Three Element Compact Broadband Parallel-Coupled Microstrip Bandpass Filter of Simple Configuration

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***Abstract* -** A simple broadband parallel-coupled microstrip line (PCML) bandpass filter with compact design is proposed. A PCML structure with two feeding network of various widths is characterized by an equivalent *J*-inverter network. The extracted parameters indicate that the normalized *J* susceptance and equivalent electrical length are frequency dependent. A pair of PCML structure with centre resonator, without ground plane aperture at PCML structure and capacitive open-ended stub at the centre resonator, is proposed. The proposed design is further optimized by adjusting the length and width of the centre resonator. Three broadband bandpass filters with PCML structure of various couplings have been designed. It was found that the simulated and measured insertion and return losses responses showed good agreement with operating bandwidth of over 80%, return loss of better than -16 dB and 250% wide upper stopband.

Keywords: Broadband Bandpass Filter; PCML; Tight Coupler; J–inverter network

1. Introduction

In recent years, compact broadband filters compatible with printed circuits board (PCB) are needed in many communication systems. The filter size is usually constrained by the number of resonators and size of the resonator structures employed in the design. The filter bandwidth is mainly limited by the achievable maximum coupling between these resonators. Various compact resonator structures are available [1]-[4].

Parallel-coupled microstrip line (PCML) structure has been used as coupling components in the design of bandpass filters [5]-[6]. A broadband bandpass filter of PCML structure can be realized by employing high coupling parallel-coupled line. High coupling PCML structure can be achieved by using narrow width and gap of parallel microstrip line.

A ground plane aperture technique for PCML structure has been proposed and developed to enhance a tight coupling over the frequency range of interest [7]. A multi-pole broadband microstrip bandpass filter is realized by attaching a single line resonator of uniform line section between the two PCML sections with backside aperture. To further realize design specifications such as low return loss, adjustable broad bandwidth and wide out-of-band rejection; a pair of capacitive open-ended stubs has been introduced into the central location of the line resonator that is used to shift downwards its second-order resonator frequency. The overall proposed design requires a ground plane aperture and a pair of capacitive open-ended stubs.

The enhancement of PCML structure tight coupling over the wide frequency range can also be realized by using microstrip transmission line with narrow width and gap of the parallel structure. The coupling characteristic depends on the width and gap of a parallel-coupled microstrip.

In this paper, a simple broadband PCML structure similar to [7] has been designed by attaching a single line resonator of specific length and width between two PCML sections without having a backside aperture and pair of capacitive open-ended stubs. The overall filter performance such as insertion loss, return loss and suppression of harmonic response has been further improved by adjusting the length and width of the centre resonator. The centre resonator behaves as a main tool in enhancing the bandwidth of the bandpass filter. The width of the centre resonator can be adjusted accordingly to improve the insertion loss and return loss performances. In addition, the length of the resonator can be adjusted for harmonic cancellation by transmission zero frequency. The overall performance shows that a simple PCML structure with centre resonator without ground plane aperture and a pair of capacitive open-ended stubs at the centre resonator can be used to design compact broadband bandpass filter.

2. PCML Structure

A simple PCML structure has been designed as shown in Figure 1(a) similar to that given in [7]. The two–port admittance *Y*–matrix of the PCML design can be effectively extracted using full–wave analysis of commercially available *em* tools.

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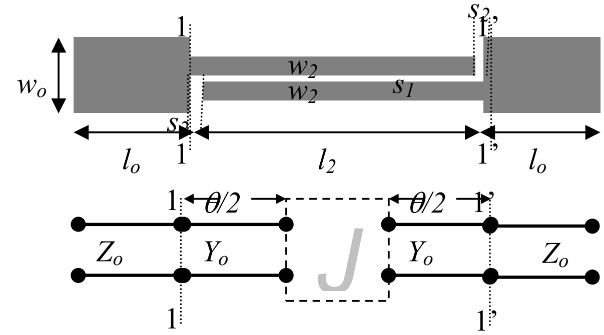

Figure 1: A PCML Structure (a) Configuration, (b) Equivalent J-inverter.

