Dual-Band Multi-Pole Directional Filter for Microwave Multiplexing Applications

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***Abstract*—A novel microstrip directional filter for multiplexing applications is presented. This device uses composite right-left-handed transmission lines and resonators to achieve dual-band frequency response. In addition, by cascading two or more stages using dual frequency immitance inverters, multi-pole configurations can be obtained. Simulation and experimental results are presented with good agreement.**

***Index Terms*—Composite right-left-handed (CRLH) lines, directional filters, microwave filters, slow-wave (SW) resonators.**

I. Introduction

Directional filters (DFs) offer a good alternative to multi-channel systems since they can be cascaded in a modular concept and use fewer components than hybrid based systems [1]–[5]. DFs can be classified into two types based on their directivity principles. The first group is designed with traveling-wave resonators [2]–[4] and the second can be made with standing-wave resonators [2], [5]. For the first group, due to the resonator nature (closed-loops of length of $n\lambda$, n being an integer), there are limitations in miniaturization and in dual-band applications as the second harmonic cannot be freely chosen. In addition, due to their directive coupling nature, they are normally designed over multi-layer and in waveguide technologies [2]–[4], where TE and TEM waves are supported. For the second group, any type of standing-wave resonator can be chosen, allowing higher design versatility in terms of miniaturization and dual-band behavior. Since the directivity in this type of filters does not depend on the resonator coupling, they can be easily designed in microstrip technology. However, their main drawback is that they present single-pole configurations [2].

In this letter, a general method for multi-pole DFs based on standing-wave resonators is proposed, where several stages can be cascaded by immitance inverters. The schematic circuit and closed design equations are presented for the first time, where any configuration such as Butterworth or Chebyshev can be obtained. Moreover, due to the effect of the immitance inverters, transmission zeros can be obtained.

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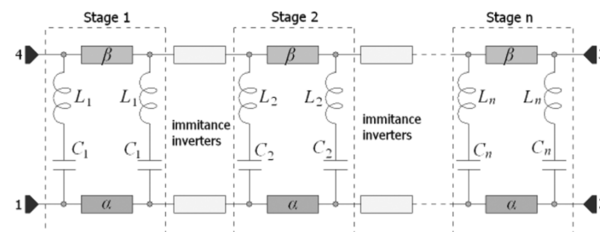


Fig. 1. Schematic of an n-pole DF. Each stage corresponds to a conventional DF composed by standing-wave resonators (modeled with series L_i and C_i), coupled by two lines having electrical lengths α and β to produce directionality of the signal, conventionally, -90° and -270° phase response respectively [1], [2]. The stages are cascaded by immitance inverters to produce a multi-pole filter response.

Additionally, since multi-band devices are becoming the norm in several communication applications [6], a dual-band configuration is designed and implemented. Slow-wave (SW) resonators are used, where the fundamental and first spurious resonances are assigned at two specific frequencies [7]. For the multi-pole filter operation, a new type of dual-band composite right-left-handed (CRLH) immitance inverter is introduced.

Table I tabulates the characteristics of DFs reported in the literature [3]–[5]. The structures are single-band DFs compared with the dual-band in this letter. Moreover, our design presents good selectivity and low dimensions.

The proposed structure is a two-pole DF designed at 0.8 and 1.9 GHz, over a Rogers RO4003C substrate with permittivity $\varepsilon_r = 3.38$ and thickness $h = 1.524$ mm. Simulation and experimental results are presented with good agreement.

II. Microstrip Multi-Pole Directional Filter

Conventional DFs based on standing-wave resonators present a single-pole filter response [1], [2]; however, resonator scalability is achieved by cascading several DFs (stages) operating at the same frequency by immitance inverters. Fig. 1 shows the schematic circuit of an n-pole DF.

