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Wideband Tunable High Common-Mode Suppression Filter Based on Varactor-Loaded Slotted Ground

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Abstract—In this study, a varactor-loaded slotted ground structure is investigated and utilized to construct a new tunable common-mode (CM) suppression filter for differential signals. A four-port distributed equivalent circuit model is developed for interpreting the working mechanism of CM signal suppression. It is found that the proposed simple structure is capable of tunable CM suppression with a wide frequency tuning range. The parameter selection and design principle are also given. Finally, the design theory is well vindicated by a common-mode filter using three periodic varactor-loaded slots. Simulated and measured results, showing good agreement, exhibit a tuning range from 0.80 to 2.10 GHz, corresponding to the fractional tuning range of 89.7% and more than 30 dB CM rejection level.

1. INTRODUCTION

In modern mixed signal systems, differential circuits have been widely applied to communication systems because of their inherent immunity to noise and electromagnetic interference [1, 2]. Among them, common-mode (CM) suppression filters are useful in steep suppression of CM noise without affecting DM performance. Recently, tunable CM suppression filters have drawn a lot of attention. They can be applied in many high-speed differential systems such as DVC, STB IEEE 1394 line, LCD panel, USB cable for personal computers and peripheral devices. However, the tunable CM suppression filters with the property of high CM rejection, wide tunable range, low DM loss and compact size are understudied. In [3], by discriminating coupling between feeding structure and resonators and employing varactors, the CM suppression and the tuning range of the filters are obtained. In [4], the defected ground structure (DGS) [5] units are embedded underneath the two rings to form a CM-suppression filter without increasing the circuit size. However, all of the proposed filters tuning range is small, and the circuit size is large. In [6], a varactor-loaded slot-ring is applied in the filter so that the tuning range is further increasing and the circuit size is miniaturized. However, two kinds of tunable capacitors are underneath the differential line so that the fabrication cost is expensive. In [7–9], the step-impedance resonator is designed to construct the tunable filter. In [10], by using a short coupled-line structure, the tuning range is widened. However, all of the proposed filters' fractional bandwidths are narrow.

In this paper, a novel tunable CM suppression filter with wideband tunability based on the varactor-loaded slotted ground is proposed. The circuit model is developed to describe both CM and DM responses. The theoretical analysis is performed. The CM-suppression filter proposed in this paper is convenient to design. Varactors are employed to enable frequency tuning. It is found that there is the capacitance of a varactor to achieve the largest frequency tuning range. Meanwhile, simple slotted ground structure further reduces circuit size. The simulated and measured results are presented, showing good accordance.

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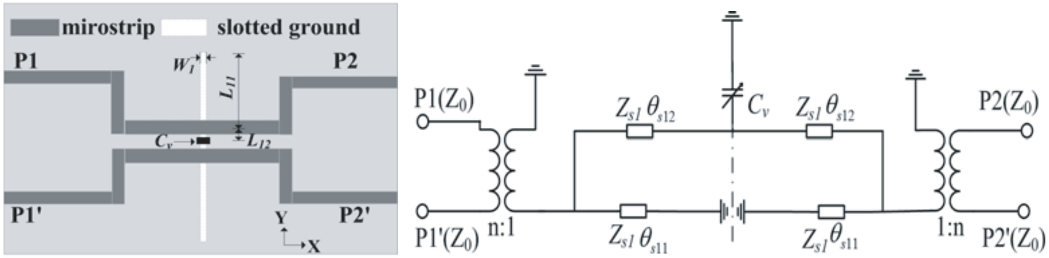
2. DESIGN CONCEPT AND MODELING

Figure 1(a) shows the proposed tunable CM suppression filter using the topology of varactor-loaded slotted ground. The slot is on the ground plane underneath the top microstrip differential lines. The dark and light gray areas in the graph represent the microstrip lines and the slotted ground plane on the top and bottom surfaces of the substrate, respectively. The slotted ground is kept symmetrical with respect to the central line of the two signal lines. The varactor is located in the middle of the slotted ground. Figure 1(b) is the equivalent model of the structure in Figure 1(a). C_v is the capacitance of the tunable capacitor. The top slot line with characteristics impedance Z_{s1} and electrical length θ_{s11} corresponds to width W_1 and length L_{11}. The middle slot line with impedance Z_{s1} and electrical length θ_{s12} corresponds to width W_1 and length L_{12}.



