Experimental Performance of Harmonic Suppressed Bandpass Filter

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Abstract **-** In this paper, the experimental performance of a fabricated single grooved broadband Parallel Coupled Microstrip Bandpass Filter (PCMBF) with improved passband response and first harmonic suppression is presented. The suppression of the first harmonic spurious response is possible through transmission zero frequency realignment method. A single groove of specific dimensions located at the center of the parallel coupled line has been employed for the realignment of the transmission zero and first harmonic frequencies. An implemented single-stage bandpass filter with various coupling gaps showed harmonics suppressions with optimized groove. Then, two–stage bandpass filters of different operating bandwidth were designed for optimized groove. It was then implemented and tested. The measured results validate real harmonics suppression performance with controllable single groove parameters.

Keywords: Broadband bandpass filter; harmonic suppression; transmission zero; J–inverter network; groove

1. Introduction

Many microwave systems widely employ Parallel-Coupled Microstrip Bandpass Filters (PCMBF). In PCMBF designs, the Parallel-Coupled Microstrip Line (PCML) structure has been used as the main coupling component [1]. An undesirable disadvantage is the existence of the first spurious passband at twice the basic passband frequency, and the worse rejection of the upper stopband than the lower stopband. Thus, the system application is greatly limited and consequently system performance will be degraded. The inequality of the even and odd mode phase velocities of coupled lines in each stage causes the phenomenon as described in the behavior of a PCML structure [2]. Various techniques were proposed in the literature to equalize these mode velocities or their electrical line lengths, thus minimize the harmonic responses, resulting in the redesigning of the filter with new physical design parameters.

In this paper, the proposed technique merely involves simple modification by introducing a single groove or notch at the center of PCML. The initial studies involve varying the number of grooves [3]. Similar studies with periodically arranged multiple grooves have been reported [4]-[5]. Next, studies focused on suppression of harmonic response using transmission zero realignment method involving a single groove at the center of PCML [6]-[8]. It has the capability of relocating the transmission zero frequency, f_z, and its harmonic response frequency, f_h. In this paper, single and two-stage PCMBF configurations were designed, implemented and tested.

2. Investigation of PCML Structures

PCML structures of width (w), gap (s) and length (l) are illustrated in Figure 1, without (PCMLng) and with groove (PCMLwg). It has specific parameters such as even mode impedance Z_{oe}, and electrical length θ_e, and odd mode impedance Z_{oo}, and electrical length θ_o. Its two-port impedance parameters [Z] of the open–circuit PCML structure with Z_o as the input and output impedances are given as [1]:

$$\begin{aligned} Z_{11} = Z_{22} &= \frac{-j}{2}\left(Z_{oe}\cot(\theta_e) + Z_{oo}\cot(\theta_o)\right) \\ &= \frac{-j}{2}\left(\frac{Z_{oe}}{\tan(\theta_e)} + \frac{Z_{oo}}{\tan(\theta_o)}\right) \\ &= \frac{-j}{2}\left(\frac{Z_{oe}\cos(\theta_e)}{\sin(\theta_e)} + \frac{Z_{oo}\cos(\theta_o)}{\sin(\theta_o)}\right) \\ &= \frac{-j}{2}\left(\frac{Z_{oe}\cos(\theta_e)\sin(\theta_o) + Z_{oo}\cos(\theta_o)\sin(\theta_e)}{\sin(\theta_e)\sin(\theta_o)}\right) \end{aligned} \quad (1)$$

$$\begin{aligned} Z_{21} = Z_{12} &= \frac{-j}{2}\left(Z_{oe}\csc(\theta_e) - Z_{oo}\csc(\theta_o)\right) \\ &= \frac{-j}{2}\left(\frac{Z_{oe}}{\sin(\theta_e)} - \frac{Z_{oo}}{\sin(\theta_o)}\right) \\ &= \frac{-j}{2}\left(\frac{Z_{oe}\sin(\theta_o) - Z_{oo}\sin(\theta_e)}{\sin(\theta_e)\sin(\theta_o)}\right) \end{aligned} \quad (2)$$

From equations (1) and (2), the zeros of $|Z_{11}|$ and $|Z_{21}|$ can be obtained by setting the conditions:

$$\alpha = Z_{oe}\cos(\theta_e)\sin(\theta_o) + Z_{oo}\cos(\theta_o)\sin(\theta_e) = 0 \quad (3)$$

$$\beta = Z_{oe}\sin(\theta_o) - Z_{oo}\sin(\theta_e) = 0 \quad (4)$$

The poles of $|Z_{11}|$ and $|Z_{21}|$ are obtained by setting $\theta_e = m\pi$ and $\theta_o = m\pi$. In this paper, all designs are implemented on RT/Duroid RT6006 board of

