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HYBRID MICROSTRIP COMPACT BANDPASS FILTER USING HIGH PERMITTIVITY SUBSTRATE

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Abstract—A four-pole elliptic function compact bandpass filter is designed by using interdigital hairpin resonator and step-impedance hairpin resonator. The miniaturized band-pass filter is also implemented using high permittivity dielectric substrate. The full-wave simulator IE3D is used to design the compact hairpin resonator, and to calculate the coupling coefficient of the basic coupling strictures. The responses of the fabricated filters using Al_2O_3 ($\varepsilon_r = 9.7$, $Q \times f = 350000\,\text{GHz}$) and $0.6Sm(Co_{1/2}Ti_{1/2})O_3$-$0.4CaTiO_3$ ($\varepsilon_r = 37$, $Q \times f = 43000\,\text{GHz}$) dielectric substrates are designed at a center frequency of 2 GHz. The size of the compact hairpin filter using $0.6Sm(Co_{1/2}Ti_{1/2})O_3$-$0.4CaTiO_3$ ceramic substrate, as compared to that of a compact hairpin filter using Al_2O_3 ceramic substrate, is reduced in size by 45%. The compact size and good agreement have been obtained between simulations and implementation results.

1. INTRODUCTION

In wireless communication systems, small size and high performance filters are needed to reduce the cost and improve the system performance. They can be designed in many different ways and by using different materials. Ceramic material with a high quality factor

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$(Q \times f)$ value and a high permittivity provides a means to create small resonator structures, such as coaxial structures, that can be coupled to form combline bandpass filters [1]. However, further miniaturization becomes more difficult for this filter. Planar filters using high-permittivity ceramic substrate provide good miniaturization ability [2–6]. Therefore, there has been much research conducted on planar filters and their components.

Since microstrip resonators are the basic components of a planar filter design, it is necessary to select proper resonator types used in a filter design. A conventional haft-wavelength open-line microstrip resonator is too large to be used in the modern communication system such as 900 MHz, 1800 MHz for personal communication systems (PCS). The hairpin filters [2, 7–9] were folded from the open line $\lambda/2$ wavelength microstrip resonator to become U-shaped resonators make progress in circuit size reduction from the parallel-coupled line structure. Since 1989, the miniaturized hairpin resonator was developed by several researchers [9–11]. The interdigital (IDT) coupled lines or coupled lines at the ends of this structure are used as a capacitor in order to reduce the resonator size. In addition, cross-coupled filter with these attractive characteristics is that of quasi-elliptic function response filters with a pair of attenuation poles at finite frequencies [12, 13]. The capability of placing attenuation poles near the cutoff frequencies of the pass-band improves the selectivity using less resonators. A cross-coupled between a pair of nonadjacent resonators was approached this type filter. The filter employing the cross coupled generally results in a compact topology.

In this paper, the miniaturized bandpass filters using high permittivity ceramic substrates such as Al_2O_3 and $0.6Sm(Co_{1/2}Ti_{1/2})O_3$-$0.4CaTiO_3$ [14] are implemented. In addition, the design of the four-pole cross-coupled elliptic function filter using compact interdigital (IDT) hairpin resonator and Step-Impedance (SIR) hairpin resonator is presented. The design approach enables one to use an EM simulator to complete the filter design, that is, to determine the physical dimensions of the filters. The results among these filters regarding performance and size are compared and investigated.

2. DESIGN CROSS-COUPLED COMPACT HAIRPIN FILTERS

Figure 1 shows the layout and equivalent electrical parameters of an IDT hairpin resonator and a SIR hairpin resonator. Its fundamental condition is hence the same as that of a conventional miniaturized hairpin resonator [15]. In the case of $Z_s > \sqrt{Z_{io}Z_{ie}}$, the total electrical length of these resonators become shorter than that of conventional. Further miniaturization can be achieved by increasing the coupling between parallel coupled lines and hence decreasing the value of $\sqrt{Z_{io}Z_{ie}}$. In addition, the resonance condition can be calculated from input admittance using ABCD matrices [16].

A four-pole elliptical bandpass filter response can be implemented by using cross coupling between nonadjacent resonators. The cross couplings provide the input signal with two paths from the input port to the output port. The magnitude and phase of the signal are changed differently though different paths. As mentioned above, the multi-path effect may cause attenuation poles at finite frequencies if the couplings among the resonators are properly designed. Figure 2 shows the four-pole elliptic-function bandpass filter using miniaturized hairpin resonators (IDT hairpin resonator and SIR hairpin resonator). In the configuration, significant couplings exist between any two nondiagonally neighboring miniaturized hairpin resonators. The structure can be extended to form cross-coupled filters of higher orders.

