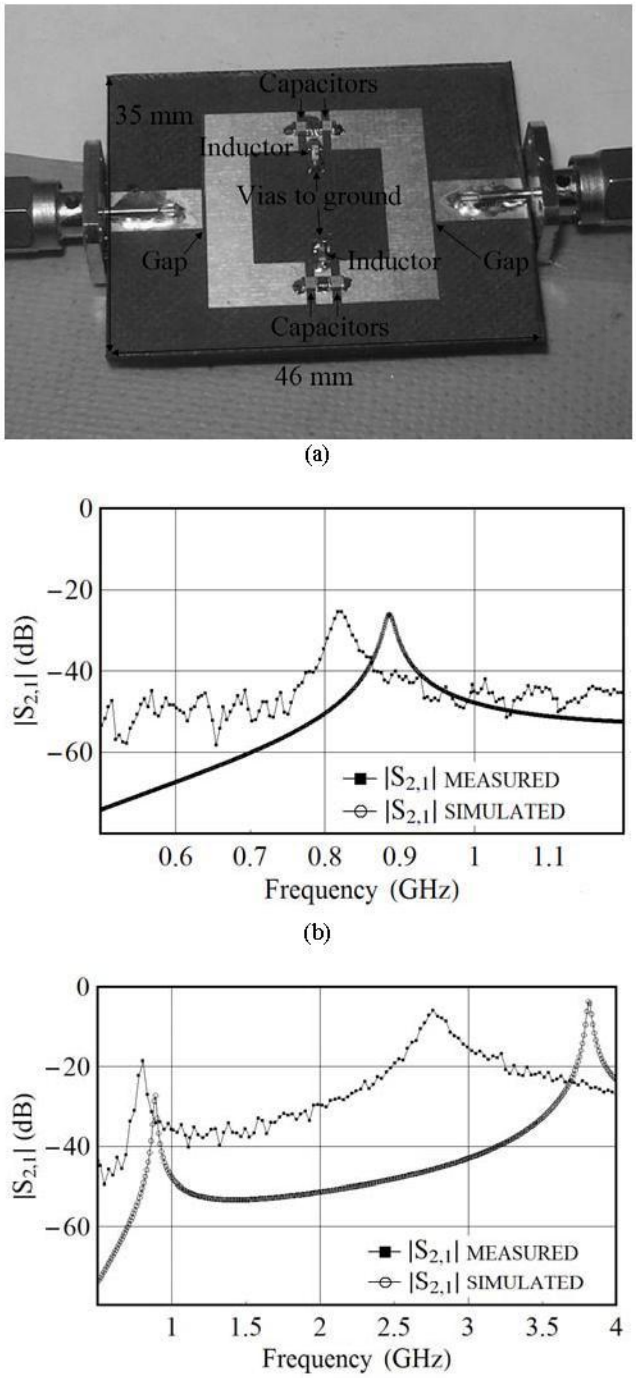


Fig 1. (a) CRLH Ring Resonator Layout. (b) Measured and simulated insertion loss of CRLH ring resonator in narrow band with measured Q_{un} = 39.04 and Simulated Q_{un} = 65.6. (c) Measured and simulated insertion loss of CRLH ring resonator in wide band with $f_b > 3f_R$.

III. 3 Pole Chebyshev Filter

The values of a low pass prototype Chebyshev filter of third order for a 0.1dB ripple are $g_0 = g_4 = 1$, $g_1 = g_3 = 1.0316$ and $g_2 = 1.147$ [20]. And by using equations 1 and 2 for a fractional bandwidth FBW of 7%, and f_0 = 859MHz the parameters of the filter can be extracted.

$$k_{i,j+1} = \frac{FBW}{\sqrt{g_i g_{i+1}}}, \text{ from } i = 1 \text{ to } n\text{-}1. \quad (1)$$

$$Q_{e1} = \frac{g_0 g_1}{FBW} \quad (2)$$

where Q_{e1} and Q_{en} are the external quality factors, $k_{i,j+1}$ are the coupling coefficients between resonators. The final values are as follows $Q_{e1} = Q_{e3}$ = 14.7371 and $k_{1,2} = k_{2,3}$ = 0.064340.

