Compact Dual-Band and Multi-Band Filters for Applications in Wireless Communications

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***Abstract* — New configurations of compact dual/triple/ multiple pass-band filters, which are well suited for applications in wireless communications, are presented. Asymmetric step-impedance resonators are the main elements for the design of these filters. In order to increase the number of attenuation poles in the vicinity of the pass-band regions, negative and positive cross coupling between source and load is applied. Filter examples are designed on RT6006 and RT6010 substrates, and their responses are verified through the use of full-wave commercial field solvers.**

***Index Terms* — Filter design; stepped impedance resonators; multi-band filters; comb-line configurations.**

I. INTRODUCTION

The increasing demand for wireless communication applications requires RF components to operate in multiple separated frequency bands in order to access different services with a single multimode terminal. In addition, high speed wireless Local Area Networks (LAN's) and other services such as WiMAX and ISM operate at frequencies between 2 GHz and 6 GHz with bandwidths up to 100 MHz. In order to accommodate this multi-band RF signal reception and transmission into a single RF transceiver, a dual-band or multi-band RF front-end circuit is required. This can be achieved by switching between separate filters, but such an approach leads to a high number of filter components, thus enlarging circuit size and increasing power consumption.

Concurrent dual-band or multi-band components are needed to integrate circuits operating in different bands into a single unit so that size, cost and component count can be reduced. Therefore, in this approach, all filter components must have the new feature of simultaneous pass-bands at separated center frequencies with adequate out-of-band suppression.

Different configurations have been proposed for realizing dual-band filters. In [1], the second resonating mode of a quarter-wave resonator is adjusted to resonate at the second pass-band of the dual-band filter. This prototype generates two transmission zeros on the upper side of the pass-bands and is suitable for miniature implementation.

Due to their dual-band and tunable harmonic properties, step-impedance resonators (SIR's) are also employed in the design of dual-band filters. Cheng [2] describes a dual-band filter with half-wave step-impedance resonator in a classical comb-line configuration, which creates a strong transmission zero between the two pass-bands.

In this paper, new dual- and multi-band filters are proposed as single-circuit filters, which generate pass-bands located at any desired frequencies. SIR's in comb-line or cascaded configurations create the highly selective dual/multiple pass-band effects. Additional design features include inductive or capacitive cross coupling between source and load. Several dual-band and multiple-band filters are designed at desired frequencies. The results obtained from two full-wave field solvers verify the design theory.

II. DUAL-BAND STEP-IMPEDANCE RESONATORS

Fig. 1 shows the basic structure of a half wavelength SIR. Z_1 and Z_2 represent the characteristics impedances of the transmission line sections, and their electrical lengths are θ_1 and θ_2, respectively. By ignoring the effects of the step discontinuities and the fringing fields at the open end, the conditions of resonance is obtained from the input admittance [3-4]. If the input admittance vanishes, resonance occurs at two distinct frequencies:

$$\begin{aligned} &\text{Resonance at } f_1: \quad K = \tan(\theta_1/2)\tan(\theta_2) \\ &\text{Resonance at } f_2: \quad K\tan(\theta_1/2) = -\tan(\theta_2) \end{aligned} \qquad (1)$$

In (1), f_1 and f_2 are the fundamental and harmonic frequencies and their corresponding electrical lengths are θ_1 and θ_2. The ratio of resonance frequencies depends on the ratio of characteristic impedances $K=Z_2/Z_1$ [4] such that

$$\begin{aligned} f_2/f_1 &< 2 \quad && if \quad K > 1 \\ f_2/f_1 &= 2 \quad && if \quad K = 1 \\ f_2/f_1 &> 2 \quad && if \quad K < 1 \end{aligned} \qquad (2)$$

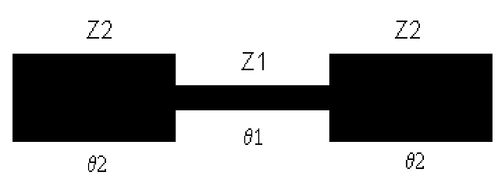

Fig. 1. Schematic of a half-wavelength SIR.

These conditions are utilized to design dual-band filters with different frequency ratios. In fact, K, θ_1 and θ_2 should be determined so that (1) is satisfied. This implies that by appropriately determining the impedance ratio K, two pass-bands with any desired frequency ratio are achieved [3].

