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A novel transversal filter with improved spurious characteristics

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Abstract

A spurious-suppressed transversal filter using the multiple-coupled line is proposed. The frequency characteristics of the multiple-coupled line are analyzed in detail. In order to compare the performances, the novel spurious-suppressed transversal filter using triple-coupled half-wavelength directional couplers is designed at 5 GHz. The spurious-suppression characteristics of the proposed transversal filter are verified by the full wave analysis and the measurement. The spurious response of the fabricated filter is effectively suppressed up to 13 GHz and the large attenuation is attained in the stopband.

Key words : transversal filter, directional coupler, UWB, spurious suppression

I. Introduction

In recent years, ultra-wide band (UWB) technologies have stimulated interest in communications and radar applications [1-3]. UWB systems are generally defined as those which have bandwidths exceeding 25 % of their center frequency or bandwidth lager than 1.5 GHz. However, it is difficult to design broadband active and passive circuits with bandwidths of more than 20 % [4].

In case of broadband planar type bandpass filters which are advantageous in integration, an overlap-gap coupling structure has been developed in a two-layered structure in order to meet the requirement of tight coupling [5]. And a parallel-coupled microstrip line filter has also been reported by forming a backside aperture in the ground plane [4]. However, the strip and slot widths of the planar type wideband filters should be reduced in order to achieve tight couplings. And this may lead to a degradation of their filtering behavior, namely, low Q-factor and high insertion loss.

With the rapid development of three-dimensional (3D) microwave and millimeter-wave integrated circuit processing techniques, much attention has been directed to the use of a high-quality multilayer planar circuit that allows for an additional degree of designfreedom along the vertical orientation [6]. However, as the operating frequency becomes higher and electronic devices are more miniaturized, manufacturing difficulties increase because of the structural sensitivity. Therefore, most microwave and millimeter-wave filters are produced through the tuning process. And this significantly decreases productivity.

Transversal filters, which can also be used even for millimeter-wave band and have low structural sensitivity, are typical ultra-wideband bandpass filters. These transversal filters have the following advantages. Firstly, the stored energy is rather smaller than that of the resonator filter. Secondly, it is easy to match the external impedance. Thirdly, tuning process might be eliminated because transversal filters do not employ resonators [7, 8].

So far, transversal filters using quarter-wavelength directional couplers have been reported [7, 9, 10]. These conventional transversal filters need lots of calculations and their frequency characteristics are seriously degraded by the connecting sections. Moreover, they are not appropriate for MMIC applications due to their lengthy structure. In order to improve these defects of the conventional transversal filters, novel transversal filter configurations using half-wavelength directional couplers have been reported by us [11, 12]. Contrary to the conventional transversal filters, the design procedure of the novel transversal filter is much simpler and the length of the filter can be reduced so as to be adequate for some applications like MMIC's [12]. However, the spurious responses of the novel transversal filters are similar to those of the conventional ones which have additional passband at the twice frequency of the filter's center frequency.

In this paper, another novel transversal filter, whose spurious response is suppressed and attenuation characteristics are improved by means of the multiple-coupled line, is proposed. The frequency characteristics of the multiple-coupled line are analyzed in detail. The performance of the spurious-suppressed transversal filter is verified by the full wave analysis and the measurement. Good agreement between simulated and measured results is achieved.

II. Conventional transversal filter theory

Transversal filters consist of delay elements and weighting elements [13]. In general, active devices are used as the weighting elements [14], but they have the problems of noise figures and unstable temperature characteristics. Directional couplers have both functions of delay elements and weighting elements, so they are suitable for use in transversal filters. Some kinds of transversal filters which use multilayer ceramic directional couplers, MMIC multilayer directional couplers, and CPW(coplanar waveguide) directional couplers have been reported [7, 10, 15]. All these transversal filters are composed of quarter wavelength directional couplers. Fig. 1 shows typical structure of the conventional transversal filters.