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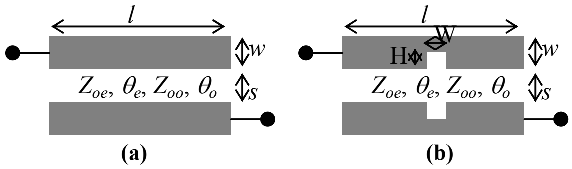

Figure 1: PCML structure (a) without (b) with groove.

relative permittivity $\varepsilon_r = 6.15$ and substrate thickness $h = 1.27$ mm. The simulated $|Z_{11}|$ and $|Z_{21}|$ results of the PCMLng structure show various poles and zeros at various frequencies as shown in Figure 2. The $|Z_{11}|$ zeros happen at 1.76 GHz, 3.16 GHz and 5.1 GHz when condition (3) is obeyed. Similarly, $|Z_{21}|$ zeros happen at 5.7 GHz when condition (4) is obeyed. The poles for $|Z_{11}|$ and $|Z_{21}|$ at 2.86 GHz are due to $\theta_e = \pi$ and at 3.62 GHz are due to $\theta_o = \pi$.

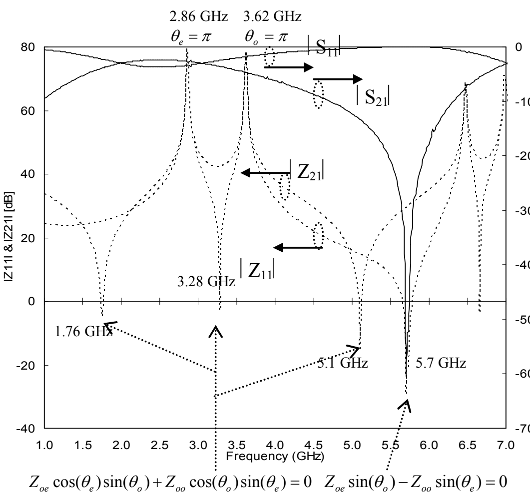

Figure 2: $|Z_{11}|$, $|Z_{21}|$, $|S_{11}|$ and $|S_{21}|$ of simple PCML structure without groove; *w*=1mm, *s*=0.2mm, *l*=14.6mm.

The insertion loss of the PCMLng structure is given by equations (5) to (7) [1]:

$$S_{21} = \frac{2Z_{21}Z_o}{(Z_{11}+Z_o)(Z_{22}+Z_o) - Z_{12}Z_{21}} \tag{5}$$

$$S_{21} = \frac{2Z_{21}Z_o}{Z_{11}Z_{22} + Z_{11}Z_o + Z_{22}Z_o + Z_o^2 - Z_{12}Z_{21}} \tag{6}$$

$$S_{21} = \frac{2\left(Z_{oe}\sin(\theta_o) - Z_{oo}\sin(\theta_e)\right)Z_o}{\left[Z_{11}^2 + Z_{11}Z_o + Z_{22}Z_o + Z_o^2 - Z_{21}^2\right]*(\sin(\theta_e)\sin(\theta_o))} \tag{7}$$

Equation (7) shows that the zeros can be obtained by obeying equation (4). Figure 2 clearly shows that $|S_{21}|=0$, when $|Z_{21}|=0$ based on condition (4). It can be concluded that the transmission zero for simple PCML structure happens due to condition (4).

Figure 3 shows simulated results of $|Z_{11}|$, $|Z_{21}|$, $|S_{11}|$ and $|S_{21}|$ of simple PCMLwg with dimensions W=1mm, H=0.7mm. It shows that by placing a single groove, the zero of $|Z_{21}|$ effectively shifted from 5.7 GHz to 4.62 GHz compared to $|Z_{11}|$ zeros which are less effectively shifted from 1.76 GHz to 1.74 GHz, 3.28 GHz to 3.16 GHz and 5.1 GHz to 4.82 GHz. It can be inferred that condition (4) changes at a faster rate compared to condition (3). Similarly, the poles for $|Z_{11}|$ and $|Z_{21}|$ effectively shifted from 2.86 GHz to 2.84 GHz due to $\theta_e = \pi$ and 3.62 GHz to 3.4 GHz due to $\theta_o = \pi$, i.e., θ_o changes effectively compared to θ_e.

