Multi-pole Microstrip Directional Filters for Multiplexing Applications

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Abstract

Theory and experiment of multi-pole microstrip directional filters for multiplexing networks are presented in this paper. Conventional microstrip directional filters present only a single-pole filter response. By applying stopband filter theory, two Butterworth microstrip directional filters are designed and tested. The desired multi-pole filter response is achieved by cascading two or more similar single stages connected by immitance inverters. These types of directional filters are ideal candidates for multiplexing applications since they present the characteristics of easy implementation and the capacity of a modular concept. Moreover, a flat response is obtained along the passband due to the multi-pole filter behavior.

1. Introduction

The principles of combining or separating frequency diverse microwave channels for interfacing with a single port antenna system have been known for many years [1]. With the growth of satellite communication systems, the greatest technical advances were made in multiplexing structures [1]. Modern communication systems require multi-band operation, which includes mobile telephony communication systems, radiolocation and satellite links.

Several configurations have been employed for multiplexing network structures, such as hybrid-coupled, circulator-coupled, manifold filters and directional filters multiplexers [1].

Hybrid-coupled multiplexers present the advantages of multi-pole filter response, and a modular concept; however, it makes use of two identical filters and two hybrids per channel, which adds physical size and weight compared to other approaches. Multiplexing by using circulators requires only one standard filter, and it allows a modular concept, but, as long as the signals must pass through circulators, they suffer extra loss per trip; also, they only present one way signal flow at the time. A manifold multiplexer requires only one filter per channel to operate, and is capable of realizing optimum performance in terms of insertion loss, amplitude and group delay; however, it presents a complex design, a high time consuming tuning process, and it is not amenable to flexible frequency channels, i.e., change of a channel frequency requires a new multiplexer design. A directional filter based multiplexer requires only one filter per channel, is simple to tune and is amenable for a modular concept; however, it is restricted to the use of a single pole filter response [1] – [4].

In this paper, the theory, design and implementation of multi-pole response microstrip directional filters for multiplexing structures is presented. It has been proved that cascading more than one stage operating at the same frequency it is possible to achieve a multi-pole response, maintaining its main advantages of easy design, implementation and management in a modular concept.

This paper is organized as follows: Section 2 presents the theory of directional filters; Section 3 shows the multi-pole theory applied to directional filters; the design and construction of multi-pole directional filters are presented in Section 4; the concept of a multiplexer based on multi-pole directional filters is shown in Section 5; conclusions are discussed in Section 6.

2. Microstrip Directional Filter design

A Directional Filter is a four-port device having a bandpass response between ports 1 and 4 (S_{41}), and its complementary rejectband response between ports 1 and 2 (S_{21}), no power is transmitted to port 3, and none is reflected to port 1 [2] – [6]. Fig. 1 shows a microstrip directional filter designed with two half-wavelength ($\lambda_g/2$) resonators [6].

The 3-dB bandwidth for this structure can be obtained in terms of its quality factor Q between ports 1 and 4 [2]

$$\frac{1}{Q} = \frac{f_2 - f_1}{f_0}, \tag{1}$$

where f_1 and f_2 are the lower and upper -3 dB cutoff frequencies and f_0 is the central frequency [2].

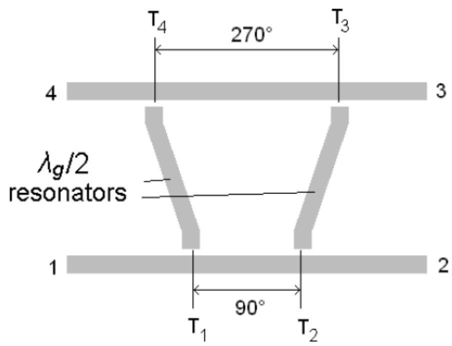


Figure 1. Microstrip directional filter.

The mechanism of directionality in this filter is explained by using the superposition principle based on the length of the lines between the coupling points (Fig. 1) T_1 and T_2 (90°), and points T_3 and T_4 (270°) [2], [3]: at the operation frequency, excitation of ports 1 and 4 at the points T_1 and T_4 with $V/2$ (even mode) amplitude waves, and excitation of ports 1 and 4 at the same points with waves of amplitude $V/2$ and $-V/2$ respectively (odd mode), are equivalent to the excitation of port 1 with a V amplitude wave. The resonator on the right side is excited by the even mode excitation of ports 1 and 4, and reflects $V/2$ amplitude waves at ports 1 and 4. The left resonator is excited by the odd mode excitation, reflecting waves of amplitude $-V/2$ and $V/2$ at ports 1 and 4 respectively. Therefore, the amplitude of the wave at port 4 is V, while at ports 1, 2 and 3 is zero. At frequencies outside resonance, the signals entering into port 1 pass unattenuated to port 2 [2] – [4].