(a) (b)

Figure 1. (a) Structure of the proposed tunable CM suppression filter. (b) Four-port equivalent circuit of the proposed filter.

2.1. CM Analysis

Under CM operation, the CM equivalent circuit can be obtained shown in Figure 2 by placing a magnetic wall at the dashed line.

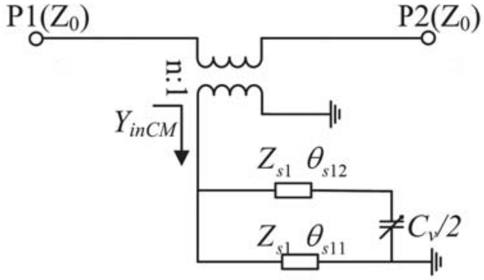


Figure 2. CM equivalent circuit.

The CM $ABCD$ parameters can be derived as follows:

$$A_C = D_C = 1; \quad B_C = \frac{n^2}{Y_{inCM}}; \quad C_C = 0; \tag{1}$$

where the input admittance Y_{inCM} can be expressed as follows:

$$Y_{inCM} = \frac{Z_{s1}\omega C_v(\tan\theta_{s12} + \tan\theta_{s11}) + 2(\tan\theta_{s11}\tan\theta_{s12} - 1)}{jZ_{s1}\tan\theta_{s11}(Z_{s1}\omega C_v\tan\theta_{s12} - 2)} \tag{2}$$

According to the transmission line theory, the CM s-parameters of the slotted ground coupled microstrip lines can be obtained as:

$$S_{21cc} = S_{12cc} = \frac{2}{A_C + B_C/Z_0 + C_C Z_0 + D_C} \tag{3}$$

$$S_{11cc} = S_{22cc} = \frac{A_C + B_C/Z_0 - C_C Z_0 - D_C}{A_C + B_C/Z_0 + C_C Z_0 + D_C} \tag{4}$$

The CM signal will be suppressed in the CM suppression frequency f_{CM} where $Y_{inCM} = 0$ ($B_C = \infty$). It can be obtained that the following equation must be satisfied at f_{CM}.

$$2\pi f_{CM}\frac{C_v}{2} = \frac{1}{Z_{s1}\tan(\theta_{s11}+\theta_{s12})} \tag{5}$$

Obviously, the CM suppression frequency tunes with the change of a capacitance. If the capacitance of C_v can be changed, the CM suppression frequency can be adjusted. Thus the capacitor with the property of capacitance change is employed to tune CM suppression frequency. The tuning range of f_{CM} is defined as:

$$R_f = \frac{f_{CM,MAX} - f_{CM,MIN}}{f_{CM,MAX} + f_{CM,MIN}/2} \tag{6}$$

where $f_{CM,MAX}$ and $f_{CM,MIN}$ represent the highest and lowest f_{CM} in the whole frequency-tuning range when C_v is tuned. Ultimately, $f_{CM,MIN}(f_{CM} = f_{CM,MIN},\ C_v = C_{MAX})$ and $f_{CM,MAX}(f_{CM} = f_{CM,MAX},\ C_v = C_{MIN})$ can be obtained as:

$$f_{CM,MIN} = \frac{1}{\pi C_{MAX} Z_{s1}\tan(\theta_{s11}+\theta_{s12})} \tag{7}$$

$$f_{CM,MAX} = \frac{1}{\pi C_{MIN} Z_{s1}\tan(\theta_{s11}+\theta_{s12})} \tag{8}$$

In order to widen the frequency-tuning range, the method is based on enlarging the variation range of the tunable capacitor as shown in Figure 3. And the capacitance ratio u of the tunable capacitor is defined as $C_{\max}/C_{\min}$.

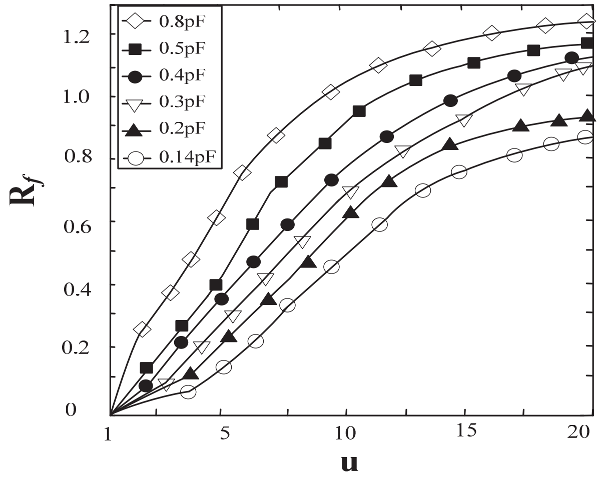


Figure 3. R_f versus different u while $Z_{s1} = 120\,\Omega$ is fixed and $C_{\min}$ is varied from 0.14 to 0.8 pF.