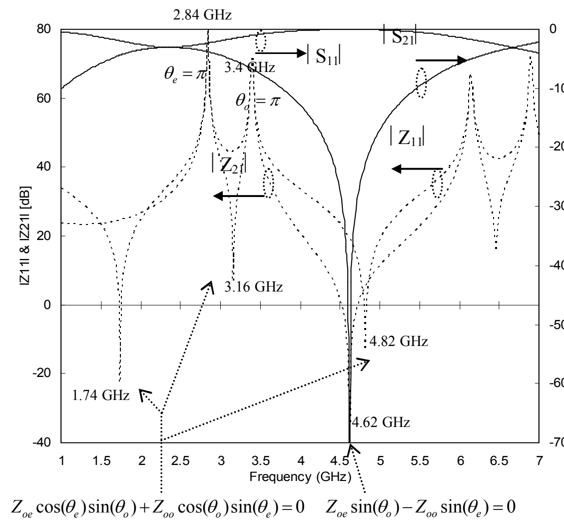

Figure 3: $|Z_{11}|$, $|Z_{21}|$, $|S_{11}|$ and $|S_{21}|$ of PCMLwg with *w*=1mm, *s*=0.2mm, *l*=14.6mm, W=1mm and H=0.7mm.

Figure 4 shows that as H increases with fixed W, Z_{oo} increases at a higher rate compared to Z_{oe}. f_{odd} decreases at a higher rate compared to f_{even}. These showed that θ_o increases at a higher rate compared to θ_e. The single groove effectively increase Z_{oo} and θ_o compared to Z_{oe} and θ_e. Hence, it can be used to shift f_z of to required position based on condition (4).

3. Investigation of a Single-Stage PCMBF

To further investigate the behavior of higher order PCML structure, a simple single–stage bandpass filter is designed with a cascade of two PCML stages. The two-port impedance parameters [Z'] of the open–circuit single–stage bandpass filter with Z_o as the input and output impedances based on equations (1) and (2) are given by [1]

$$Z_{21}' = \frac{-j\beta^2}{4\alpha\chi} \tag{8}$$

$$Z_{11}' = \frac{j\left[\beta^2 - 2\alpha^2\right]}{4\alpha\chi} \tag{9}$$

$$\alpha = Z_{oe}\cos\theta_e\sin\theta_o + Z_{oo}\cos\theta_o\sin\theta_e \tag{10a}$$

$$\beta = Z_{oe}\sin\theta_o - Z_{oo}\sin\theta_e \tag{10b}$$

$$\chi = \sin\theta_o\sin\theta_e \tag{10c}$$

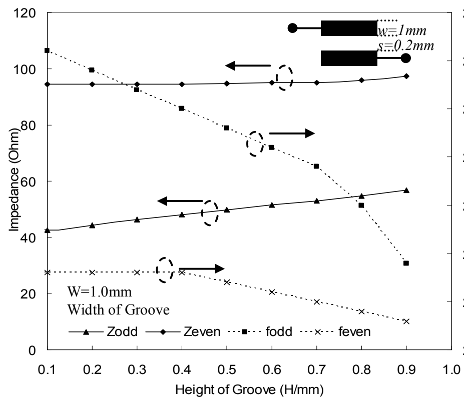

Figure 4: Even and odd mode parameters with respect to various single groove dimensions.

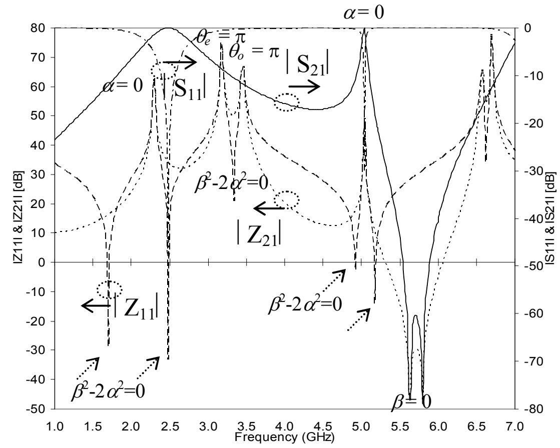

Figure 5: $|Z_{11}|$, $|Z_{21}|$, $|S_{11}|$ and $|S_{21}|$ of simple single-stage PCMBFng with w=1mm s=0.2mm and l=14.6mm.