Directional filters can be arranged to form multiplexing networks (separation or combination of different channels). Fig. 2 shows a multiplexing structure composed by four directional filters operating at different channels each one [2]. The structure can also act as a channel combiner if all arrows are reversed [2].

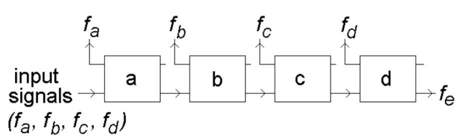


Figure 2. A Multiplexing structure composed by directional filters.

3. Multi-pole directional filters

Conventionally, the main drawback of these directional filters is that they are limited to only two resonators, which gives a single-pole filter response. This degrades the stopband and limits the bandwidth to very narrow responses [1] – [6]. However, resonator scalability is possible due to the cascading of directional filters, operating at the same frequency, by immitance inverters (quarter wavelength lines) between each stage. Fig. 3 shows a three-pole directional filter. Each stage corresponds to a single conventional directional filter.

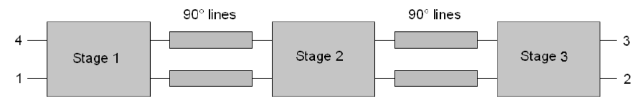


Figure 3. Three-pole directional filter composed by single stages connected by 90° lines.

The correspondent multi-pole design procedure is based on narrow stopband filter theory [7]. Due to the directional characteristic of these filters, a stopband response is obtained between ports 1 and 2, and its complementary bandpass response is achieved between ports 1 and 4, so each stage of the multi-pole directional filter, from ports 1 to 2 (Fig. 1), acts as a notch resonator. By cascading several stages connected by immitance inverters (90° lines in Fig. 3) it is possible to achieve a multi-pole stopband response between ports 1 and 2 of the overall structure, consequently, its complementary multi-pole bandpass response is generated between ports 1 and 4 of the complete configuration.

A general approach for the design of narrow stopband filters is based on reactance slope parameters of the resonators [7]. Based on a lowpass prototype, the transition from bandstop filter design is effected by frequency mapping [7]

$$\Omega = \frac{\Omega_c FBW}{\omega / \omega_0 - \omega_0 / \omega}, \qquad (2)$$

$$\omega_0 = \sqrt{\omega_1 \omega_2}, \qquad (3)$$

$$FBW = \frac{\omega_2 - \omega_1}{\omega_0}, \qquad (4)$$

where Ω is the normalized frequency of the lowpass prototype, Ω_c is its cutoff, ω_0 is the midband frequency and FBW represents the fractional bandwidth of the bandstop filter limited by ω_1 and ω_2 [7]. An equivalent model for the n-pole stopband filter is shown in Fig. 4 [7].

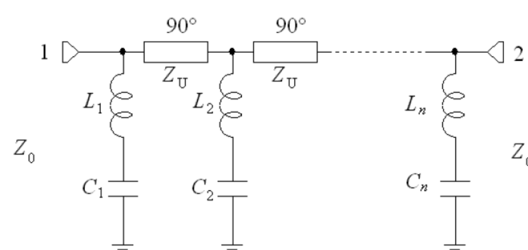


Figure 4. Equivalent model of an n-pole stopband filter.

The parameters Z_0 and Z_U from Fig. 4 correspond to the terminating and characteristic immitance inverter impedances respectively [7]. All the circuit parameters including inductances L_i and capacitances C_i can be defined in terms of the lowpass prototype elements [7]. For the schematic model of Fig. 4 [7]:

$$\left(\frac{Z_U}{Z_0}\right)^2 = \frac{1}{g_0 g_{n+1}}, \tag{5}$$

$$x_i = \omega_0 L_i = \frac{1}{\omega_0 C_i} = Z_0 \left(\frac{Z_U}{Z_0}\right)^2 \frac{g_0}{g_i \Omega_c FBW}, \tag{6}$$