2.2. DM Analysis

Under DM operation, the DM equivalent circuit can be obtained shown in Figure 4 by placing an electrical wall at the dashed line. The tunable capacitor C_v has been shorted to the ground and has no effect on the DM resonant frequency.

Similarly, the DM s-parameters of the slotted ground coupled microstrip lines can be obtained as:

$$S_{21dd} = S_{12dd} = \frac{2}{A_D + B_D/Z_0 + C_D Z_0 + D_D} \tag{9}$$

$$S_{11dd} = S_{22dd} = \frac{A_D + B_D/Z_0 - C_D Z_0 - D_D}{A_D + B_D/Z_0 + C_D Z_0 + D_D} \tag{10}$$

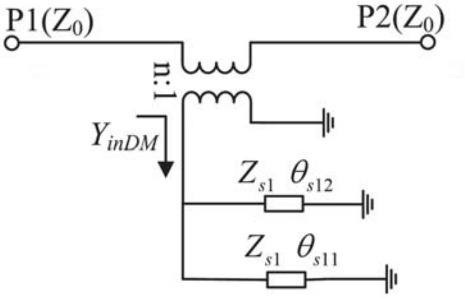


Figure 4. DM equivalent circuit.

The input admittance Y_{inDM} can be formulated as:

$$Y_{inDM} = \frac{\tan\theta_{s11} + \tan\theta_{s12}}{jZ_{s1}\tan\theta_{s11}\tan\theta_{s12}} \tag{11}$$

According to the formula derived in (11), the DM $ABCD$ parameters can be calculated as follows.

$$A_D = D_D = 1; \quad B_D = \frac{n^2}{Y_{inDM}}; \quad C_D = 0 \tag{12}$$

According to the DM resonant condition that $Y_{inDM} = 0$, the calculated results of the coefficient are $B_D = \infty$ and $S_{dd21} = 0$. DM resonant frequency f_{DM} can be obtained, and the following formula (13) is satisfied.

$$\theta_{s11} + \theta_{s12}\,|_{f=f_{DM}} = \pi \tag{13}$$

While in the CM suppression frequency, the electrical lengths θ_{s11} and θ_{s12} satisfy the following formula:

$$\theta_{s11} + \theta_{s12}\,|_{f=f_{CM,MAX}} < \frac{\pi}{2} \tag{14}$$

Thus, the relation of f_{DM} and $f_{CM,MAX}$ can be obtained as:

$$\frac{f_{DM}}{f_{CM,MAX}} > 2 \tag{15}$$

It is worth mentioning that though the tuning range of f_{CM} is very wide, no DM resonance occurs in CM tuning range. Moreover, the tunable capacitor has no influence on the DM response. Therefore, it provides convenience for the design of the CM suppression filters.

3. DESIGN OF WIDEBAND TUNABLE CM-SUPPRESSION FILTER

Based on the above analysis, CM suppression frequency can be obtained by following the procedures listed as follows:

(1). Determine the range of the CM suppression frequency ($f_{CM,MIN} \sim f_{CM,MAX}$).

(2). Choose the proper varactors whose minimum capacitance is more than 0.6 pF.

(3). Obtain the characteristic impedance Z_{s1} and electrical length of the slotline in accordance with the varactors and the range of the CM suppression frequency.

(4). In order to enhance coupling, the length L_{12} is much less than L_{11} and L_{12} is as short as possible.

