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Novel Miniature Slow-Wave Resonator Filter Using Multilayer LCP Circuit Technology

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***Abstract*—This paper presents a novel microwave bandpass filter using microstrip slow-wave open-loop resonators and multilayer liquid crystal polymer (LCP) technologies. The new filter has not only very compact size due to the slow-wave effect, but also exhibits a ultra-wider upper stopband resulting from the dispersion property. A five-pole microstrip filter of this type, i.e., a bandpass filter centered at f_c=1.18 GHz with -3dB fractional bandwidth of 17%, has been designed and fabricated. No spurious response, which are at least 30-dB rejection, occurs for the frequency up to 10GHz. Moreover, the fabricated filter also has the compact size of $0.102\lambda_g \times 0.081\lambda_g$ and the light weight less than one gram by using multilayer LCP circuit technology. Good agreement can be observed between the simulation and measurement.**

***Keywords*—microstrip filter, bandpass filter, slow-wave open-loop resonators, ultra-wide stopband.**

I. INTRODUCTION

Microwave bandpass filters with broad stopband is in great demand for modern communication systems to transmit the desired signals in the passband and suppress harmonics and spurious signals in the stopband. The traditional microstrip half-wavelength resonator filter not only has long physical length, even on a higher dielectric constant substrate, but also has a spurious passband at $2f_0$, where f_0 is the midband frequency of the filter [1]. In order to reduce interference by keeping out-of-band signals from reaching a sensitive receiver, a wider upper stopband (including $2f_0$), may also be required.

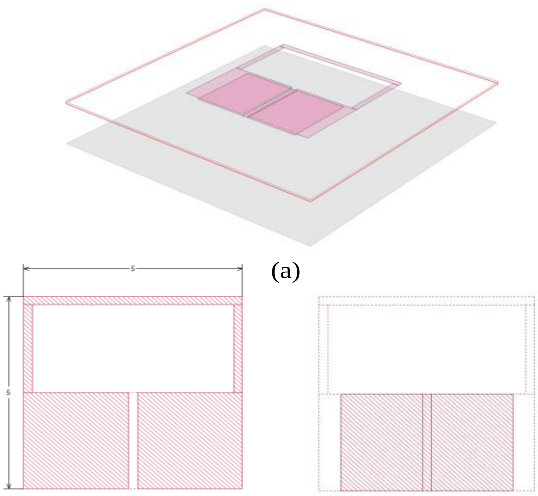
However, lots of planar bandpass filters which consist of half-wavelength resonators have inherently a spurious passband at $2f_0$, so that a cascaded bandstop filter or low-pass filter may be needed to suppress the spurious passband at the cost of extra size and insertion loss. The quarter-wavelength resonator filters require short-circuit (grounding) connections with via holes, which is not quiet compatible with planar fabrication techniques, although they have the first spurious passband at $3f_0$ [2].

So far, various structures have been proposed to implement good bandpass and stopband performance [3]-[5]. However, these bandpass filters suffer from large circuit size or insufficient stopband rejection rate performance.

In this paper, a new class of microstrip bandpass filter based on coupled slow-wave open-loop resonators is introduced. The filter has not only very compact size, but also a ultra-wide upper stopband performance. The filter is fabricated by using multilayer LCP circuit technologies, which have excellent electrical characteristics in a wide frequency range and low loss tangent over the frequency bands under consideration. It has low moisture absorption and the cost is much cheaper compared with that of LTCC materials. In Section II, we present the novel multilayer slow-wave open-loop resonator. The designs of a five-pole bandpass filter is described in Section III, including the experimental result of the filter. Conclusions is followed in Section IV.

II. MULTILAYER SLOW-WAVE OPEN-LOOP RESONATOR

The 3D structure of the proposed novel multilayer slow-wave open-loop resonator is shown in Fig 1(a). It consists of three metal layers supported by dielectric substrates with a relative dielectric constant of 3 and a total thickness of 0.625mm. The top and middle layer layouts are shown in Fig 1(b) and (c).