for $i = 1$ to n,

where g_i are the element values of the lowpass prototype. The parameters x_i are the reactance slopes of the shunt series resonators [7], which are related to the 3-dB bandwidth (Δf_{3dB}) of each stage by

$$\frac{x}{Z_0} = \frac{f_0}{2\Delta f_{3dB}} = \frac{Q}{2}. \tag{7}$$

Equation (7) is very useful because it relates the normalized reactance slope parameter to the frequency response of a stopband resonator [7]. In a single directional filter (stage), Eq. (7) is applied to the transmission S_{21} response, due to the stopband resonator nature of this structure between ports 1 and 2, and it can be easily obtained by EM simulation or measurement [7]. Fig. 5 plots the S_{21} response of a single stage for normalized x_i parameter extraction.

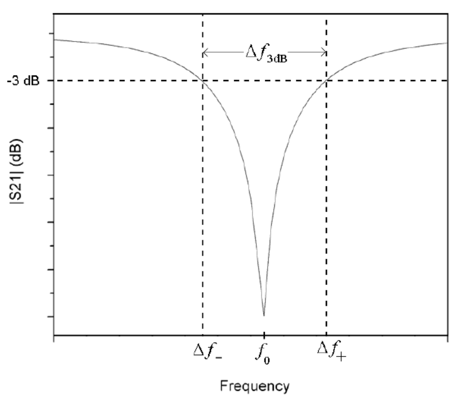


Figure 5. S_{21} frequency response for x_i parameter extraction.

4. Design of Multi-pole directional filters

A two-pole Butterworth directional filter is designed for GSM applications at $f_0 = 0.858$ GHz and $FBW = 0.086$ (8.6 %) [8]. Table 1 tabulates the correspondent lowpass design parameters [7] and the resultant normalized x_i parameters based on (5) and (6). For maximum transmission and optimum performance, $Z_0 = Z_U = 50\ \Omega$ [7]. The filter is implemented on a Rogers RO4003C substrate with $\varepsilon_r = 3.38$ and thickness $h = 1.524$ mm [9]. Fig. 6 shows the first single stage of the directional filter.

Table 1. Lowpass parameters for Butterworth filter, $\Omega_c = 1$ [7], and x_i values.

g_0	g_1	g_2	g_3	$\frac{x_1}{Z_0}$	$\frac{x_2}{Z_0}$
1.0000	1.4142	1.4142	1.0000	8.1987	8.1987

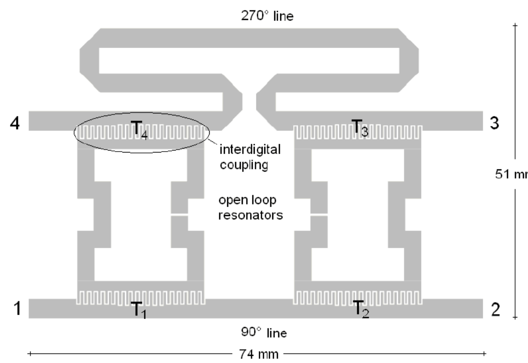


Figure 6. One stage of the proposed Butterworth directional filter.

The first stage of the multi-pole Butterworth directional filter is a symmetrical structure composed by open loop resonators of 22 mm x 28 mm, and coupled to the corresponding lines by interdigital coupling, which consists of 37 fingers of 0.2 mm width and 2.2 mm length, separated by 0.2 mm gap between them. The line which connects T_1 and T_2 coupling points is of 53 mm length (90°), and the upper line, which connects T_3 and T_4 coupling points, is a meandered line of 159 mm length (270°). All the lines are of 3.4 mm width for 50 Ω characteristic impedances.

By using a full wave EM simulator [10], the structure is analyzed in terms of its S parameters. Eq. (7) is used for the calculation of the required normalized x_i values, which can be achieved by varying the resonator couplings.

The structure is optimized to achieve the normalized x_1 value of 8.1987 by varying the length of the interdigital fingers. Fig. 7 shows the variation of the normalized x_i versus length of the fingers for the stage of Fig. 6; it is observable that larger the interdigital fingers, larger the resonator coupling, and consequently, lower the normalized x_i parameter value, according to Eq. (7).

The optimized simulated frequency responses of the stage of Fig. 6 are plotted in Fig 8.

It can be appreciated from Fig. 8 that good rejection level in S_{21} (near -30 dB) is achieved by the structure at f_0. The complementary S_{41} curve, allows total transmission at f_0. No reflection (S_{11}) is generated to port 1, and port 3 (S_{31}) remains isolated (below -20 dB).