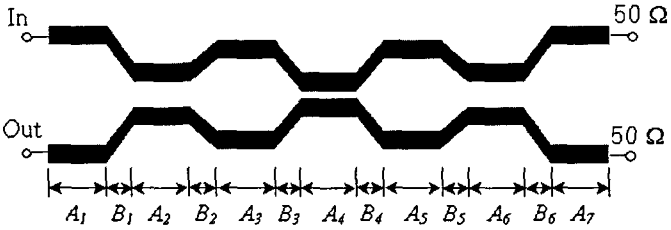


Fig. 1. Typical structure of the conventional transversal filters.

In Fig. 1, A_i's and B_i's indicate the coupled sections and the connecting sections, respectively. The T matrix of the transversal filter using directional couplers is given by

$$T_{total} = T_1 T_2 \cdots T_i \cdots T_n \tag{1}$$

where T_i is the T matrix of the ith directional coupler [16]. And the transmission characteristic (S_{21}) of the filter is

$$S_{21} = \frac{T_{12\,total}}{T_{22\,total}} . \tag{2}$$

The Fourier translation relationship between the desired filter characteristic $C(\omega)$ and the reflection coefficient distribution function $p(x)$ are expressed as [16]

$$C(\omega)=2\int_0^{L/2}\sin(2\omega x/v)p(x)dx \tag{3}$$

$$p(x)=-\frac{2}{\pi v}\int_0^{2\omega_c}\sin(2\omega x/v)C(\omega)d\omega \tag{4}$$

where L is the total length of the coupler, v is the velocity in the guide, and ω_c is the angular center frequency.

The coupling coefficients of the transversal filter, which are calculated from $p(x)$, usually have both positive and negative values [7], but coupling coefficients of the directional couplers are physically positive. Therefore, additional procedures to make the coupling coefficients all positive are needed. Since the relationship between $p(x)$ and k_i is nonlinear, several generalized methods which require bothersome calculations have been introduced to find the realizable k_i's [9]. Moreover, the frequency characteristics of the conventional filter are degraded by the connecting sections.

III. Novel transversal filter

A novel transversal filter configuration, which consists of triple-coupled-line directional couplers, is shown in Fig. 2 [12]. Frequency characteristics of the multiple-coupled-line directional couplers were analyzed and the general equations for output signals at each port were also derived by us [12, 17]. In Fig. 2, the dashed areas represent dielectric substrates and the shaded areas indicate the conductor patterns on the dielectric layers. A_i's and B_i's mean the directional couplers and the connecting sections, respectively.

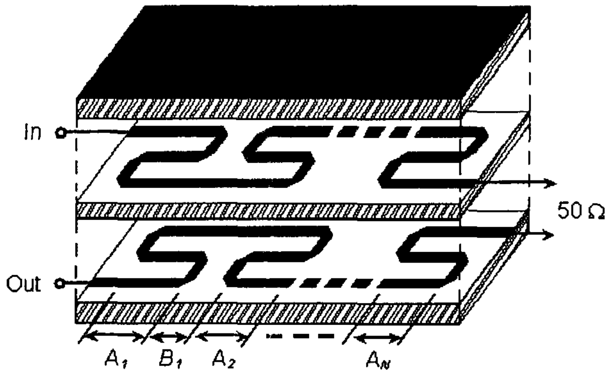


Fig. 2. Structure of the novel transversal filter.

Because the novel transversal filter is composed of half-wavelength directional couplers, the coupling coefficients can be directly obtained from the Fourier translation relationship between the coupling coefficients and the frequency characteristics, without computing $p(x)$. The coupling coefficients of the novel transversal filter can be calculated as

$$k_i=A_m\mathrm{sinc}\left[\frac{2}{N+1}\left(i-\frac{N+1}{2}\right)\right],\qquad i=1,2,\cdots,N \tag{5}$$

where N represents the number of the directional couplers. In the same way as of the conventional transversal filters, Am is optimized by the frequency responses calculated from (2).