There are four significant couplings, namely, M_{12}, M_{23}, M_{34}, and M_{14}, in the structure. The coupling M_{34} is identical to M_{12}, so that required couplings specify the three basic coupling structures to be identified in the design of the cross-coupled filter. In each coupling structure, the two resonators have opposite orientations and are spaced apart. The coupling M_{14} is for electric coupling because the electric-fringe fields are strong near the open ends of the resonators. Similarly, the coupling M_{23} provides a magnetic coupling because the magnetic-fringe fields are stronger near the center of the resonators. The coupling structure in M_{12} or M_{34} provides both electric and magnetic coupling, which is called a mixed coupling. The understanding of these coupling natures is helpful in determining the coefficients of the

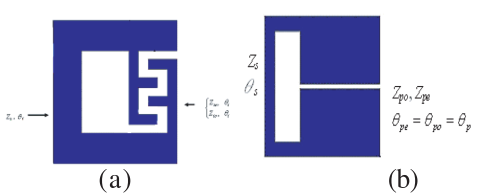


Figure 1. (a) IDT hairpin resonator (b) SIR hairpin resonator.

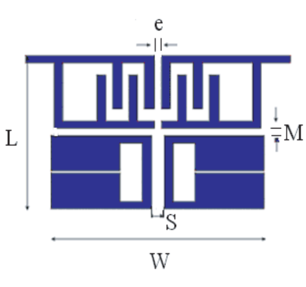


Figure 2. Layout of the hybrid microstrip four-pole elliptic function compact filter.

coupling structures.

Cross-coupled bandpass filters with using compact hairpin resonators are designed to have a fractional bandwidth of 5% at a mid-band frequency $f_o = 2\,\text{GHz}$. The filter was fabricated on two kinds of dielectric material, such as Al_2O_3 substrate $\varepsilon_r = 9.7$, $Q \times f = 350000\,\text{GHz}$, and thickness is 0.64 mm) and $0.6Sm(Co_{1/2}Ti_{1/2})O_3$-$0.4CaTiO_3$ substrate ($\varepsilon_r = 37$, $Q \times f = 43000\,\text{GHz}$, and thickness is 1.6 mm). The design parameters such as external quality factor and coupling coefficients of cross coupled filters can be determined in terms of circuit elements of a low-pass prototype filter, which consists of lumped capacitors and ideal admittance inverters. A four-pole ($n = 4$) Elliptic function low-pass prototype with a Ω_a value of 1.85 is chosen. The lumped circuit element value with $\Omega_a = 1.85$ of low-pass prototype filter are found to be $C_1 = 0.95826$, $C_2 = 1.40972$, $J_1 = -0.19685$ and $J_2 = 1.10048$ [17]. The relationships between the bandpass design parameters can the low-pass elements are [17]

$$\begin{cases} Q_{ei} = Q_{eo} = \frac{C_1}{FBW} = 19.1652 \\ M_{1,2} = M_{3,4} = \frac{FBW}{\sqrt{C_1 C_2}} = 0.042 \\ M_{1,4} = \frac{FBW \cdot J_1}{C_1} = -0.01 \\ M_{2,3} = \frac{FBW \cdot J_2}{C_2} = 0.038 \end{cases} \tag{1}$$

where FBW denotes the fractional bandwidth of the band-pass filter, C is the capacitance of the lumped capacitor and J is the characteristic admittance of the inverter, and N is the degree of the filter. The cross-coupled structure provides electric, magnetic and mixed coupling. Using a parameter-extraction technique, we carry out EM-simulations to extract the external Q and coupling coefficient M against the physical dimensions. The coupling coefficient M_{ij} of each pair of coupled resonators can be calculated by using the following equation:

$$M_{ij} = \frac{f_2^2 - f_1^2}{f_2^2 + f_1^2} \tag{2}$$

where f_1 and f_2 are the lower and higher split-resonant frequencies, respectively. Therefore, the design curves for these coupling structures can be presented and shown in Figure 3. Figure 3 also shows the feed location topology used in this filter design. The external Q of such feed structure can be characterized by

$$Q = \frac{f_0}{\Delta f_{3\,\text{dB}}} \tag{3}$$

where f_0 is the resonant frequency of the resonator and $\Delta f_{3\,\text{dB}}$ is the 3-dB bandwidth [17]. The design curve of the feed location on the