The insertion loss S_{21} for the above single–stage PCMBF based on equations (8) and (9) are:

$$\frac{1}{S_{21}} = \frac{j\left(\frac{\alpha}{2Z_o}\right)\left[\beta^2 - \alpha^2 + 4Z_o^{\ 2}\chi^2\right]}{\beta^2} - \frac{\chi\left(\beta^2 - 2\alpha^2\right)}{\beta^2} \qquad (11)$$

From equations (8) and (9), the poles of $|Z_{11}|$ and $|Z_{21}|$ can be obtained by setting a condition $\alpha = 0$, based on equation (3) and also by setting $\theta_e = m\pi$ and $\theta_o = m\pi$. The zeros are obtained by setting $\beta = 0$ based on equation (4) for $|Z_{21}|$ and $\beta^2 - 2\alpha^2 = 0$ for $|Z_{11}|$. For $|S_{21}|$, the first pole (or resonant frequency) is mainly due to $\beta^2 - 2\alpha^2 = 0$, and second pole (harmonic frequency) due to $\alpha = 0$. While f_z for $|S_{21}|$ is obtained by setting a condition $\beta = 0$ based on equation (4). It shows that f_z for simple PCML structure and single–stage PCMBF based on cascaded PCML structure obey the condition (4). Meanwhile, f_h presence in a single–stage PCMBF is due to (3).

Figure 5 shows simulated results of $|Z_{11}|$, $|Z_{21}|$, $|S_{11}|$ and $|S_{21}|$ of a simple single-stage PCMBF of PCMLng structure with w=1mm s=0.2mm and l=14.6mm. It clearly shows $|Z_{11}|$ zeros exist at 1.7 GHz, 2.48 GHz, 3.34 GHz, 4.92GHz and 5.18 GHz when $\beta^2 - 2\alpha^2 = 0$. Similarly, $|Z_{21}|$ zeros exist at 5.64 GHz and 5.8 GHz when $\beta = 0$. The poles for $|Z_{11}|$ and $|Z_{21}|$ at 3.18 GHz are due to $\theta_e = \pi$, 3.46 GHz since $\theta_o = \pi$. That at 2.24 GHz and 5.04 GHz are due to $\alpha = 0$. Similarly, $|S_{21}|$ has a first pole at 2.48 GHz due to $\beta^2 - 2\alpha^2 = 0$, the second pole at 5.04 GHz due to $\alpha = 0$ and the f_z at 5.64 GHz (5.8 GHz) due to $\beta = 0$.

From the observations, for the harmonic presence in a simple single-stage PCMBF is due to $\alpha = 0$ and f_z is due to $\beta = 0$ as given for a simple PCML structure. By placing such a single groove, f_z can be effectively shifted to the required frequency. A similar study was carried out for a single-stage PCMBF by placing a single groove to investigate the shifting of f_z and f_h.

Figure 6 shows that f_z shifting to a lower frequency at higher rate compared to f_h as the single H increases. In other words $\beta = 0$ changes at a higher rate compared to $\alpha = 0$. The effects are mainly due to changes in odd mode parameters as H increases with fixed W. When H = 0.7mm, $f_z = f_h$ and $\beta = 0$, $\alpha = 0$ also obeyed. Based on these conditions,

$$\cos(\theta_e) + \cos(\theta_o) = 0 \qquad (12)$$

and hence it can be solved as

$$\theta_o = n\pi \pm \theta_e \quad n = 1,2,3....... \qquad (13)$$

For first f_h and harmonic cancellation by f_z, n = 1,

$$\theta_o = \pi - \theta_e \qquad (14)$$

$$Z_{oo} = Z_{oe} \qquad (15)$$

This shows that f_h of a single–stage PCMBF can be cancelled by f_z if electrical length and characteristic impedance of odd mode conditions (14) and (15). This can be effectively achieved by using a simple optimized groove at the centre of a PCML.

The simulated results of $|Z_{11}|$, $|Z_{21}|$, $|S_{11}|$ and $|S_{21}|$ of a simple single–stage PCMBF of PCML structure with W=1mm, H=0.7mm shows that by placing an optimized single groove, all f_h are effectively cancelled by f_z. From these findings, a single-stage PCMBF can be designed with full harmonics suppression by using an optimized single groove. In the following section, various single–stage PCMBFs with different coupling factors have been designed and the optimized groove was identified for harmonic cancellation. The optimized grooved single–stage PCMBF of PCML structure was used to design various bandwidths of two-stage PCMBF with first harmonic suppression. The groove size was further optimized to improve the harmonic suppressions.