Since the *J*–inverter network with the susceptance (*J*) and two equal electrical lengths of θ/2 at the two sides can be modeled equivalent to PCML, the equivalent circuit of a two–port network admittance of PCML can be used to calculate the *J*-susceptance and electrical length (θ) as shown [8]:

$$\frac{J}{Y_o} = \left|\tan\left(-\frac{\theta}{2} + \theta_{add}\right)\right| \; Siemen \qquad (1)$$

$$\theta = n\pi + \left[\theta_{sub} + \theta_{add}\right] radians \qquad (2)$$

where

$$\theta_{sub} = \left[\tan^{-1}\left(\frac{B_{11}}{Y_o} - \frac{B_{12}}{Y_o}\right)\right] radians \qquad (3)$$

and

$$\theta_{add} = \left[\tan^{-1}\left(\frac{B_{11}}{Y_o} + \frac{B_{12}}{Y_o}\right)\right] radians \qquad (4)$$

n is an integer number given as $n = 0, 1, 2\ldots$, and Y_o is the characteristic admittance of the uniform lines that excite the open–circuited of PCML at the two sides.

Figure 2 shows the computed normalized *J*-inverter susceptance $\bar{J}$ of a PCML structure with various feeding network widths as listed in Table 1. It can be observed that $\bar{J}$ varies in a periodic manner with frequency for various feeding network widths. These indicate the frequency dispersion behavior of the network. In Figure 2, it can be seen that as w_o increases from 1.3 mm to 3.1 mm, $\bar{J}$ increases from 0.6 to 1.8. The bandwidth also increases between first frequency of $\bar{J}$ =1 to second frequency of $\bar{J}$ =1. The peak value of $\bar{J}$ also shifted to a higher frequency as w_o increases. These behaviours demonstrate that feeding network with smaller value of characteristic impedance or higher value of characteristic admittance of a PCML structure is able to improve both the coupling factor and bandwidth.

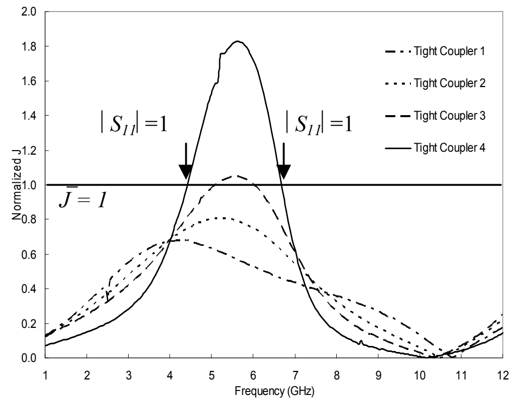

Figure 2: Frequency–Dispersive Behavior of Normalized *J*-Susceptance of a PCML with varying w_o

Table 1: PCML Tight Coupler with varying w_o

Board parameters: ε_r = 6.15, *h* = 1.27 mm						
PCML Tight Coupler	w_o mm	w_2 mm	s_1 mm	s_2 mm	l_o mm	l_2 mm
1	1.3	0.6	0.1	0.2	4.0	7.0
2	1.9	0.6	0.1	0.2	4.0	7.0
3	2.5	0.6	0.1	0.2	4.0	7.0
4	3.1	0.6	0.1	0.2	4.0	7.0

From Figure 1(b), by looking into the *J*-inverter network, the return loss can be obtained as [7]:

$$S_{11} = \frac{1-\bar{J}^2}{1+\bar{J}^2} \qquad (5)$$

Eqn. (5) clearly shows that the S_{11} will be zero when $\bar{J}$ = 1. The frequency of $\bar{J}$ = 1 corresponds to the S_{11} pole location over the bandpass range. In Figure 3, the simulated return and insertion losses of the PCML structure with various feeding network widths is shown. It can be seen that for PCML Tight Coupler 3 and 4, the corresponding S_{11} pole frequency is the same as the frequency for $\bar{J}$ = 1.

The overall performance shows the coupling factor for any given PCML structure with specific width and gap can be enhanced by using a feeding network with comparatively lower characteristic impedance. The idea can be applied to replace the ground plane aperture method as proposed in [7] for implementing a simple PCML broadband bandpass filter.

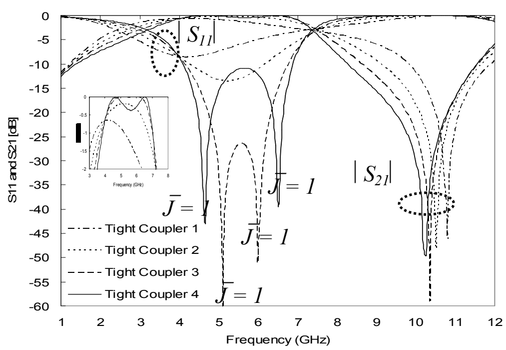

Figure 3: Insertion and Return Losses of PCML Structure with Varying w_o.