Figure 5 shows a novel low-cost filter design for CM suppression in high-speed differential signals. It is realized by periodically etching the slotted ground. In order to improve the CM suppression level, the structure uses the three-cascaded varactor-loaded slotted ground. After optimization, the proposed structure has a quite compact size of 1181 mil × 3543 mil as shown in Figure 6, corresponding to $0.02430\lambda_g^2$, where λ_g is the guided wavelength of a $50\,\Omega$ microstrip line at its central frequency. The length between slot line is 1003.9 mil. It is the quarter wavelength at the central frequency. The

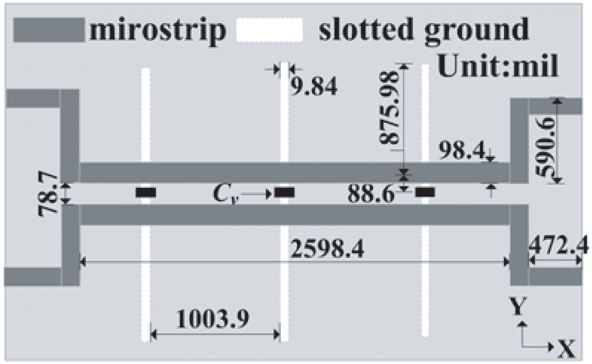
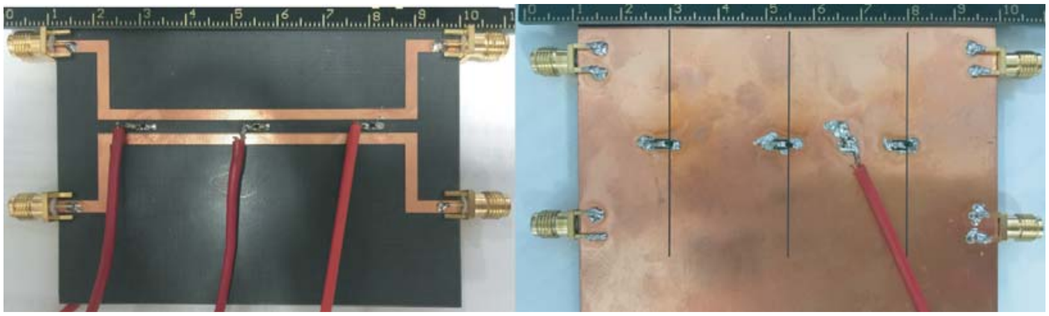


Figure 5. Structure of the tunable CM suppression filters using three-cascaded varactor-loaded slotted ground.



(a) (b)

Figure 6. Photograph of the fabricated tunable CM suppression filter. (a) Top view. (b) Bottom view.

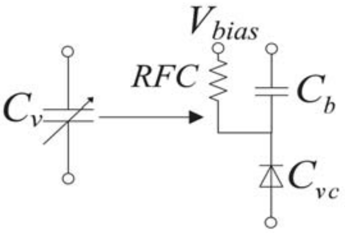


Figure 7. The implementation of the tunable capacitor.

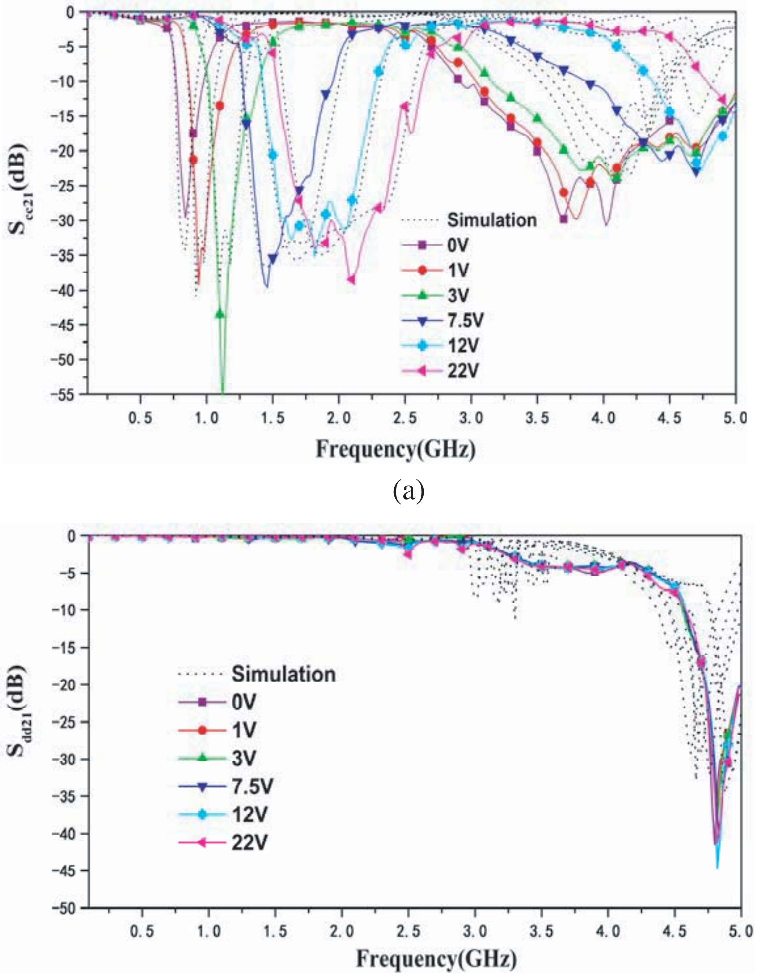
substrate used in this design has the dielectric constant of 2.65, thickness of 39.37 mil and loss tangent of 0.0035.