Band-pass filters in the microwave frequency range are typically realized by cascaded resonators with proper inter-resonator coupling circuits. Filter design parameters, e.g. coupling coefficients and the number of stages, are derived from given filter specifications such as center frequency at fundamental resonance, bandwidth, return loss and attenuation characteristics. Then, the electrical parameters such as characteristic impedances, electrical lengths and impedance/admittance inverters are calculated. By assuming an open-end coupling section of a SIR, the coupling coefficient in the fundamental resonance is given by [3]

$$k_{ii+1} = \frac{\Delta}{\sqrt{g_i g_{i+1}}} \tag{3}$$

where Δ is the normalized bandwidth, and g_i are the filter coefficients. The structural parameters of the coupled sections can be determined by utilizing the well-known even- and odd-mode characteristic impedances of coupled line sections. In addition, based on specifications of the two center frequencies, the impedance ratio K and the electrical lengths of the SIR are found using (1). Hence, the characteristic impedance of the un-coupled section of the SIR can be calculated through the impedance ratio and the characteristic impedance of coupled sections.

III. New Multi-Band Filter Configurations

An appropriate choice for dual-band filters is to utilize the inter-coupled open ends of transmission-line resonators. This has the advantage that the coupling remains electric for both first and second pass-bands. In a center-coupled arrangement, the magnetic coupling at the fundamental resonance converts to an electric coupling at the next harmonic due to the decrease in guided wavelength. In order to create more attenuation poles and retain bandwidth flexibility in the pass-bands, new dual-band filter structures based on the classical comb-line topology but with different input/output coupling sections are proposed in Fig. 2.

The structures in Fig. 2b and 2c also involve cross coupling between the inputs and outputs of the dual-band filters. Compared to Fig. 2a, this creates additional transmission zeros, which are located between the pass-bands for the configuration with inductive source/load coupling (Fig. 2b) and in the upper stop-band region for the structure with capacitive source/load coupling (Fig. 2c). Note that compared to other dual-band filters, the new schemes proposed here have smaller size and do not require input/output impedance matching transformers.

Other configurations of dual-band and multi-band filters are shown in Fig. 3. They form cascaded sections of SIR's similar to a ladder configuration with coupling through an out-of-phase feed structure. The coupling between resonators at fundamental and harmonic resonances is adjusted through the location of feeds on the SIR's and the length and characteristic impedance between the feed points. These new configurations generate two transmission zeros by the feed structure, one in the lower stop-band region and one between the pass-bands. The positions of the input and the output are used to control the transmission zeros. Furthermore, additional pass-bands are created due to harmonics and the extra transmission line between the feed locations of the SIR's. Therefore, the new schemes are capable of generating multi-band filter responses, which are suitable for wireless applications.

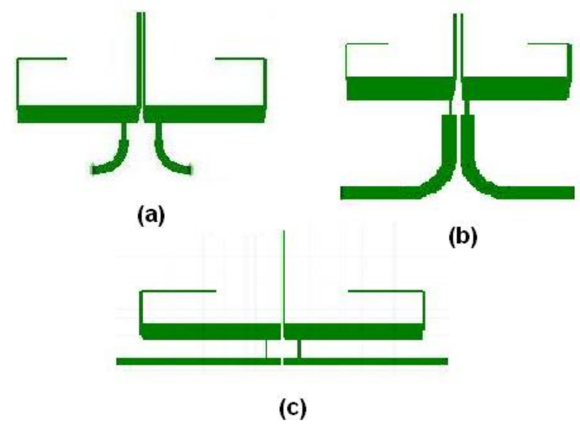

Fig. 2. New dual-band filters based on the classical comb-line coupling configuration: (a) without source/load coupling; (b) with inductive source/load coupling; (c) with capacitive source/load coupling.

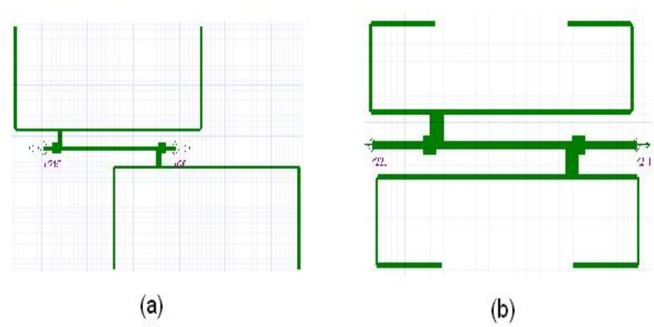

Fig. 3. New cascaded/ladder multi-band filter configurations.