Due to the directional characteristics of this type of filter, at the frequency of operation, a bandstop response is obtained between ports 1 and 2, and the complementary bandpass is generated between ports 1 and 4. No signal is reflected to port 1 and no transmission is generated to port 3. Under these conditions, the multi-pole design is based on the bandstop response (S_{21}) filter approximation [2], which is achieved from the reactance slope parameter (x_i) of each stage

$$x_i = \frac{\omega_0 L_i}{2} = \frac{1}{2\omega_0 C_i} = Z_0 \frac{1}{g_{n+1} g_i \Omega_c FBW}, \quad i = 1 \text{ to } n,\ g_0 = 1 \tag{1}$$

TABLE I
COMPARISON OF SEVERAL CONFIGURATIONS FOR MULTI-POLE DIRECTIONAL FILTERS

filter	resonator	technology	freq. bands	bandwidth (%)	dimensions*	poles	selectivity	dual band
[3]	Traveling-wave	SIW	12 GHz	2.1	1.96 x 2.04	2	Medium	No
[4]	Traveling-wave	Multi-layer	6 GHz	3.5	0.14 x 0.33	3	Medium	No
[5]	Standing-wave	Microstrip	0.9 GHz	6.9	0.48 x 0.15	2	High	No
Proposed	Standing-wave	Microstrip	0.8, 1.9 GHz	6.9, 2.7	0.38 x 0.23	2	High	Yes

* Dimensions are expressed as width by height in terms of λ_0, as a guided wavelength in free space at the frequency of operation.

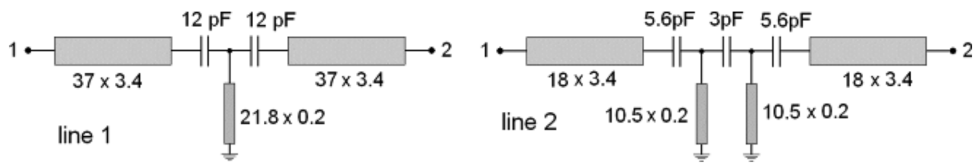


Fig. 2. Designed dual-band CRLH lines. Dimension units are in mm.

where g_i and Ω_c are the element values and cutoff of the lowpass prototype respectively, FBW is the fractional bandwidth, Z_0 is the terminating characteristic impedance of the ports and n is the order of the filter [2].

The parameter x_i is related to the notch 3-dB bandwidth ($\Delta f_{3\text{ dB}}$) of each stage by

$$\frac{x_i}{Z_0} = \frac{f_0}{2\Delta f_{3\text{ dB}}} \tag{2}$$

which relates the frequency response of a single stage to the required resonator slope parameter [2].

III. DUAL-BAND MULTI-POLE DIRECTIONAL FILTER

The proposed structure is a two-pole DF based on Butterworth parameters with $FBW = 0.08$ (8%) at $f_1 = 0.8$ GHz and $FBW = 0.038$ (3.8%) at $f_2 = 1.9$ GHz. The parameters for both the operation bands are $g_0 = g_3 = 1$, $g_1 = g_2 = 1.4142$ [2] obtaining $x_1/Z_0 = x_2/Z_0 = 8.57$ for f_1 and 18.66 for f_2.

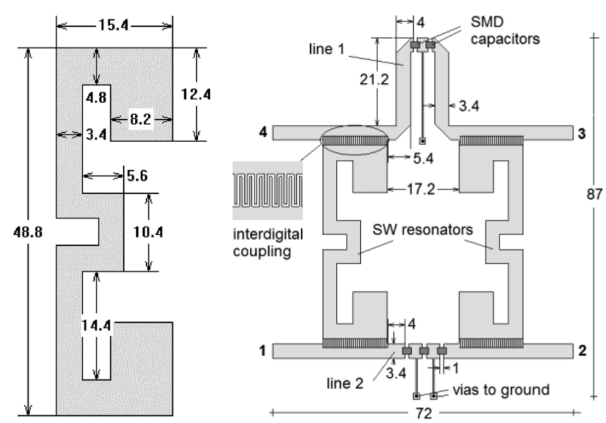
Using the non-linear phase response of CRLH lines, a dual-band directional filter can be obtained by matching the conditions of directionality at the proposed frequencies, $f_1 = 0.8$ GHz and $f_2 = 1.9$ GHz.