3. Physical Implementation

A prototype broadband bandpass filter of PCML structure as shown in Figure 4(a) is proposed. The simple structure consists of a microstrip line of Z_L characteristic impedance. Z_L is connected across two identical PCML sections. A complete J–inverter based equivalent circuit for the PCML broadband bandpass filter is given in Figure 4(b). The centre resonator with characteristic admittance Y_L and electrical length ϕ can be used as a tool to enhance the normalized $\bar{J}$ susceptance. In addition, it provides additional phase factor ϕ. The total electrical length Φ between two identical J – inverters is made up of three separate parts, i.e., $\Phi = \theta/2 + \phi + \theta/2$. The centre resonator is formulated to enhance the normalized J susceptance value and generate additional bandpass poles from its resonant modes as proposed in [7].

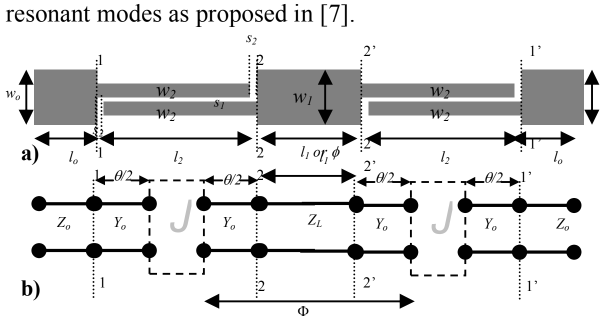

Figure 4: A PCML Broadband Bandpass Structure (a) Configuration, (b) Equivalent J-inverter.

Based on the transmission line theory given in [7], the normalized input admittance $\bar{Y}_{in} = Y_{in} / Y_o$ at termination 1, looking into its opposite termination 1', can be given as:

$$\bar{Y}_{in} = \bar{J}\frac{Y_o}{Y_L}\left(\frac{1+j\left(\bar{J}\frac{Y_o}{Y_L}\right)\tan\Phi}{\bar{J}\frac{Y_o}{Y_L}+j\tan\Phi}\right) \qquad (6)$$

For the normalized input impedance, the return loss S_{11} at 1 can be further simplified as:

$$S_{11} = \frac{j\tan\Phi\left(1-\bar{J}^4\frac{Y_o}{Y_L}\right)}{2\bar{J}\frac{Y_o}{Y_L}+j\tan\Phi\left(1+\bar{J}^4\frac{Y_o}{Y_L}\right)} \qquad (7)$$

Referring to equation (7), $S_{11} = 0$ when $\tan\Phi = 0$ or $(1 - \bar{J}^4 Y_o/Y_L) = 0$. The respective frequency when $S_{11} = 0$ is referred as pole. It shows multiple poles of frequency can be obtained when $\Phi = 180°$ (i.e., $\theta/2=90°$), $\Phi = 360°$ (i.e., $\theta/2=180°$), $\Phi = 540°$ (i.e., $\theta/2=270°$) and also when $\bar{J} = (Y_L/Y_o)^{1/4}$.

A prototype PCML broadband filter with various feeding networks and middle resonator widths have been designed for center frequency at 5 GHz based on physical dimensions stated in Table 2.

Table 2: Prototype PCML Filter with varying w_o

Board parameters: $\varepsilon_r = 6.15$, $h = 1.27$ mm at 5 GHz								
PCML Filter	w_o mm	l_o mm	w_2 mm	l_2 mm	s_1 mm	s_2 mm	w_1 mm	l_1 mm
1	1.3	4.0	0.6	7.0	0.1	0.2	1.3	6.7
2	1.9	4.0	0.6	7.0	0.1	0.2	1.9	6.7
3	2.5	4.0	0.6	7.0	0.1	0.2	2.5	6.7
4	3.1	4.0	0.6	7.0	0.1	0.2	3.1	6.7