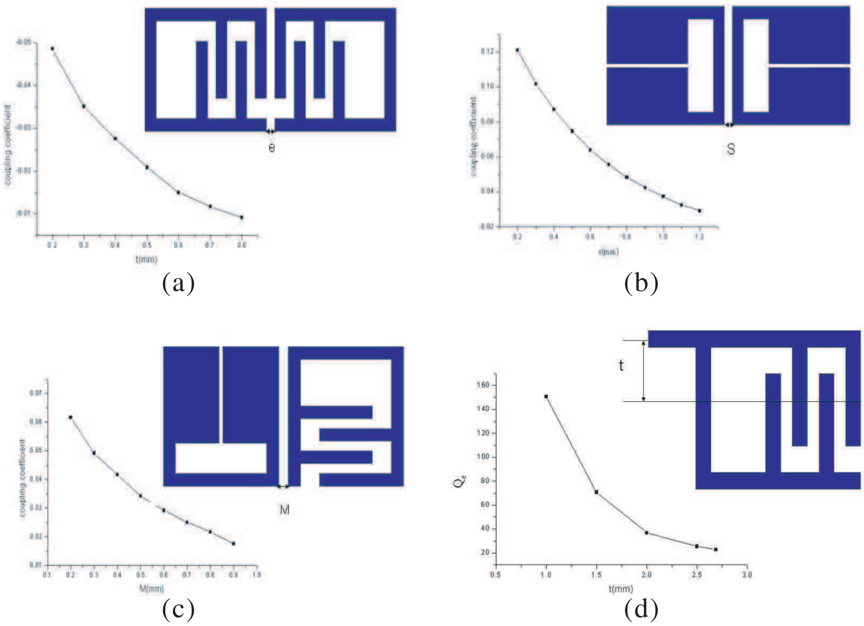


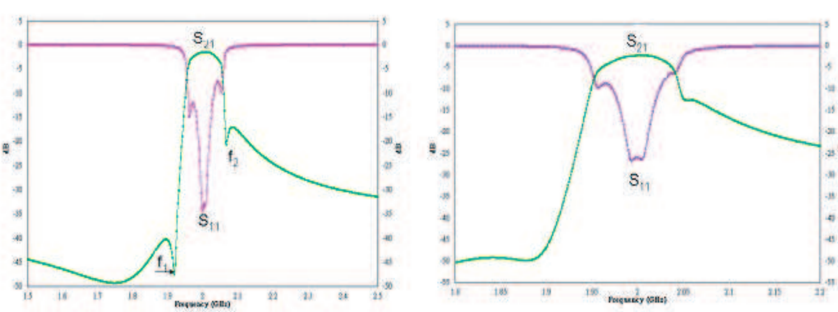
Figure 3. Design curves for (a) electric coupling versus spacing, (b) magnetic coupling versus spacing, (c) mixed coupling versus spacing, and (d) external Q versus feed location.

resonator for a given external Q can be obtained by using an EM simulation tool such as IE3D [18]. By using the design curves of the coupling coefficient and the external Q, this filter can be realized.

Substrates of bandpass filter were synthesized by a conventional solid-state method. The starting materials were mixed according to a stoichiometric ratio, and were weighted and mixed for 24 h in distilled water. The mixture was dried at 100°C, then thoroughly milled before it was calcined at 1150°C for 2 h. The calcined powder was ground and sieved through a 100-mesh screen. The calcined powder was then remilled for 24 h, and then added 2 wt% of a 10% solution of polyvinyl alcohol (PVA) as binder. The milled powders were pressed into circular molds, and a pressing pressure of 2000 kg/cm^2 was used for all samples. The pellets were sintered between 1420°C for 4 h in the air. Thereafter, patterns of compact filters are screen-printed on it and silver pasted.

3. SIMULATED AND MEASURED RESULTS

Figure 4 shows the calculated filter response of the cross coupled compact hairpin filters with Al_2O_3 and $0.6Sm(Co_{1/2}Ti_{1/2})O_3$-$0.4CaTiO_3$ substrates. The 3-dB fractional bandwidth of the crosscoupled filter's frequency response were 5.1% for Al_2O_3 ceramic substrate and 4.5% for $0.6Sm(Co_{1/2}Ti_{1/2})O_3$-$0.4CaTiO_3$ ceramic substrate. The bandwidth of each filter agrees quite well with the desirable values. It was found that the skirt properties of the cross-coupled filter were sharper. The dimensions of the compact hairpin filters with different high-permittivity ceramic substrates are provided in Table 1. Figure 5 shows photographs of the fabricated filters. The size of the compact hairpin filter using $0.6Sm(Co_{1/2}Ti_{1/2})O_3$-$0.4CaTiO_3$ ceramic substrate, as compared to that of a compact hairpin filter using Al_2O_3 ceramic substrate, is reduced in size by 45%. The measurements are performed with an HP8757D network analyzer. The measured performance is shown in Figure 6. Using Al_2O_3 substrate, the midband insertion loss is about 1.73 dB, the return loss is about 32.3 dB at the center frequency of 2.015 GHz, and the 3-dB passband width is about 7%. On the other hand, using $0.6Sm(Co_{1/2}Ti_{1/2})O_3$-$0.4CaTiO_3$ substrate, the midband insertion loss is about 2.83 dB, the return loss is about 19.96 dB at the center frequency of 2.007 GHz, and the 3-dB passband width is 5%. The comparison between the measured and simulated results shows that the measured response is strongly influenced by the surface roughness of the ceramic substrate, the shrinkage of conductor thickness or width, and electric contact.