4. Harmonic Suppressed Single-Stage PCMBF

The simulated insertion and return losses of a single–stage PCMBF of Figure 7 under three different

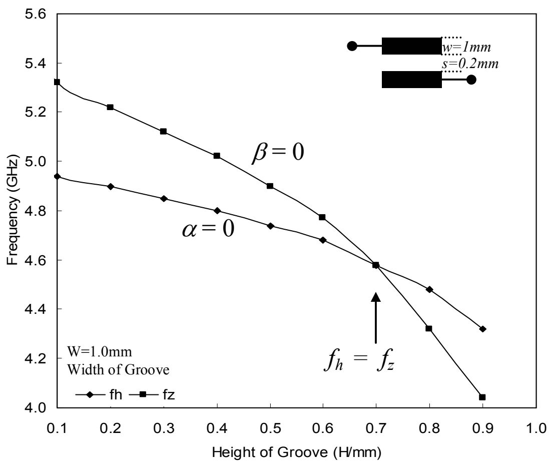

Figure 6: Behavior of f_z and f_h for a single groove of W=1.0mm and various H at center of PCMLng of a single-stage PCMBF.

coupling gaps (tcg1 s = 0.2 mm, tcg2 s = 0.6 mm and tcg3 s = 1.0 mm) shown in Figure 8. This initially demonstrates the controllable f_h and f_z. The tcg1 with s = 0.2 mm, shows f_z = 5.7 GHz and f_h = 5.04 GHz, tcg2 with s = 0.6 mm, shows f_z = 5.94 GHz and f_h = 4.98 GHz and tcg3 with s = 1.0 mm, shows f_z = 6.12 GHz and f_h = 4.94 GHz, respectively.

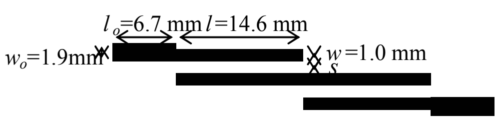

Figure 7: Layout of the proposed single–stage PCMBF.

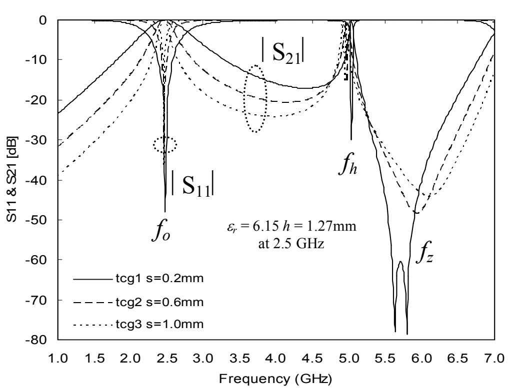

Figure 8: Insertion and return losses of a single–stage PCMBF with varying coupling gaps.

In order to cancel the harmonics, a single groove was introduced. The optimum groove size was obtained from Figure 6. Figure 9 shows the full harmonics suppression for various single–stage PCMBFs with optimum groove. For tcg1: $f_z = f_h$ = 4.58 GHz with optimized groove W=1.0mm, H=0.7mm, tcg2: f_z = f_h = 4.36 GHz with optimized groove W=2.6mm, H=0.7mm and tcg3: f_z = f_h = 4.24 GHz with optimized groove W=4.8mm, H=0.7mm. It can be inferred that the harmonics can be suppressed by f_z regardless of the coupling gap. The optimized groove width increases and f_z = f_h shifted to a smaller frequency as the coupling gap increases.

5. Harmonic Suppressed Two-Stages PCMBF

Next, a two–stage PCMBF was designed with various combinations of single–stage PCMBF with optimized groove for harmonic suppression at different operating bandwidths. Figure 10 shows two–stage PCMBF made by cascading of two various coupling gap single–stage PCMBF with optimized groove. Filter 1 was designed by using two tcg1 with optimized groove, Filter 2 was designed by using tcg1 and tcg2 with optimized groove and finally Filter 3 was designed by using tcg1 and tcg3 with optimized groove. All three filters simulated and groove at tcg1 further optimized to full harmonics suppression of two–stage PCMBF. The optimized filters were then fabricated and measured. Both measured and simulated results in Figure 11 agree well with each other, showing full suppression of harmonic response for various bandwidths. Filter 1 with wideband response of more than 30%, Filter 2 with moderate wideband response of bandwidth > 18% while Filter 3 with narrowband response of ~ 11%.