A. Dual-Band CRLH Lines

Lines 1 and 2 of each stage, with electrical length α and β, respectively (Fig. 1), are designed with CRLH lines. The reader is referred to [6] for full design procedure of dual-band CRLH transmission lines. Line 1 has a phase response of -90° and -270° at f_1 and f_2 respectively; line 2 presents a response of $+90^\circ$ and -90° at f_1 and f_2, respectively. The lines use SMD capacitors and shunt stub inductors for the left-handed (LH) cell. For the right-handed (RH) section, conventional 50 Ω lines are utilized. The designed lines are shown in Fig. 2.

B. Slow-Wave Resonators

For dual-band operation, slow-wave (SW) resonators are chosen since their fundamental resonance (f_1) and first spurious (f_2) can be adjusted at specific frequencies. This resonator is designed as a microstrip line with folded capacitive patches at both ends, following the procedure detailed in [7]. By varying the dimensions of the folded open-stubs of the SW resonator, it is possible to achieve ratios f_2/f_1 between 1.9 and 2.7 [7]. For the proposed filter, an SW resonator showing a ratio $f_2/f_1 = 2.375$ is designed on the RO4003C substrate. Fig. 3(a) shows the geometry of the resonator.



(a) (b)

Fig. 3. Geometries of (a) designed SW resonator, and (b) single stage dual-band directional filter. All units are in mm.

C. Dual-Band Single Stage

A single stage is realized by using the designed CRLH lines and SW resonator. Two identical resonators are coupled to the CRLH lines by interdigital fingers for a capacitive coupling. Simulations in [8] are carried out in order to optimize the x_i/Z_0 ratio for each stage. By varying the length of interdigital fingers, it is possible to modify the 3-dB bandwidth, which is related to x_i by (2). Additionally, the physical length of lines 1 and 2 are optimized for good directivity. The required x_i/Z_0 values are achieved with a coupling of 39 fingers of 0.2 mm width, 0.2 mm gap between them and 2.4 mm length. Since for a given interdigital coupling, x_i/Z_0 is fixed at both bands, the overall FBW at f_1 and f_2 cannot be adjusted independently [7]. The final layout of the stage is shown in Fig. 3(b).

D. Dual-Band Immitance Inverters

CRLH dual-band immitance inverters are designed to generate the multi-pole response at both f_1 and f_2.

An immitance inverter can be realized as a transmission line with a phase response of -90° or an odd multiple at a particular frequency [2]. For the proposed structure, symmetrical 50 Ω CRLH lines with $+90^\circ$ and -90° at f_1 and f_2, respectively,

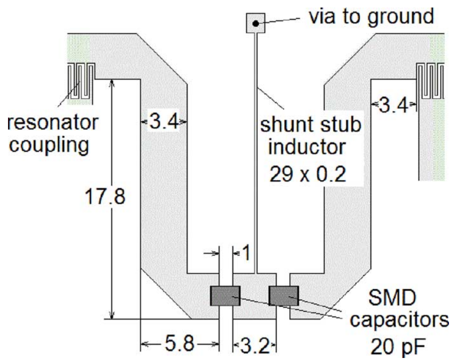


Fig. 4. Designed CRLH dual-band immitance inverter formed by one LH symmetrical cell of two series SMD capacitors and a shunt stub inductor, and RH conventional lines. The inverter has been folded for space saving. Dimension units are in mm.

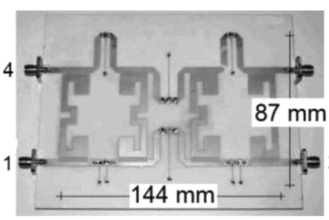


Fig. 5. Photograph of the two-pole dual-band directional filter.