(a)

(b) (c)

Fig.1. Proposed multilayer slow-wave open-loop resonator.

(a) 3D view (b) Top layer (c) Middle layer

The bottom metal layer serves as solid ground. The resonator has a small footprint of 5mm by 5mm. *The floating metal on the middle layer is essential for achieving two desired effects: (i) the slow wave effect to shift the fundamental resonant frequency down for the given footprint; (ii) the dispersion effect to shift the spurious resonances away from the fundamental one.*

For the fundamental resonant mode, which is an odd mode, the symmetrical plane through the open gap of the top layer is an electrical wall that would virtually makes the floating metal grounded along the symmetrical plane resulting in a typical capacitively loaded lossless transmission line resonator of Fig. 2(b), where C_L is the loaded capacitance, Z_a, β_a and d are the characteristic impedance, the propagation constant, and the length of the unloaded line, respectively. Thus, the electric length $\theta_a = \beta_a d$. The circuit response of Fig. 2(b) may be described by [2]:

$$\begin{bmatrix} V_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \cdot \begin{bmatrix} V_2 \\ -I_2 \end{bmatrix} \quad (1)$$

with

$$A = D = cos\theta_a - \frac{1}{2}\omega C_L Z_a sin\theta_a \quad (2a)$$

$$B = jZ_a sin\theta_a \quad (2b)$$

$$C = j\left(\omega C_L cos\theta_a + \frac{1}{Z_a} sin\theta_a - \frac{1}{4}\omega^2 C_L^2 Z_a sin\theta_a\right) \quad (2c)$$

where $\omega = 2\pi f$ is the angular frequency; A,B,C and D are the network parameters of transmission matrix.
Assume that a standing wave has been excited subject to the boundary conditions $I_1 = I_2 = 0$. For no vanished V_1 and V_2, it is required that

$$\frac{C}{A} = \frac{I_1}{V_1}\bigg|_{I_2=0} = \frac{I_2}{V_2}\bigg|_{I_1=0} = 0 \quad (3)$$

$$A = \frac{V_1}{V_2}\bigg|_{I_2=0} = \begin{cases} -1, & \text{for fundamental resonance} \\ 1, & \text{for first spurious resonance} \end{cases} \quad (4)$$

The resonant frequency responses of the multilayer slow-wave resonator is shown in Fig.3. The fundamental resonance is at 1.18GHz; the first spurious resonance is at 11.25GHz and the second spurious resonance at 14.95GHz. Note that the free-space wavelength at the fundament resonant frequency of 1.18GHz is about 254mm, which is much larger that the resonator dimensions and the miniaturization of the proposed resonator results from a very low phase velocity or slow-wave associated with the fundamental resonant mode. Another distinct feature of this proposed resonator is that its first spurious resonant frequency is shifted far away from the fundamental one (C_{IF}); in this case, it is about $12 \times C_{IF}$, which is very important for realizing ultra-wide stopband IF filters. The current distribution of the fundamental and the first spurious resonance are shown in Fig. 4(a) and (b) respectively.

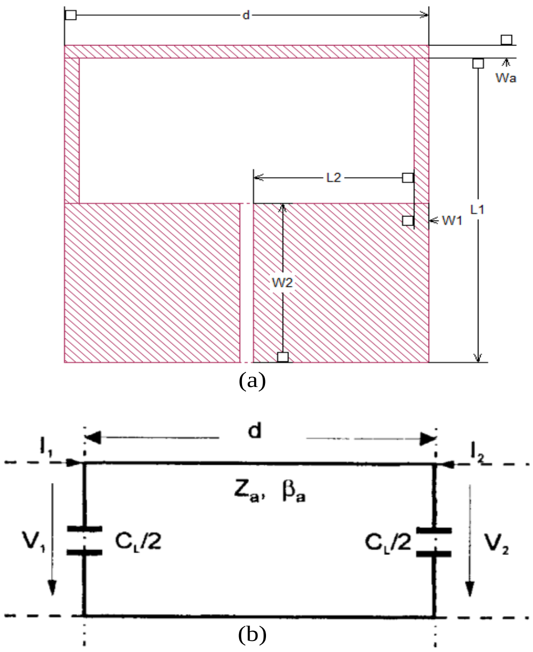


Fig.2. (a) Top layer slow-wave open-loop resonator and (b) Equivalent capacitively loaded transmission line resonator

