A Novel Design of Compact Low-Pass Filter and Its Equivalent Circuit Model

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ABSTRACT

A novel design of compact low-pass filter based on microstrip structure and its equivalent-circuit model are developed. The philosophy of the structure behind this novel microstrip low-pass filter is simple as it is composed of a pair of symmetrical parallel coupled-line and an open-stub. With this configuration, a finite attenuation pole near the stopband cutoff frequency is available and adjustable by simply tuning the circuit parameters. Furthermore, the rejection bandwidth of this type of low-pass filter can be extended. In order to validate the feasibility of the proposed design method, a low-pass filter based on a microstrip structure is designed, fabricated, and measured. Experimental results agree very well with the simulation and analytical results.

1. Introduction

In many communication systems such as mobile and radar systems, the low-pass filters are often employed to suppress harmonics and spurious signals, with the demand for compact size, low insertion loss, and high attenuation. The conventional low-pass filters, such as open-stub low-pass filters and stepped impedance low-pass filters can not meet the requirements for modern communication systems because of their large size and narrow stopband. For sharper cutoff and high attenuation at stopband, the order of the stepped-impedance low-pass filter must be very high [1], [2], thereby the circuit size and insertion loss will be increased. In literature, many design approaches have been proposed to improve the low-pass filter's performances. A compact semi-lumped low-pass filter with broad stopband was proposed in [3]. However, the passband insertion loss is increased and fabrication becomes difficult due to the employed lumped element. The low-pass filters using PBG and DGS structures [4], [5] can improve the skirt characteristics and provide wide and deep stopband as compared with the conventional low-pass filters. A low-pass filter using multiple cascaded hairpin resonators can provide a very sharp cutoff frequency response with low passband insertion loss was demonstrated in [6] and [7], but the design method is a little complicated and just used to synthesize some parts of available prototype low-pass filters.

In this paper, a new compact low-pass filter, which consists of a pair of symmetrical parallel coupled-line and an open-stub based on a microstrip structure, is proposed. The proposed approach demonstrates many attractive features: very simple structure, low passband insertion loss, broad stopband, and sharp skirt characteristics. Its equivalent-circuit model is derived and provides a useful method to design this type of filters and other relative circuits.

2. Equivalent-Circuit Model Analysis

Figure 1 shows the basic layout of the proposed low-pass filter. This low-pass filter consists of an open-stub with a length of lh and a pair of parallel coupled-line with a length of lc. ZS is the characteristic impedance of the open-stub, while Zoe and Zoo represent the even- and odd-mode impedances of the symmetrical parallel coupled-line, respectively.

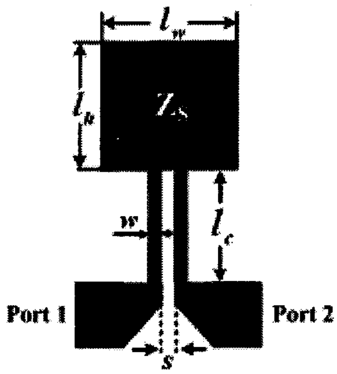
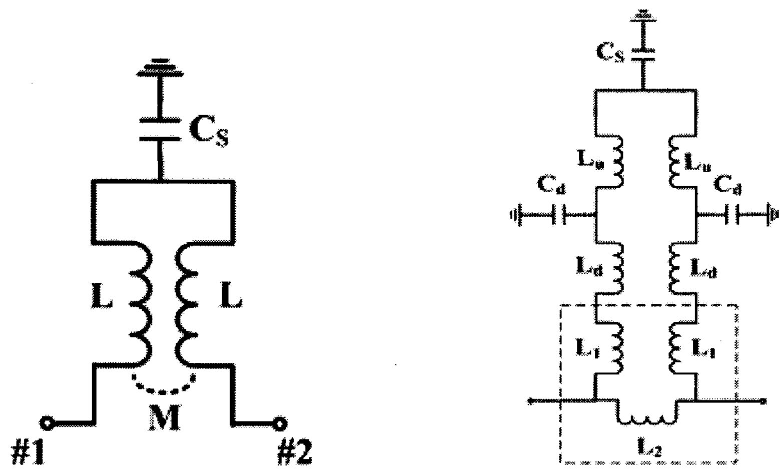


Fig. 1 Structure of the proposed low-pass filter



(a) (b)

Fig. 2 Equivalent circuit of the proposed low-pass filter: (a) General model. (b) Expanded model

We assume that the structure is lossless and the width of the feeding lines is negligible. Under these assumptions, the low-pass filter can be divided into two sections, namely open-stub section and symmetrical parallel coupled-line section with the far end shorted. The open-stub section is modeled as an equivalent capacitor Cs and the symmetrical coupled-line section is modeled as a pair of inductors L with mutual inductance M as depicted in Fig. 2(a). In the proposed low-pass filter structure, the discontinuity between the parallel coupled-line and the open-stub cannot be neglected. The discontinuity modeling is described in Fig. 3 and the elements values can be calculated by Eqs. (1) ~ (4).