A novel transversal filter which consists of 9 triple-coupled-line directional couplers is designed at 5 GHz. The thickness and dielectric constant of each layer are 0.254 mm and 2.2. The coupling coefficients calculated from (4), distances (D), and widths (W) of the coupled lines are summarized in Table I. The total size of the designed filter is 75×20×0.762 mm^3. The layout of the designed filter is shown in Fig. 3 and simulation results are plotted in Fig. 4.

Table I. Coupling coefficients and structural parameters.

Position	k_i (dB)	D (mm)	W (mm)
1, 9	-24.66	0.81	0.49
2, 8	-17.98	0.60	0.48
3, 7	-14.46	0.47	0.47
4, 6	-12.62	0.38	0.47
5	-12.04	0.35	0.46

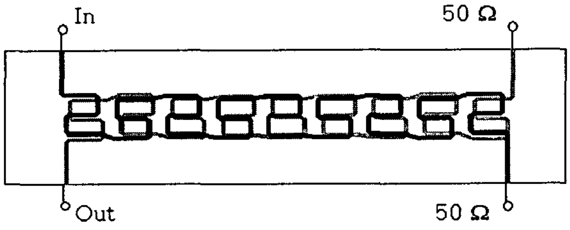


Fig. 3. Layout of the designed transversal filter.

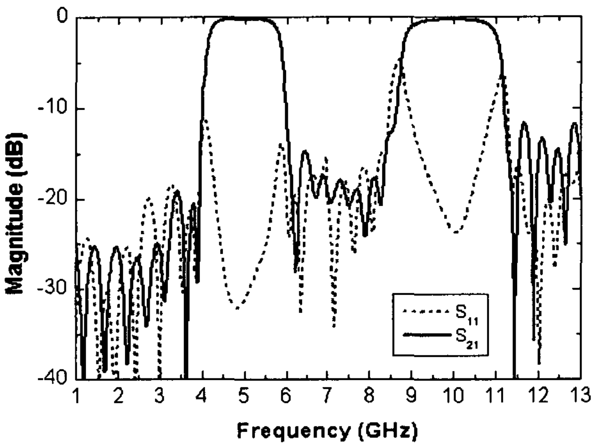


Fig. 4. Simulation results of the novel transversal filter.

The novel transversal filter can easily achieve tight coupling and frequency characteristics are not deteriorated by the connecting sections. Moreover, its structure is more advantageous for MMIC applications than the conventional one [12].

IV. Spurious-suppressednovel transversal filter

Large attenuation characteristics in the stopband can be obtained by cascading transversal filters as shown in Fig. 5 [12]. Fig. 6 shows the calculated frequency characteristics of the cascaded transversal filters, each of which is designed at 5 GHz and consists of 9 triple-coupled line directional couplers. It can be observed that even though several transversal filters are cascaded, the first spurious response which may be serious in some applications is not suppressed, while the stopband attenuation is improved as the number of the cascaded transversal filters increases. In this paper, a method of suppressing the first spurious response is proposed.

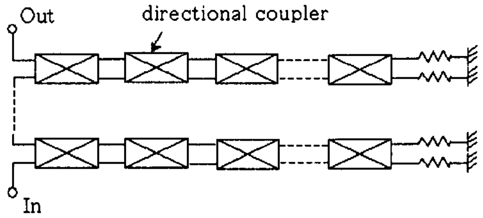


Fig. 5. Cascaded transversal filter.