In Figures 5 and 6, multiple resonances present at various frequencies. For PCML Filter 1 and 2, since $\bar{J} < 1$, the resonances are mainly due to $\Phi = 180°$ and $\Phi = 360°$ which made up passband response centered at 5 GHz and $\Phi = 540°$ as the first harmonic response. For PCML Filter 1, first resonance frequency is at $f_1 = 3.5$ GHz, second resonance frequency at $f_2 = 6.75$ GHz and third resonance frequency at $f_3 = 10.1$ GHz. The first and second resonance frequencies become passband frequencies with centre frequency at 5 GHz, while third resonance frequency becomes the first harmonic frequency. Transmission zero frequency is at $f_z = 10.5$ GHz. The corresponding maximum value for $\bar{J}$ is approximately 0.6, indicating a relatively weak coupling. This leads to a worse bandpass behavior with a return loss of $|S_{11}| = -3$ dB between two resonant frequencies f_1 and f_2.

Further increase in the width of the feeding network and centre resonator of PCML Filter 3, shows that the $|S_{11}|$ response exhibits additional two poles around the central location which separates completely f_1 and f_2. The enlarged portion of Figure 5, shows that as additional poles exist between f_1 and f_2, the value of insertion loss $|S_{21}|$ gradually increases close to 0 dB. In can be inferred that the presence of additional poles at f_4 and f_5 are physically generated by $\bar{J} = 1$ as shown in Figure 2 as the width increases.

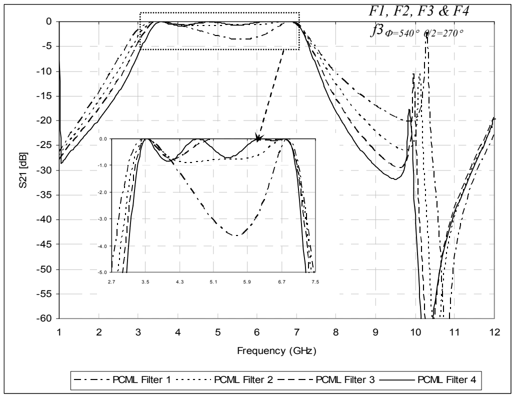

Figure 5: Insertion Loss Responses of PCML Broadband Filter with various w_o and w_1

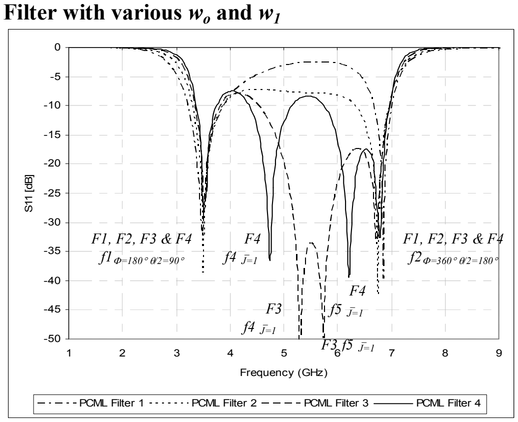

Figure 6: Returns Loss Responses of PCML Broadband Filter with various w_o and w_1

As the feeding network and centre resonator width decreases, the f_4 and f_5 get closer whilst the separation between f_1 and f_2 increases. These effects are mainly due to the decrease and broaden effects on $\bar{J}$ value. It can be inferred that the centre resonator width can be fine tuned to meet the requirement of its J-inverter susceptance in the optimization procedure of broadband PCML bandpass filter with extremely good passband responses of insertion and return losses.

Based on these findings, an optimized broadband PCML bandpass filter with a low return and high insertion losses over the passband can be designed. The physical parameters of PCML Filter 2 from Table 2 are used.

4. Optimization and Testings

Figure 5 shows that harmonic frequency appears near to the passband frequency, which will degrade the overall performance of the system. A simplest way to perform harmonic cancellation is by transmission zero frequency realignment method [9]-[10] which can be achieved by adjusting the length of centre resonator l_1. By changing the length of l_1, the first harmonic can be shifted towards the transmission zero frequency. However, as the centre resonator length l_1 decreases, the passband insertion loss response also decreases due to decreasing coupling effects of the PCML structure.

In order to improve the coupling of two tight couplers, the characteristic impedance of the centre resonator is varied by changing the width, w_1. As w_1 increases, the return and insertion losses reponses show much improvement. It can be inferred that clearly the width of the centre resonator can be used as a main tool to improve the passband response of the filter. Hence, it can be concluded that the centre resonator width and length can be used as main tools for designing PCML broadband bandpass filter with good response.