To determine the respective coupling configurations, a full wave simulator was used. Due to the extremely small size of the resonator strong couplings are difficult to realize. To achieve the desired Q_e, the input transmission line was inserted through underneath the SMD capacitor looping the resonator as shown in Fig. 2a. For the external coupling, extra coupling transmission lines were added to achieve the required k coupling as exhibited in Fig. 2b.

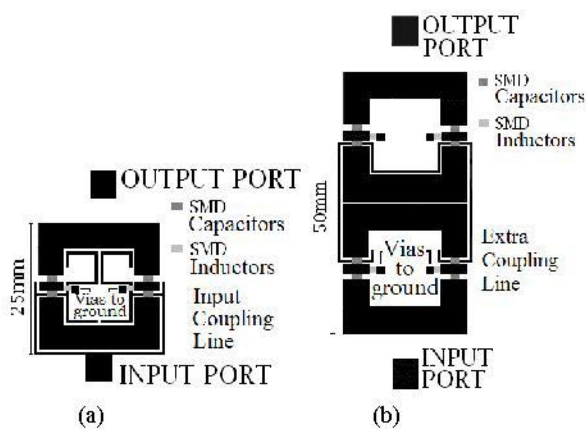
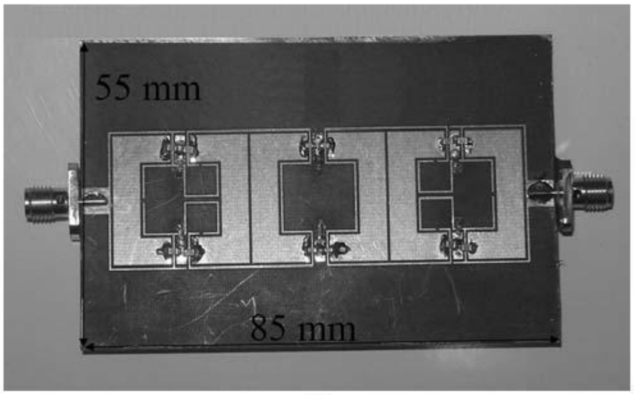
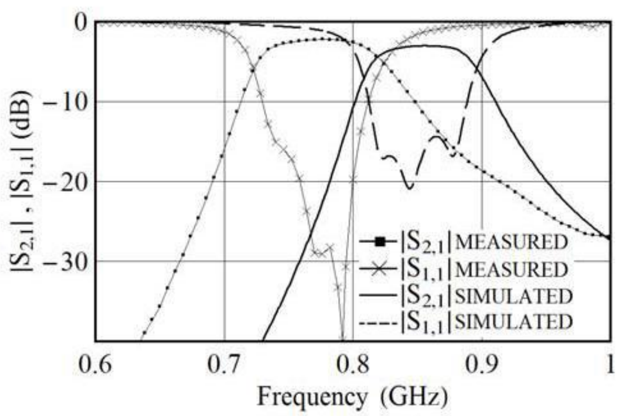


Fig. 2. Coupling configurations. (a) To achieve the desired Q_e. (b) To achieve the required k coupling.

The final filter layout is shown in Fig. 3a and the simulated and experimental results in Fig. 3b. It is seen that the simulation including losses had a BW of 84MHz (896-811MHz) with an insertion loss of -2.98 dB at the center frequency and a return loss greater than -14.35 dB throughout the band. While the experimental results had a BW of 99MHz (824-725MHz, 12.7%) with an insertion loss of -2.2 dB at the center frequency and a return loss greater than -15 dB. It is believed that the simulated insertion losses are higher since the actual SMD Q factors are higher than the specified by the manufacturer. There was a frequency shift of 84MHz due to the SMD components.