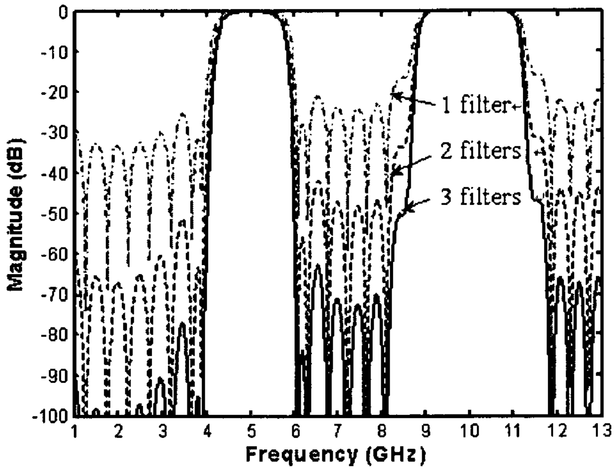


Fig. 6. Frequency responses of the cascaded filters.

4-1. Multiple-coupled line

In order to realize a broadband bandpass filter which has transmission zeros in the stopband and has compatible structure with the novel transversal filter that is shown in Fig. 3, the multiple-coupled-line structure is devised and utilized. A multiple-coupled line that consists of three layers having a broadside-coupled stripline structure is shown in Fig. 7. Herein, the dashed areas represent dielectric substrates and the shaded areas indicate the conductor patterns on the dielectric layers. Each dielectric layer has the same thickness and property.

If the discontinuity effect is ignored, the equivalent circuit of the multiple-coupled line can be represented as Fig. 8, where L_1 and L_2 indicate the lengths of coupled lines and connecting lines. As depicted in Fig. 8, Z_{1e}, Z_{1o}, and k mean the even-/odd-mode impedances and the coupling coefficient, respectively.

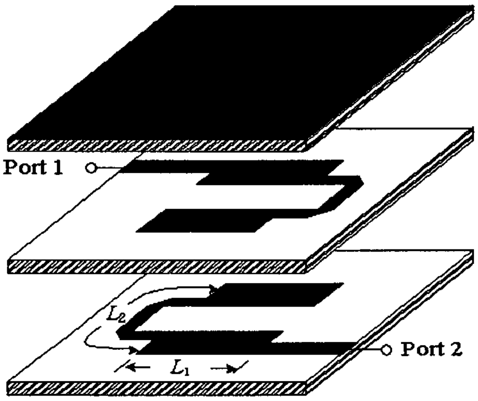


Fig. 7. Structure of the multiple-coupled line.

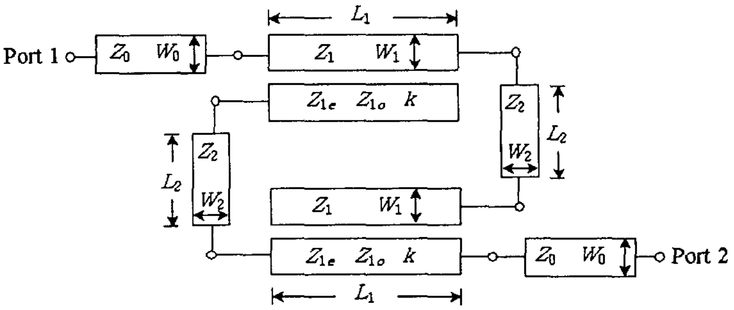


Fig. 8. Equivalent circuit of the multiple-coupled line.

If a signal is excited at port 1 in Fig. 8, the signal is coupled at the first coupled line and then, the coupled and the direct signal are coupled again at the second coupled line after traveling through the connecting lines. When all the line impedances are 50 Ω, that is, $Z_0 = Z_1 = Z_2 = 50\ \Omega$, and the electrical lengths of L_1 and L_2 are θ and ϕ, the output signal at port 2 can be derived as

$$S_{21} \approx \frac{2M_1M_2}{M_3^2}\left\{1 + \frac{\left(M_1^2 + M_2^2\right)^2}{M_3^4} e^{-j2\phi}\right\} e^{-j\phi} \tag{6}$$

where

$$M_1 = \sqrt{1-k^2}$$
$$M_2 = jk\sin\theta$$
$$M_3 = \sqrt{1-k^2}\cos\theta + j\sin\theta.$$

When k varies from 0.2 to 0.4, and L_1 and L_2 are 1/6 wavelengths at 5 GHz, the magnitudes of the output signals calculated from (6) are shown in Fig. 9. Fig. 9 shows that if the coupling coefficient of the coupled line is large enough, say k=0.4, there exist both the transmission zeros and a passband between the transmission zeros.