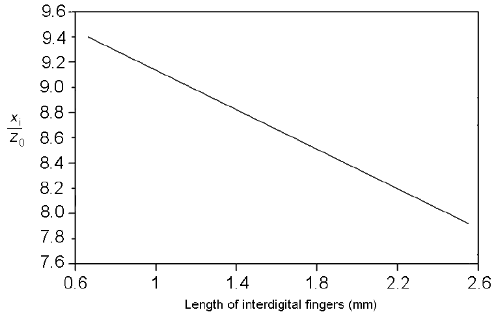


Figure 7. Normalized x_i parameters versus length of interdigital fingers.

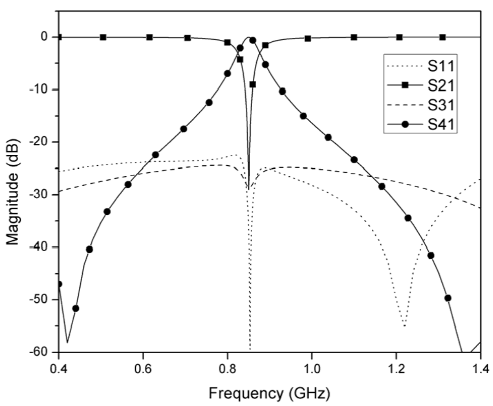


Figure 8. Frequency response of the stage of Fig. 6.

From Table 1, it is noticeable that the complete multi-pole structure is symmetrical ($x_1/Z_0 = x_2/Z_0$), so the stage of Fig. 6 is repeated and cascaded by immitance inverters (90° lines) to form the multi-pole directional filter. Fig. 9 shows the complete structure of the proposed two-pole Butterworth directional filter.

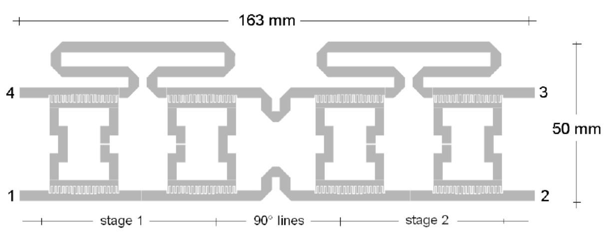
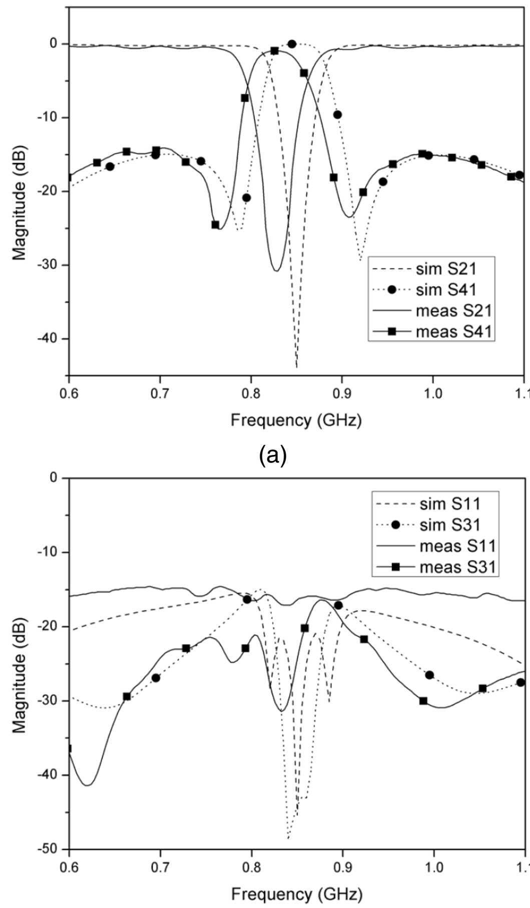


Figure 9. Two-pole Butterworth directional filter for 850 GSM applications.

The proposed filter is implemented, and tested using an Agilent PNA-series vector network analyzer (VNA) E8361A. The simulated and experimental S_{21} and S_{41} responses are plotted in Fig. 10(a), and the simulated and experimental S_{11} and S_{31} curves are plotted in Fig. 10(b).