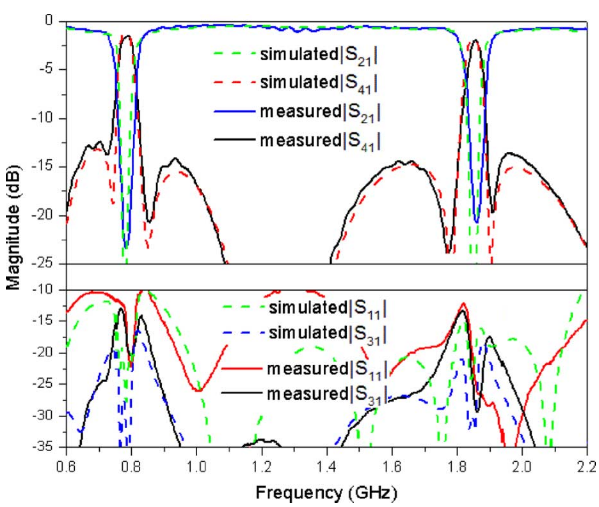


Fig. 6. Simulated and experimental responses of the proposed filter.

are designed as the dual-band immitance inverters following the procedure detailed in [6]. Fig. 4 shows the designed CRLH immitance inverter.

E. Proposed Dual-Band Directional Filter

Due to the symmetry of the filter ($x_1 = x_2$), two identical stages [Fig. 3(b)] are connected by the dual-band CRLH immitance inverters and optimized by simulations [8]. The structure is implemented on a Rogers RO4003C substrate, of height 1.524 mm, by conventional photolithography. A photograph of the two-pole dual-band DF is shown in Fig. 5.

IV. Measurements

Experimental measurements are performed using an Agilent PNA-series vector network analyzer E8361A. The simulated and experimental frequency responses are plotted in Fig. 6.

From Fig. 6, it is noticeable that simulated and measured responses are in excellent agreement. Although this filter is based on a Butterworth approach, it is seen that ripples are generated along the S_{41} stopband region. This is because the $\pm 90^\circ$ line sections between stages are frequency-sensitive and they approximate immitance inverters only over a limited range generating standing waves outside the operating bands [3]. However, this improves the S_{41} selectivity as transmission zeros are generated for both bands.

The measured bandwidth is 6.9% for f_1 and the S_{41} measured insertion losses are of 1.3 dB. For f_2, the measured bandwidth is 2.7% and the measured S_{41} losses are below 1.7 dB. Return losses (S_{11}) and isolation (S_{31}) are below -10 dB and -13 dB, respectively, throughout the band. Signal directivity ($|S_{41}|/|S_{31}|$) of 30 dB is observed at both bands.

From simulations of the lossy CRLH lines, it was observed that insertion losses are below 0.64 dB at the operating frequencies f_1 and f_2, obtaining low losses in the frequency response of the complete structure.

A 5 MHz shift at the operating frequency between simulated and experimental responses is observed at f_2. There is almost no variation at f_1. In order to quantify this frequency shift, a sensitivity analysis was carried out by changing all dimensions within $\pm 5\%$ and substrate permittivity to its extreme tolerance values (from 3.33 to 3.55) [9]. It was observed that the resonant frequency shifted 50 MHz and 100 MHz at f_1 and f_2, respectively. Therefore, the experimental frequency variations lie within the expected tolerances. The higher discrepancies of S_{11} between simulation and measurements are due to the inclusion of SMA connectors and soldering of the SMD capacitors in the measured circuit.

V. Conclusion

A novel microstrip multi-pole standing-wave directional filter design has been proposed. The structure uses CRLH lines as immitance inverters to give dual-band response. Slow-wave resonators were implemented for operation at the two frequencies of interest. For demonstration, a two-pole structure was designed at 0.8 and 1.9 GHz. Simulation and experimental results show good agreement.

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