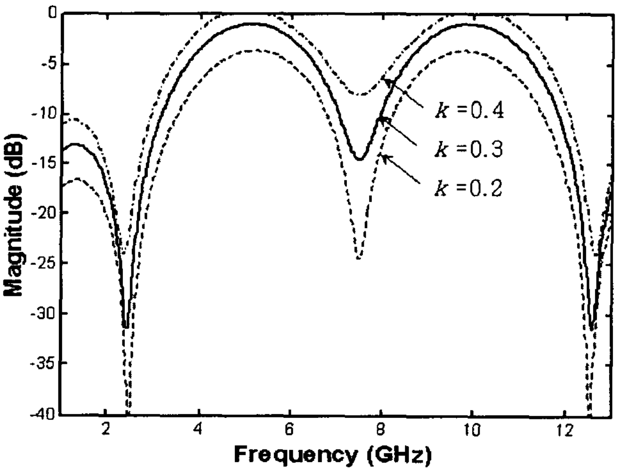


Fig. 9. Calculated frequency responses of the multiple-coupled line.

If there are impedance differences among the coupled, the uncoupled, and the input/output lines, reflection which causes very complicated coupling occurs at each mismatched junction. When the dielectric constant and the thickness of the dielectric layer in Fig. 7 are 2.2 and 0.254 mm, frequency characteristics are plotted by varying Z_c in Fig. 10 and Fig. 11 under the condition of Z_0 and Z_2 are 50 Ω, where Z_c is the ratio of the coupled line impedance Z_1 to the connecting line impedance Z_2. The structural parameters of the investigated multiple-coupled line are summarized in Table II.

Table II. Structural parameters of the multiple-coupled line.

	$Z_c = 1$	$Z_c = 0.8$	$Z_c = 0.6$	$Z_c = 0.4$
W_0, W_2 (mm)	0.508	0.508	0.508	0.508
W_1 (mm)	0.448	0.624	0.919	1.510
L_1, L_2 (mm)	6.737	6.737	6.737	6.737
k	0.360	0.385	0.411	0.435

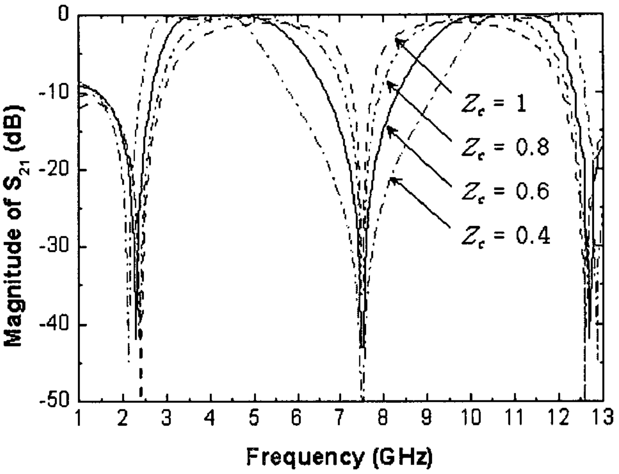


Fig. 10. S21characteristics of the multiple-coupled line.