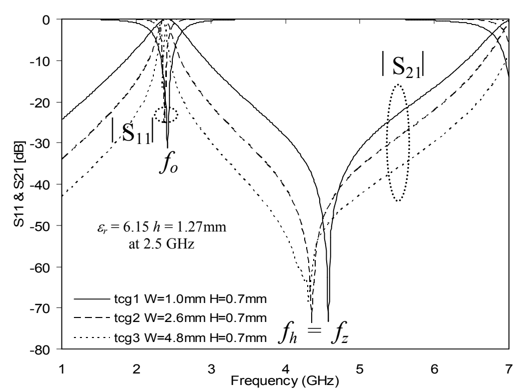

Figure 9: Insertion and return loss of single–stage PCMBF with optimized groove for various coupling gaps.

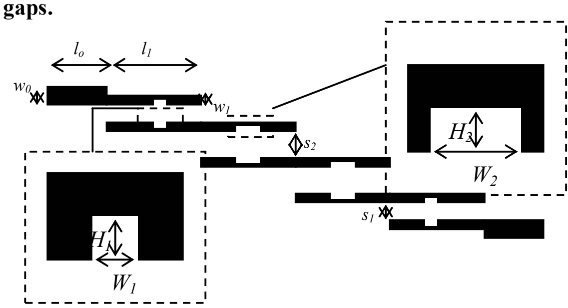

Figure 10: Layout of two–stage PCMBF with single groove at center of PCML structure.

6. Conclusion

Detailed investigations done on harmonics cancellation by using f_z realign method have been presented. This can be done by using specific single groove located at the center of the PCML structure. Then, a simple two–stage PCMBF is demonstrated for the first time for various operating bandwidths. Various operating filter bands with sharp-rejection stopbands and excellent rejection of first harmonic spurious response can be achieved. For validation, three 2.45 GHz of various operating bands in a two-stage PCMBF prototype, useful in full-duplex Local Area Network (LAN) communication, have been demonstrated. The resulting agreement between measurements and simulations has confirmed the experimental viability of the filter topology.

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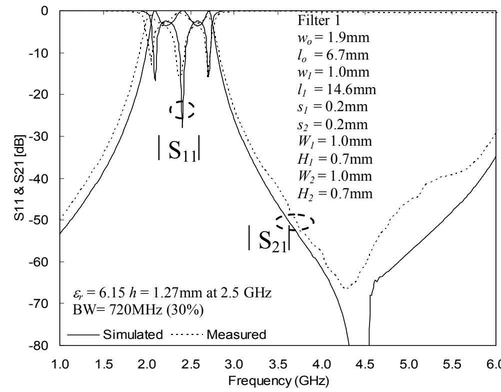
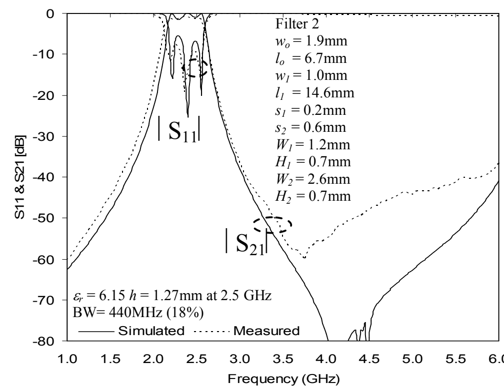
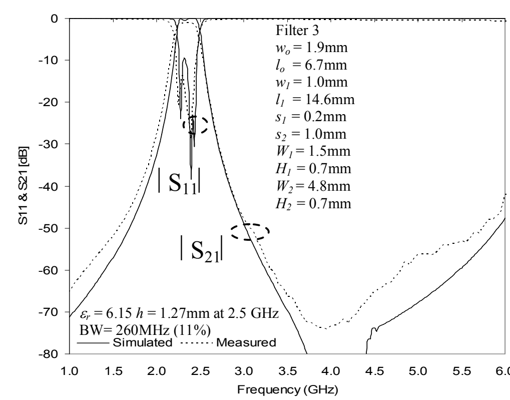


(a) Filter 1



(b) Filter 2



(c) Filter 3

Figure 11: Performances of two–stage PCMBFs.