From Fig. 10, it is noticeable that responses are in agreement. The overall simulated bandwidth is of 7.2 %, while the measured bandwidth results of 6.9 %. The experimental frequency of operation shifted 23 MHz down due to fabrication tolerances. The experimental bandpass insertion loss at the central frequency is of -0.9 dB. S_{11} and S_{31} curves are below -15 dB in simulations and measurements.



(b)

Figure 10. Simulated and experimental frequency responses for the 850 GSM directional filter, (a) S_{21} and S_{41}, (b) S_{11} and S_{31}.

A second two-pole Butterworth directional filter is designed for operation in the Radiolocation and Space Research band [8], from f_1 = 1.215 GHz to f_2 = 1.3 GHz, with f_0 = 1.257 GHz, and FBW = 0.068 (6.8 %), on the same Rogers substrate. The lowpass filter g_i parameters are the same as for the 850 GSM filter. Due to the symmetry of the model and the structure, the resulting normalized reactance slope parameters are $x_1/Z_0 = x_2/Z_0 =$ 10.4553. The filter is designed by following the same procedure as for the 850 GSM-band filter. Fig. 11 shows the two-pole directional filter for the Radiolocation and Space Research band.

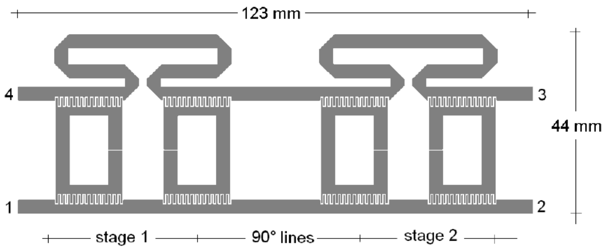
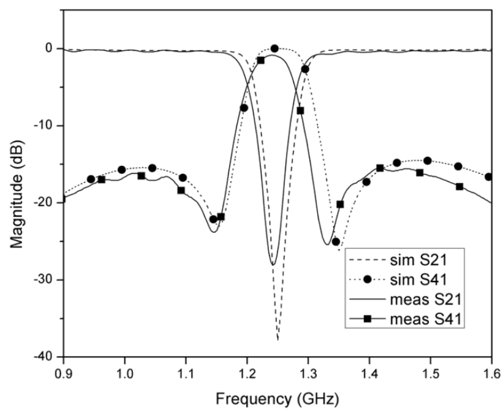
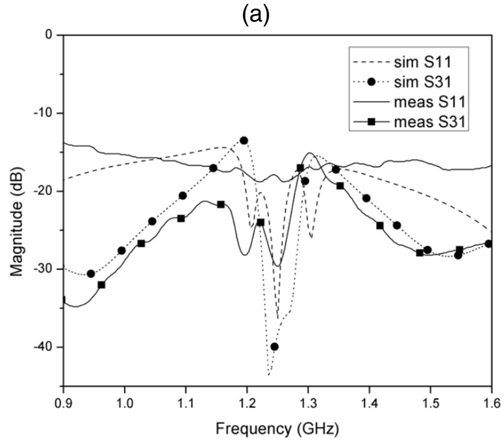


Figure 11. Two-pole Butterworth directional filter for radiolocation and space research applications.



(a)



(b)

Figure 12. Simulated and experimental responses for the filter of Fig. 11, (a) S_{21} and S_{41}, (b) S_{11} and S_{31}.

The filter of Fig. 11 is composed by open loop resonators coupled by 27 interdigital fingers of width 0.2 mm, length 2.2 mm, and 0.2 mm gap between them. The overall length of each resonator loop is 76 mm. The length of the lines that connect the coupling points $T_1 - T_2$ and $T_3 - T_4$ are 38 mm and 114 mm respectively. The lines that connect both the stages are of 38 mm length. All the lines are of 3.56 mm width to achieve 50 Ω impedances.

The filter is implemented and tested for the frequency response. Simulated and experimental S_{21} and S_{41} parameters are plotted in Fig. 12(a), the correspondent S_{11} and S_{31} curves are shown in Fig. 12(b).

From Fig. 12, it is clearly observable that simulated and experimental curves are in good agreement. The overall bandwidth of the simulated filter is of 7.1 %. From measurements, the overall bandwidth results of 6.7 %. A frequency shift down of 9 MHz is observed for the measured response. Insertion losses at the passband (S_{41}) are of -0.8 dB. S_{11} and S_{31} parameters are below -14 dB.