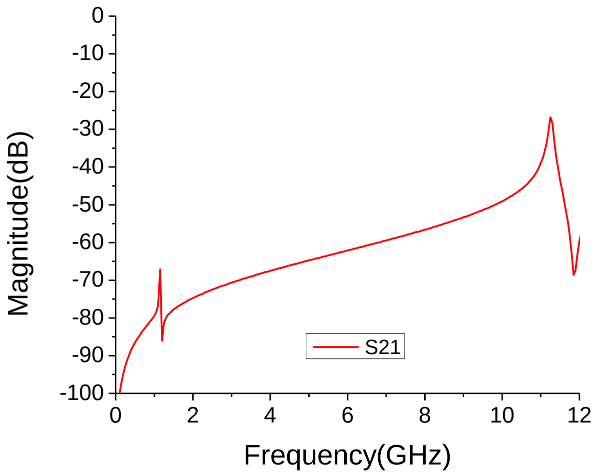


Fig.3. Resonant frequency responses

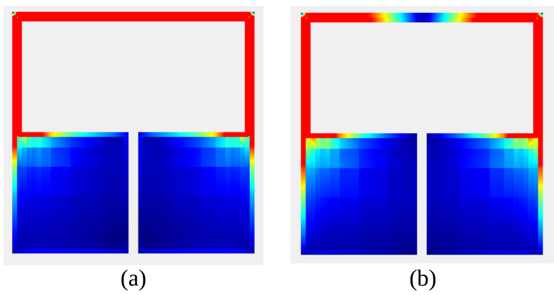


Fig.4. (a) Current distribution of the fundamental resonance and (b) Current distribution of the first spurious resonance

III. FIVE-POLE BANDPASS FILTER DESIGN

A five-pole slow-wave open-loop resonator filter is designed to meet the following specifications.

Center frequency	1.18GHz
3-dB bandwidth	180MHz
Stopband rejection	dc to 1GHz, >40dB
	1.3- 10GHz, >40dB

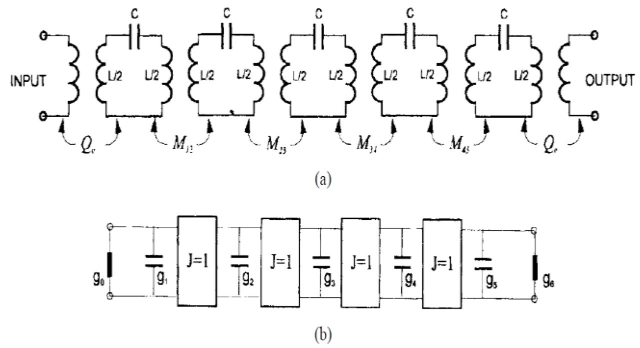


Fig.5. (a) An equivalent circuit of the five-pole coupling bandpass filter and (b) an associated low-pass prototype filter.

The five-pole bandpass filter can be represented by an equivalent circuit shown in Fig. 5(a), where $\frac{1}{\sqrt{LC}} = \omega_0$ is the center angular frequency of the filter;$M_{12}, M_{23}, \dots, M_{45}$ are the coupling coefficients between adjacent resonators, and Q_e is the external quality factor denoting the input and output coupling. The coupling coefficients and external quality factor can be synthesized from a low-pass prototype filter shown in Fig. 5(b), where the rectangular boxes represent frequency invariant immittance inverters defined through a transmission matrix of the form [2]

$$\begin{bmatrix} 0 & j/J \\ jJ & 0 \end{bmatrix} \tag{5}$$

in which J is the characteristic admittance of the inverter, and in our case $J = 1$. The other elements $g_1, g_2, \dots, g_5$ of the prototype filter could be determined by synthesizing a standard Chebyshev filter. The external quality factor and coupling coefficients can then be found by

$$Q_e = \frac{g_0 g_1}{FBW}$$

$$M_{12} = M_{45} = \frac{FBW}{\sqrt{g_1 g_2}}$$

$$M_{23} = M_{34} = \frac{FBW}{\sqrt{g_2 g_3}} \tag{6}$$

where FBW denotes the fractional bandwidth of bandpass filter.