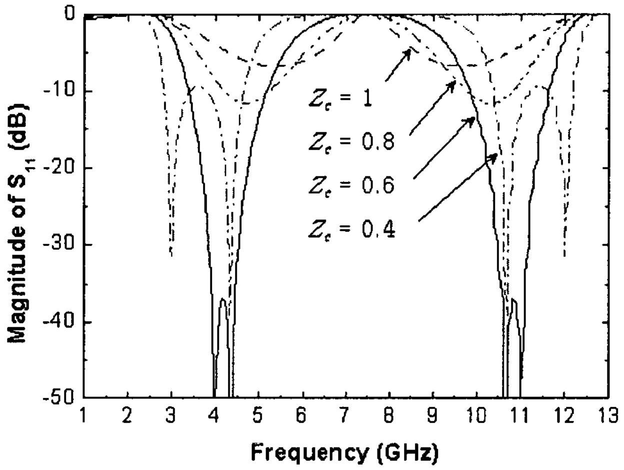


Fig. 11. S11characteristics of the multiple-coupled line.

Fig. 10 and Fig. 11 show that the multiple-coupled line behaves like a dual mode resonator, so that it can be used as a bandpass filter. Lower impedance ratio means wider width of the coupled line and tighter coupling. When the impedance ratio is getting small, the first passband moves to lower frequency and the second passband shifts to higher frequency.

When Z_0 and Z_2 are 50 Ω and Z_1 is 27.2 Ω, the frequency characteristics by varying L_c are shown in Fig. 12, where L_c is the ratio of the coupled line length L_1 to the connecting line length L_2. Structural parameters of each multiple-coupled line are summarized in Table III.

Table III. Structural parameters of the multiple-coupled line.

	L_c = 1.304	L_c = 1.000	L_c = 0.662
W_0, W_2 (mm)	0.508	0.508	0.508
W_1 (mm)	1.040	1.040	1.040
L_1 (mm)	6.000	5.440	4.500
L_2 (mm)	4.600	5.440	6.800

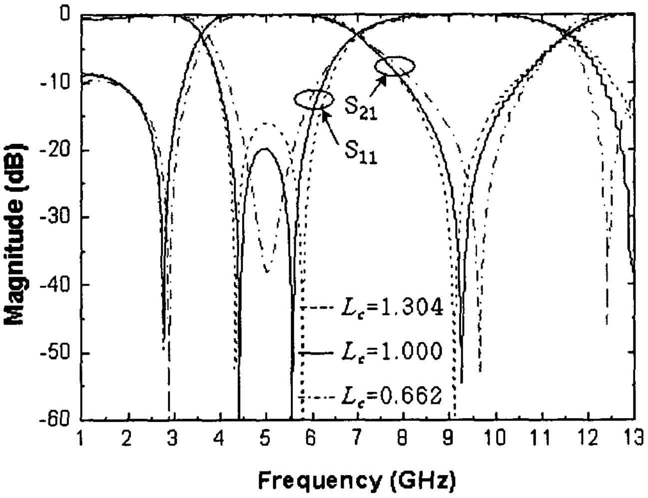


Fig. 12. Frequency characteristics of the multiple-coupled line.

From Fig. 12, it is known that bandwidth become wider and the upper transmission zero frequency moves higher as L_c increases. Therefore, if the length and impedance of each line are properly chosen, the multiple-coupled line can behave as a bandpass filter whose upper transmission zero frequency can be arbitrarily controlled.

Multiple-coupled-line bandpass filters (MCLF), whose upper transmission zero frequencies are in the vicinity of 10 GHz, are designed at 5 GHz. The designed structural parameters and transmission zero frequencies of each MCLF are shown in Table IV, and the full wave analysis results are plotted in Fig. 13.

Table IV. Structural parameters of the multiple-coupled-line filters.