Good PCML broadband bandpass filter operating at 5 GHz, having bandwidth of 4.35 GHz (or 87%), with passband insertion loss response of less than -0.2 dB and less than -13 dB return loss has been successfully obtained. The main draw back is the harmonic picked up again. Hence, fine tuning was employed at the centre resonator length to suppress the harmonic. Based on these findings and approach, an optimized broadband PCML bandpass filter of varying coupling factor has been fabricated and measured for the insertion and return losses performances.

Figure 7 shows the simulated and measured frequency responses for an optimized three PCML filters with various coupling factors. It can be observed that the simulated and measured insertion and return loss responses are almost identical over the frequency range. The summary of the results are given in Table 3. It shows that a cost effective compact broadband PCML bandpass filter with excellent passband response can be realized.

Table 3: Summary of simulated and measured results of optimized filters.

PCML Filter	Simulated			Measured			Dimension
	BW %	S11 dB	S21 dB	BW %	S11 dB	S21 dB	Length (mm)× width (mm)
1	87	< -13	> -0.2	85	< -13	> -0.5	27.9 × 10
2	96	< -22	> -0.03	93	< -20	> -0.3	28.2 × 10
3	82	< -15	> -0.1	80	< -12	> -0.3	28.2 × 10

5. Conclusion

The paper has shown that for given any PCML structure, the coupling factor can be enhanced by employing feeding network of smaller characteristic impedance. A simple PCML structure with two feeding networks of characteristic impedance $Z_c << Z_o$ shows two poles when $J > 1$. The presence of multipoles show the filtering characteristics of the PCML structure. This idea leads to the design of an improved version of PCML broadband bandpass filter without ground plane aperture. By modifying the centre resonator width and length, an improved broadband PCML bandpass filter can be realized. The technique proposed in this research is easiest and simplest.

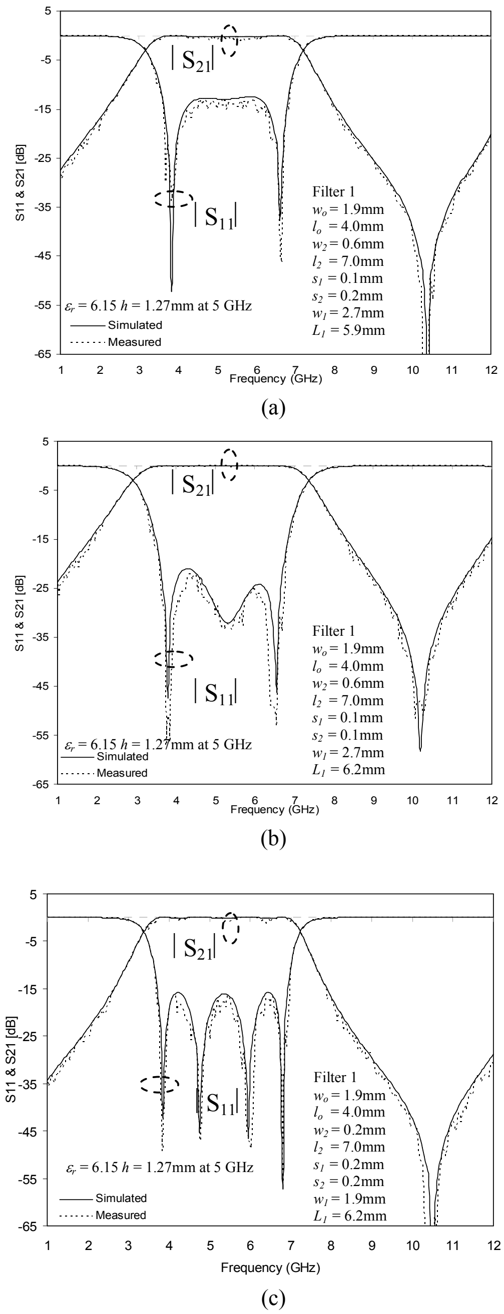

Figure 7: Simulated and measured results of the three PCML broadband bandpass filters.

Three PCML broadband bandpass filters have been designed. All exhibit excellent broadband characteristics with bandwidth of over 80%, insertion loss better than -0.2 dB at pass band, and return loss of better than -13 dB. It can be concluded that the proposed filter exhibited excellent broadband bandpass performance in the desired operating band. The simulated and experimental results are in good agreement, thus validating the theory and design methods.

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