(a) (b)

Figure 4. (a) Simulated frequency response for Al_2O_3 substrate; (b) simulated frequency response for $0.6Sm(Co_{1/2}Ti_{1/2})O_3$-$0.4CaTiO_3$ substrate.

Table 1. Dimensions of hybrid compact hairpin filters with different ceramic substrates.

Design (mm)	W	L	e	S	M
Al_2O_3 Ceramic Substrate	14.8	12.6	0.7	1	0.6
$0.6Sm(Co_{1/2}Ti_{1/2})O_3$-$0.4CaTiO_3$ Ceramic substrate	12.98	7.9	1.3	0.9	1.9

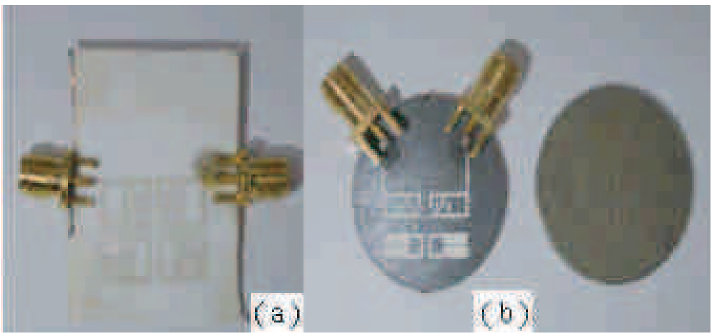
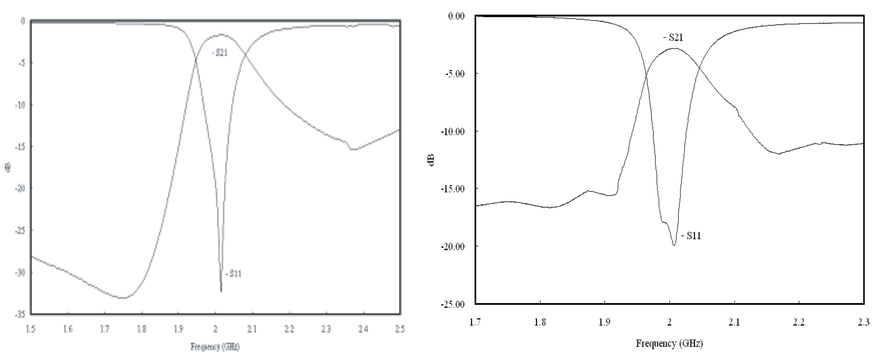


Figure 5. Shows photographs of the fabricated filters (a) Al_2O_3 substrate, (b) $0.6Sm(Co_{1/2}Ti_{1/2})O_3$- $0.4CaTiO_3$ substrate.



(a) (b)

Figure 6. (a) Measured frequency response for Al_2O_3 substrate; (b) measured frequency response for $0.6Sm(Co_{1/2}Ti_{1/2})O_3$-$0.4CaTiO_3$ substrate.

4. CONCLUSION

Miniaturized hairpin bandpass filters on high-permittivity ceramic substrates have been implemented. The simple and accurate design technique makes extensive use of EM simulation. The validity of the proposed method was confirmed through the design, fabrication, and measurement of the compact hairpin bandpass filter at 2 GHz on high-permittivity Al_2O_3 ($\varepsilon_r = 9.7$) and $0.6Sm(Co_{1/2}Ti_{1/2})O_3$-$0.4CaTiO_3$ ($\varepsilon_r = 37$) ceramic substrates. The insertion loss of the filter using Al_2O_3 ceramic substrate is about 1.73 dB; however, the out-of-band attenuation values were below 33.1 dB in the lower-frequency region, and approximately 15.4 dB in the higher-frequency region. On the other hand, the insertion loss of the filter using $0.6Sm(Co_{1/2}Ti_{1/2})O_3$-$0.4CaTiO_3$ ceramic substrate is about 2.83 dB; however, the out-of-band attenuation values were below 15.48 dB in the lower-frequency region, and below 11.96 dB in the higher-frequency region. The compactness of the circuit size makes the cross-coupled filters using microstrip miniaturized hairpin resonators and high-permittivity ceramic substrates an attractive design for further development and applications in modern communication systems.

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