It is well known that the variation range of the tunable capacitor determines the tuning range of f_{CM}.

Therefore, C_v should have wide variation range. In consideration of the above condition, the varactor JDV2S71E from Japan with the wide tunable capacitance 0.75 to 15 pF is selected. The tunable capacitor consists of the DC block C_b, varactor C_{vc} and an RFC (depicted in Figure 7). The loaded capacitance of C_b is 30 pF and an RFC which the reversed voltage bias V_{bias} is supplied through is realised by a 50 kΩ resistor. The implementation of the tunable capacitor C_v is obtained as

$$C_v = \frac{C_{vc} C_b}{C_{vc} + C_b} \tag{16}$$

Therefore, the capacitance of C_v is from 0.73 to 10 pF when the varactor is tuned.



(a)

(b)

Figure 8. Simulated and measured S-parameters of the proposed filter. (a) Simulated (dashed line) and measured (solid line) S_{cc21}. (b) Simulated (dashed line) and measured (solid line) S_{dd21}.

Table 1. The performance of tunable CM suppression filter in this work.

	30.1 dB at 0.80 GHz	0.42 GHz
1	39.3 dB at 0.94 GHz	0.54 GHz
3	58.3 dB at 1.12 GHz	0.64 GHz
7.5	39.6 dB at 1.46 GHz	1.04 GHz
12	32.9 dB at 1.64 GHz	1.44 GHz
22	38.5 dB at 2.10 GHz	1.88 GHz

4. RESULTS AND DISCUSSION

All of the following results are measured using an Agilent network analyzer and simulated by HFSS [11] software. As shown in Figure 8, when V_{bias} alters from 22 to 0 V, the CM suppression frequency can be tuned from 2.10 to 0.80 GHz corresponding to fractional tuning range R_f of 89.7%. The rejection level of CM signals is better than 30 dB (indicated in Table 1). Meanwhile, the three-cascaded varactor-loaded slotted ground structure has no influence on DM signals and f_{DM} maintains at 4.80 GHz. The insertion loss S_{dd21} is always less than 0.7 dB in the DM passband. The maximum S_{cc21} and the bandwidth are summarized in Table 1. It is obtained that the bandwidth is wide and more than 0.42 GHz. A comparison of the proposed filter with reported CM suppression designs is listed in Table 2. It is noted that only the proposed filter has the largest tuning range of the CM suppression frequency while the only one kind of varactor is employed. Furthermore, it behaves high CM rejection level and low insertion loss with the compact size.

Table 2. Performance of previous works and this work.

	S_{cc21} in passband [dB]	The insertion loss S_{dd21} [dB]	R_f [%]	Circuit size [λ_g^2]	Variety of varactors
Ref. [3]	> 50	$1.6 \sim 2.7$	31	0.0181	1
Ref. [4]	> 16	$1.45 \sim 4.21$	22.2	0.0588	1
Ref. [6]	> 25	< 0.4	64.3	0.0308	2
Ref. [7]	> 20	$1.7 \sim 6.0$	75	0.0312	1
This work	> 30	< 0.7	89.7	0.243	1

5. CONCLUSIONS

This paper presents a novel structure of wideband common-mode suppression filter based on varactor-loaded slotted ground. The relationship between frequency-tuning range and the varactor-loaded slotted ground characteristics is constructed and discussed in detail. The common mode suppression level can be greater than 30 dB by increasing the number of cascades. Meanwhile, the structure uses a simple structure, reducing the circuit area and production cost. The simulated and measured results of the proposed filter show good consistency. The wide tuning responses and high common-mode suppression will make it attractive in many high-speed differential applications.

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