The calculated design parameters of the five-pole bandpass filter are listed below

$$Q_e = 3.1593$$

$$M_{12} = M_{45} = 0.2407$$

$$M_{23} = M_{34} = 0.1669 \tag{7}$$

Having characterized the couplings we designed the filter with the aid of EM simulator. The filter was fabricated by using multilayer LCP technologies. Fig. 6 shows a photograph of the fabricated filter.

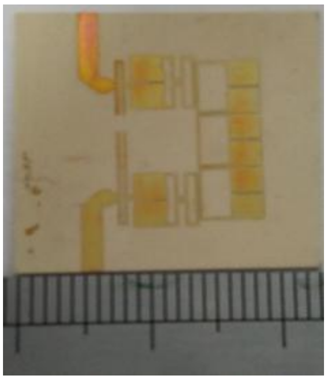


Fig. 6. A photograph of the fabricated five-pole slow-wave open-loop resonator filter using multilayer LCP technologies.

The size of circuit area of this filter is about 15mm by 12mm ($0.102\lambda_g \times 0.081\lambda_g$), where λ_g is the guided wavelength of a 50-Ω line on the substrate at the midband frequency. The weight of the filter is less than 1 gram due to the LCP fabricate technologies.

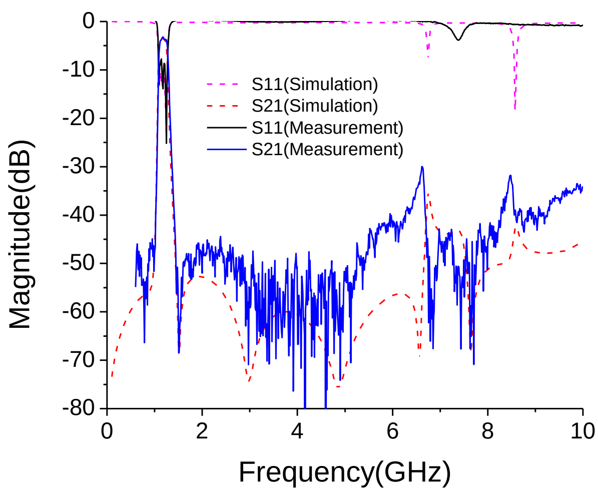


Fig. 7. Simulation and measured results of proposed filter.

TABLE I

Performance comparison with reported wideband bandpass filter with wide stopband

	Techniques	f_0 (GHz)	Stopband width @rejection (dB)	Selective	Size (mm^2)
[3]	Wiggly-line	2.5	5.6× f_0@30dB	Good	~50 × 20
[4]	Periodic floating metal between coupled lines	2	2.8× f_0@40dB	Poor(3-pole Chebyshev)	~50 × 10
This work	Slow-wave open-loop resonator	1.18	8.5× f_0@30dB	Good	~15 × 12

The simulated and measured results are shown in Fig. 7. The measured results have good agreement with the simulation results. The fabricated filter is centered at 1.18GHz with 3-dB bandwidth of 16%. It has a ultra-wide upper stopband up to 10 GHz with high rejection. A performance comparison of the fabricated filter with some reported works is given in Table I.

IV. Conclusion

We have proposed a new microstrip bandpass filter using slow-wave open-loop resonator. It has been shown that the slow-wave effect makes the filter more compact, whereas the dispersion effect results in a ultra-wider upper stopband. We have designed and fabricated a five-pole bandpass filter of this type. The measured results show good agreement with the simulation results, which has verified that this filter has not only very compact size, but also a wider upper stopband performance.

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