(a)



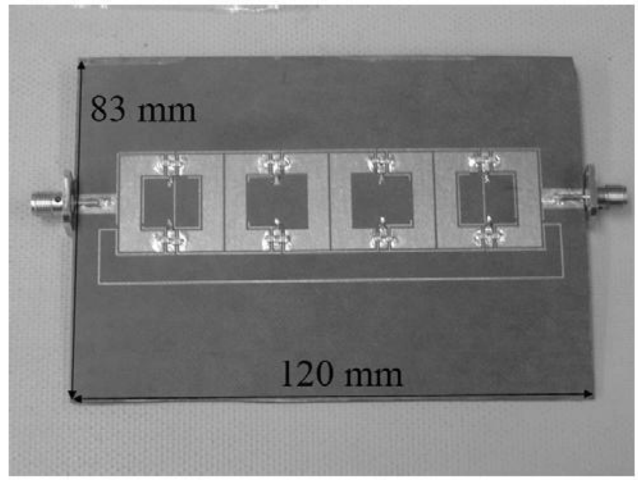
(b)

Fig. 3. (a) Final 3 Pole Chebyshev Filter layout. (b) Simulated and experimental results.

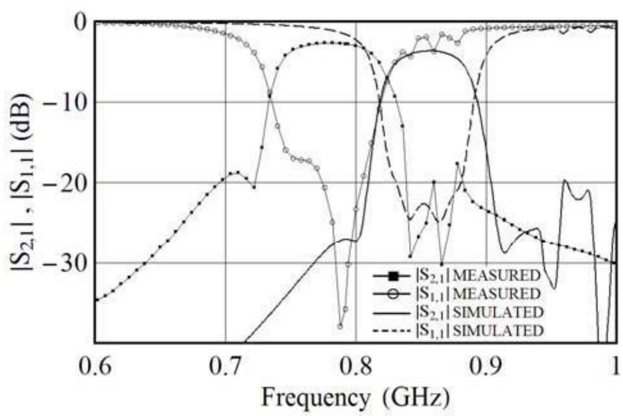
IV. 4 Pole Quasi Elliptic Filter

The low pass prototype elements for a 4th order quasi elliptic filter with a ripple of 0.044dB are [21], $\Omega_a = 1.8$, $g_1 = 0.95974$, $g_2 = 1.42192$, $J_1 = -0.21083$, $J_2 = 1.11769$. In the same way as in the 3 pole filter, the parameters are calculated for a FBW = 7.2% at a center frequency f_0 = 859MHz. The final values are: $Q_{e1} = Q_{e4} = 13.3297$, $M_{1,2} = M_{3,4} = 0.06163$, $M_{2,3} = 0.056595$ and $M_{1,4} = -0.015816$. Similar coupling schemes as for the previous filter were used to achieve tight couplings. To accomplish a negative coupling the line between resonators 1 and 4 is made 180° longer. The final layout of the filter is shown in Fig. 4a and the experimental and simulated responses in Fig. 4b.

The simulated BW was 63MHz (824 - 887MHz or 7.33%) with an insertion loss of -3.65 dB at the center frequency and a return loss greater than -22.62 dB in the pass band. For the experiment, the BW was 80MHz (740-820MHz or 10.2%) with an insertion loss of -2.6 dB and an insertion loss lower than -15 dB. There was a 76MHz frequency shift caused mainly by the SMD components.



(a)



(b)

Fig. 4. (a) Final 4 Quasi Elliptic Filter layout. (b) Simulated and experimental results.

V. Conclusions

MTM closed loop resonators have been demonstrated with a miniaturization of 80% at the 800MHz band and without harmonic generation. Using these resonators two filters (one 3 pole Chebyshev and a 4 pole quasi elliptic) were successfully implemented showing good agreement between simulation and experiment.

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