5. Multiplexer with directional filters

To implement a multiplexing network structure, directional filters are cascaded, as shown in Fig. 2. The designed two pole directional filters are connected in a modular concept to form a multiplexing network which operates at 850 GSM (filter 1), and Radiolocation and Space Research bands (1.26 GHz, filter 2). Photograph of the two-band multiplexer is shown in Fig. 13. The stopband filter response for both the bands is obtained at port 2. The 850 GSM band is received at port 4 (S_{41}); the Radiolocation and Space Research band is obtained at port 5 (S_{51}). Ports *iso* and 3 (Fig. 13) are isolated. The correspondent measured frequency curves of the multiplexer are shown in Fig. 14.

From the graphics of Fig. 14, it can be observed that good filter response for both the bands is obtained without interference between them. Reflection S_{11} and isolation S_{31} parameters are below -14 dB, showing a good performance of the structure.

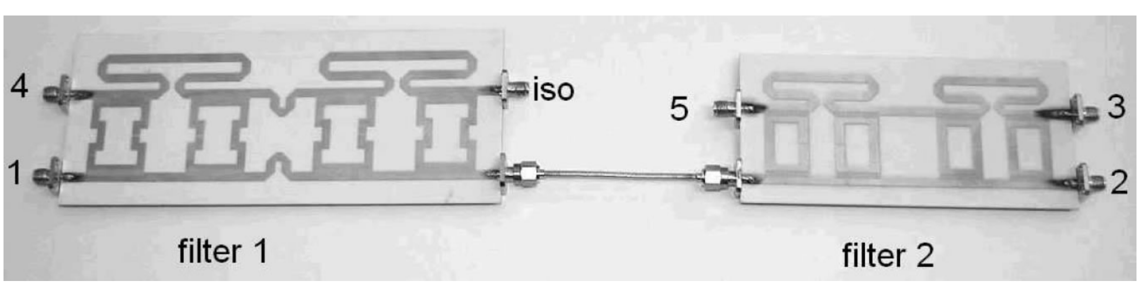
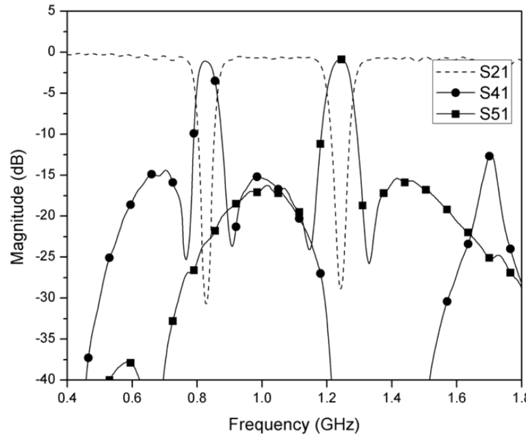
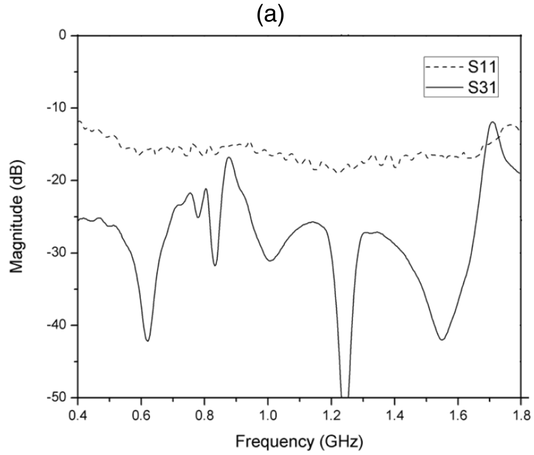


Figure 13. Photograph of the two band multiplexing network.



(a)



(b)

Figure 14. Experimental multiplexer responses, (a) S_{21}, S_{41} and S_{51}, (b) S_{11} and S_{31}.

6. Conclusions

Microstrip multi-pole directional filters are successfully proposed, analyzed and designed based on narrow stopband filter theory. Two microstrip directional filters for wireless applications are designed and tested. A two-band multiplexing network is implemented based on the proposed directional filters showing a good frequency performance, and maintaining the multi-pole response for each proposed band.

The directional filter scalable modular concept is demonstrated for multiplexing applications, adding the novel and particular characteristic of a multi-pole response for each band. These characteristics make this type of filters ideal candidates for multiplexing networks at microwave frequencies, compared with other technologies.

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