IV. Results

This section presents typical performance characteristics of the proposed dual- and multi-band filters. The designs use RT6006 and RT6010 with 1oz metal thickness, 25mils and 75mils substrate heights, respectively, and are verified by the commercial packages IE3D® and Ansoft Designer®. Note that slight differences between Ansoft Designer® and IE3D® results have been observed previously [5]. They are attributed to slightly different implementations of the method-of-moments in both packages.

Fig. 4 shows the performance of the new microstrip dual-band step-impedance filter in Fig. 2a on RT6006 substrate. The results demonstrate the existence of two 100MHz-wide pass-bands centered at 2.6 GHz and 3.75 GHz. Three transmission zeros are observed at 1.75 GHz, 2.25 GHz and 3 GHz. Two additional transmission zeros form a complex pair at 4.25 GHz. This is due to the harmonics of the zeros in the lower stop-band region and the phase displacement in this structure. Note that such a performance cannot be achieved with a classical comb filter structure.

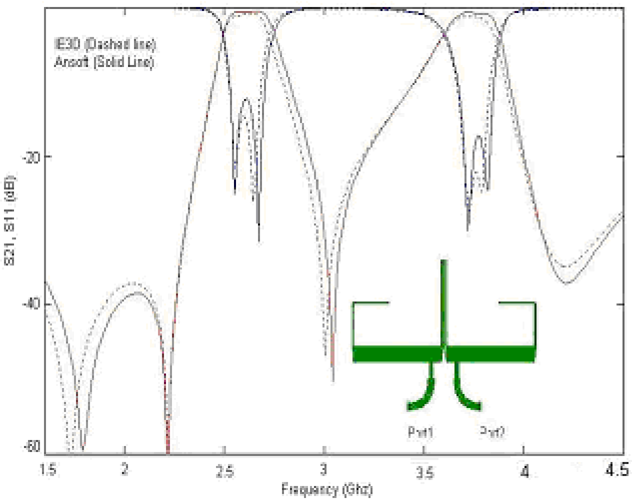

Fig. 4. Performance of the new dual-band comb-line configuration according to Fig. 2a.

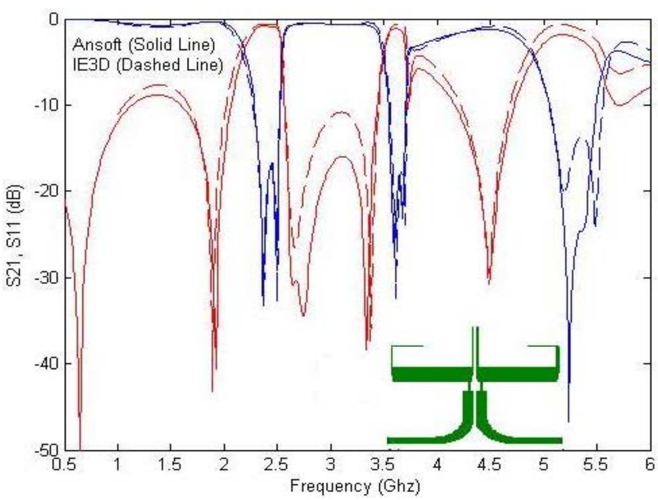

Fig. 5. Performance of the new dual-band comb-line filter with inductive source/load coupling according to Fig. 2b.

Fig. 5 shows the results for the filter configuration in Fig. 2b on RT6010 substrate. The performance shows the existence of two 200MHz pass-bands centered at 2.4 GHz and 3.5 GHz. Compared to Fig. 4, additional transmission zeros are placed between the two pass-bands by allocating inductive (positive) cross coupling between the source and the load. This cross coupling also compensates the phase displacement in Fig. 2a (c.f. Fig. 4) and generates a zero in the upper stop-band region.

Fig. 6 presents the performance of the filter scheme in Fig. 2c on RT6006 substrate. This structure is similar to that in Fig. 5, but it uses capacitive cross coupling between the source and the load. The effect of capacitive source/load cross coupling is to compensate the phase displacement that causes the complex pair of zeros in Fig. 4. Consequently, we observe the appearance of the two transmission zeros on the upper side of the second passband.