	MCLF 1	MCLF 2	MCLF 3
L_1 (mm)	7.40	4.80	3.70
L_2 (mm)	3.00	5.40	6.30
W_1 (mm)	0.82	1.04	1.27
W_2 (mm)	0.40	0.40	0.40
f_{p1} (GHz)	2.64	2.82	2.94
f_{p2} (GHz)	8.62	9.42	10.64

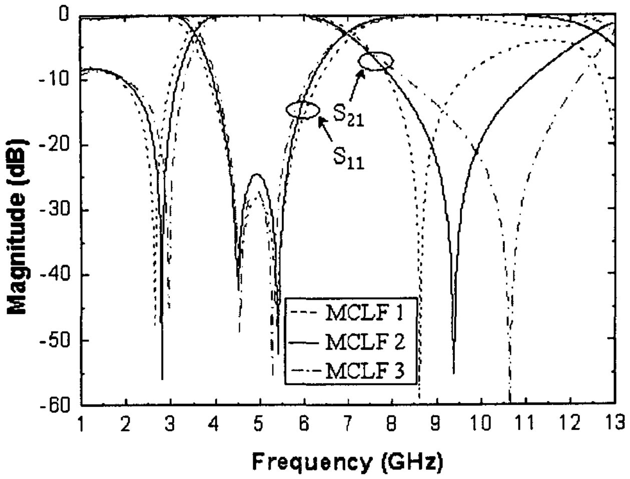


Fig. 13. Simulation results of the designed multiple-coupled-line filters.

From Fig. 13, it can be seen that the upper transmission zero frequency f_{p2} increases significantly from 8.62 GHz to 10.64 GHz as L_2 varies from 3.0 mm to 6.3 mm while the lower transmission zero frequency f_{p1} changes slightly.

4-2. Simulated and measured results of the spurious-suppressed transversal filter

A spurious-suppressed transversal filter can be obtained by adding the multiple-coupled-line filters at the input and output ports of the novel transversal filter shown in Fig. 3. In this paper, this filter has been designed by means of the multiple-coupled-line filter MCLF 2 whose frequency characteristics are shown in Fig. 13. The size of the designed filter is $85 \times 20 \times 0.762$ mm^3 and conductor patterns are shown in Fig. 14.

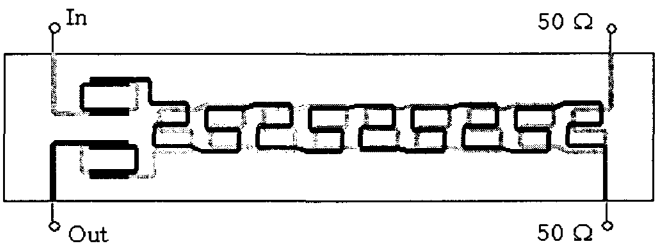


Fig. 14. Layout of the transversal filter with multiple-coupled lines.

In Fig. 15 the full wave analysis results of the spurious-suppressed transversal filter are compared with those of the previous transversal filter shown in Fig. 3. Not only the spurious response is effectively suppressed up to 13 GHz but also the attenuation is considerably increased around 2.7 GHz and 9.4 GHz. Therefore, it can be seen that the multiple-coupled line can improve the attenuation characteristics as well as the spurious characteristics.

The spurious-suppressed transversal filter is fabricated by laminating three 0.254-mm Cu-clad Teflon sheets with relative permittivity of 2.2. The fabricated Teflon sheets and the assembled filter are shown in Fig. 16.

The simulated and the measured results of the fabricated filter are shown in Fig. 17. The minimum insertion loss and the 3-dB bandwidth of the measured results are 1.07 dB and 28 %, respectively. The spurious response is effectively suppressed about 20 dB at 10 GHz and the attenuation in the stopband is more than 15 dB up to 13 GHz.