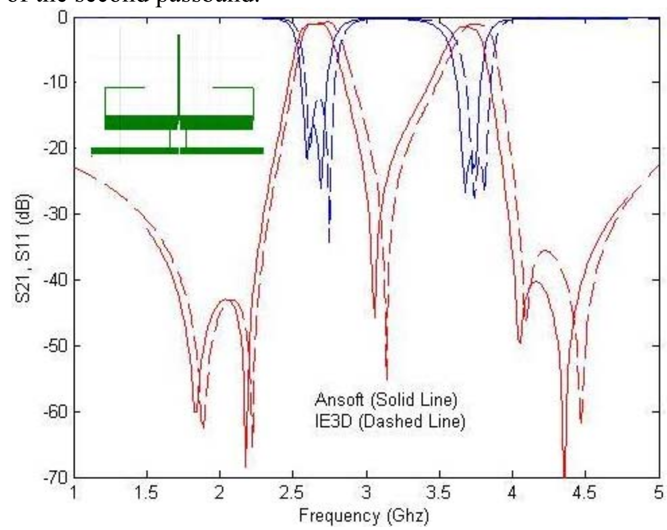

Fig. 6. Response of the new dual-band comb-line filter with capacitive source/load coupling according to Fig. 2c.

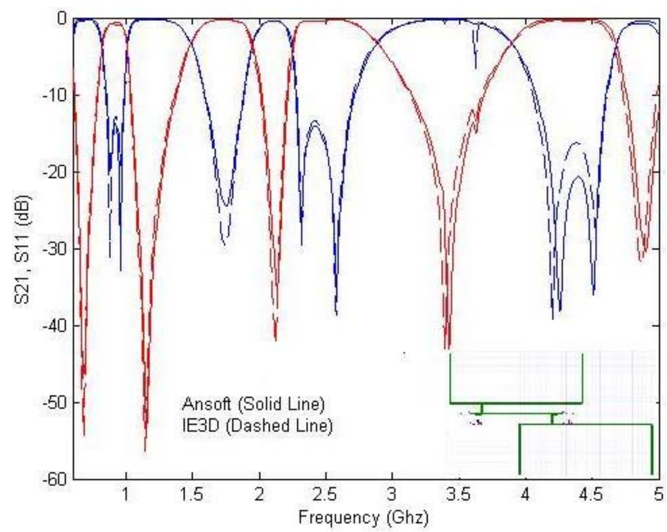

Fig. 7. Response of the new cascaded/ladder multi-band filter configuration according to Fig. 3a.

The examples in Fig. 7 and Fig. 8 show the performances of multiple-band filters with the cascaded-ladder configurations in Fig. 3 on RT6006 substrate. The center frequencies are located at 0.925 GHz, 1.8 GHz and 2.4 GHz with 100 MHz, 100 MHz and 250 MHz bandwidths (-20dB), respectively.

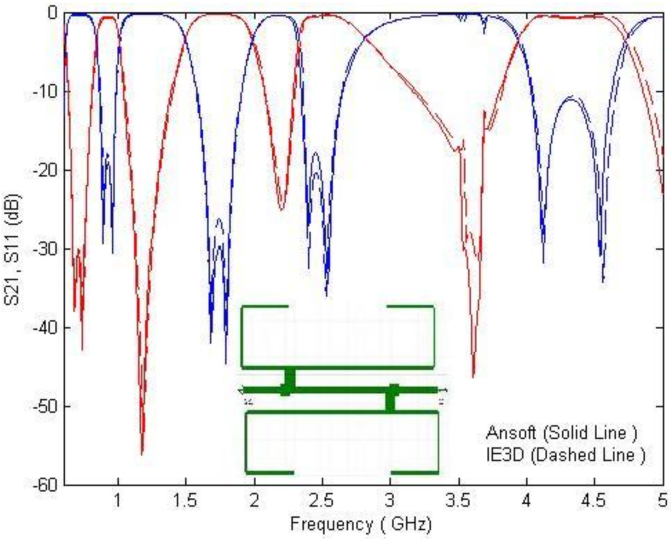

Fig. 8. Response of the new cascaded/ladder multi-band filter configuration according to Fig. 3b.

The main advantage of these configurations is that they are capable of creating multiple pass-bands at desired center frequencies, which are suitable for wireless applications. Other advantages include small size, low cost and high efficiency. Note that both structures create four pass-bands between 0.5 GHz and 5 GHz. Compared to the dual-band filters in Figs. 4-6, the third pass-band is determined by the main line spacing between the feed points to the individual filters and, therefore, can be controlled. The fourth passband appears as a harmonic of the first one.

V. CONCLUSIONS

This paper presents new dual-band and multiple-band filter designs based on step-impedance resonators. The performance of the new filters exhibits additional transmission zeros on each side of the central bandwidth, thus increasing out-of-band rejection. The cascaded-ladder filter configuration is capable of generating multiple pass-bands at desired frequencies, which are suitable for wireless applications. In addition and in comparison with traditional dual-band filters, the new designs require less circuit-board space, size and cost because of their compressed structure without input/output matching network.

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