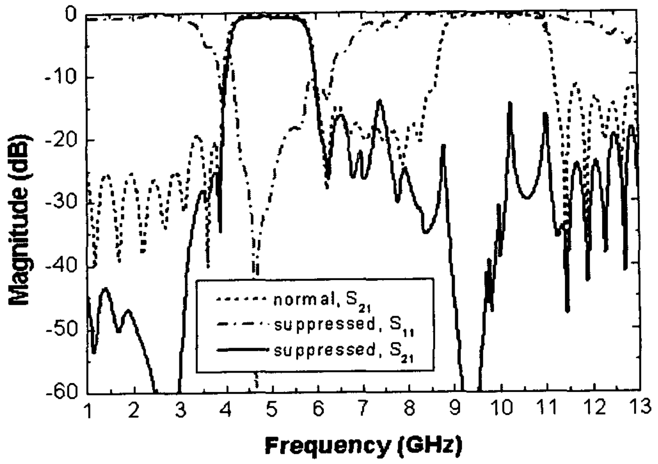
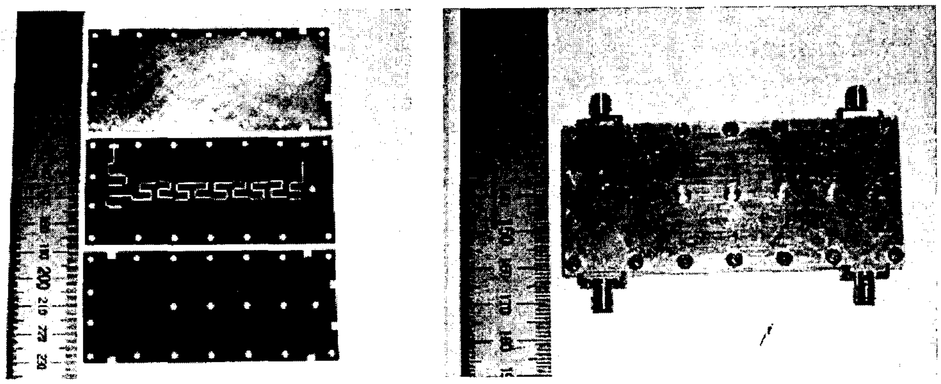


Fig. 15. Comparison of simulated frequency characteristics.



(a) (b)

Fig. 16. Photographs of the fabricated transversal filter.
(a) printed Teflon sheets, (b) housing.

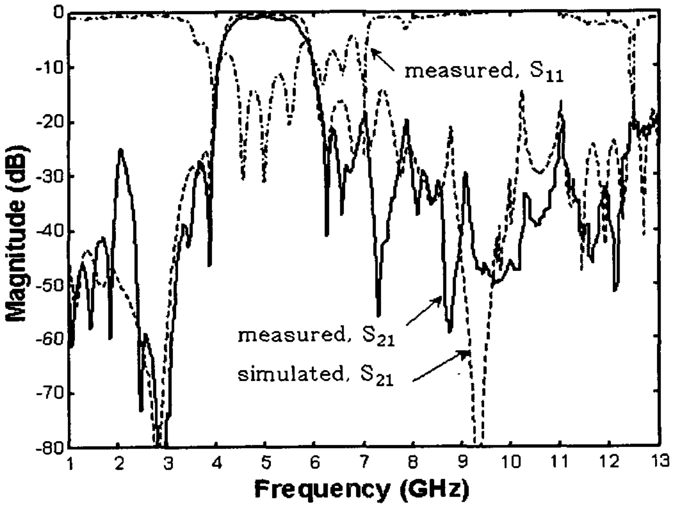


Fig. 17. Measured frequency responses.

V. Conclusions

Transversal filters have spurious responses at the twice frequency of the center frequency. In order to solve this spurious problem, a spurious-suppressed transversal filter using the multiple-coupled line is proposed. The frequency characteristics of the multiple-coupled line are analyzed in detail. The novel spurious-suppressed transversal filter, which is composed of triple-coupled half-wavelength directional couplers, is designed at 5 GHz. The spurious-suppression characteristic of the proposed transversal filter is verified by the full wave analysis and the measurement. The measured results agree well with the simulated ones.

It is expected that the proposed transversal filter can be applicable to the UWB systems as well as millimeter-wave MMIC's.

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