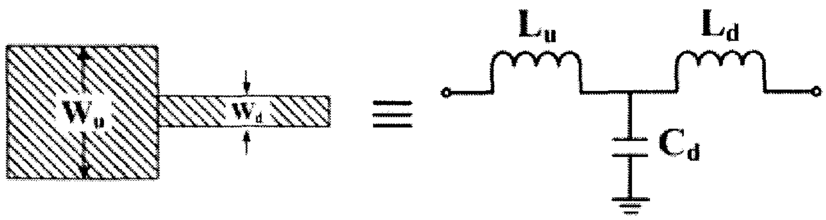


Fig. 3 Equivalent Modeling of the microstrip transmission line discontinuity step

$$L_s = 0.000987h\left(1-\frac{Z_u}{Z_d}\right)^2 \tag{1}$$

$$C_d = 0.00137h\frac{\sqrt{\varepsilon_r}}{Z_u}\left(1-\frac{W_d}{W_u}\right)h\left[\frac{\sqrt{\varepsilon_r}+0.3}{\sqrt{\varepsilon_r}-0.258}\right]\left[\frac{W_u/h+0.264}{W_d/h+0.8}\right] \tag{2}$$

$$L_u = \frac{Z_u\sqrt{\varepsilon_r}}{c}L_s \tag{3}$$

$$L_d = \frac{Z_d\sqrt{\varepsilon_r}}{c}L_s \tag{4}$$

where h and εr represent the thickness and the relative dielectric constant of the microstrip substrate, respectively. c is the velocity of the light, Wu and Wd represent the widths of the corresponding transmission lines as shown in Fig. 3.

The coupled inductors are analyzed as a pi-type network depicted within the dashed lines in Fig. 2(b) [9]. The relevant equivalent inductances are given by Eqs. (5) ~ (8):

$$L = \frac{(Z_{oe}+Z_{oo})\sin\theta}{4\pi f_c} \tag{5}$$

$$M = \frac{(Z_{oe}-Z_{oo})\sin\theta}{4\pi f_c} \tag{6}$$

$$L_1 = L + M \tag{7}$$

$$L_2 = (L^2 - M^2)/M \tag{8}$$

where θ is the electrical length of the microstrip transmission line, fc is the operation frequency.

The proposed low-pass filter is designed at the cutoff frequency of 2 GHz based on a 1.524 mm thickness substrate with relative dielectric constant of εr = 3.5. The dimensions of the low-pass filter are lw = 7.1 mm, lh = 6.0 mm, lc = 5.5 mm, w = 0.36 mm and s = 0.67 mm. All the values of the equivalent circuit elements are L1 = 4.7 nH, L2 = 9.30 nH, Ld = 0.72 nH, Lu = 0.17 nH, Cd = 0.13 pF and Cs = 1.20 pF.

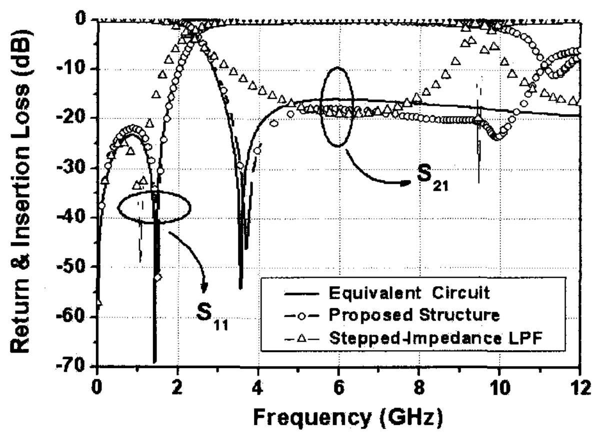


Fig. 4 Simulated performances of the proposed low-pass filter, equivalent-circuit model, and the stepped-impedance low-pass filter

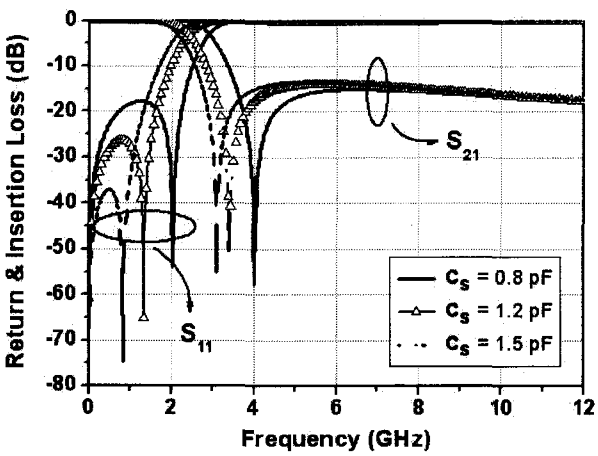


Fig. 5 Low-pass filters with different open-stop length, namely, with different Cs

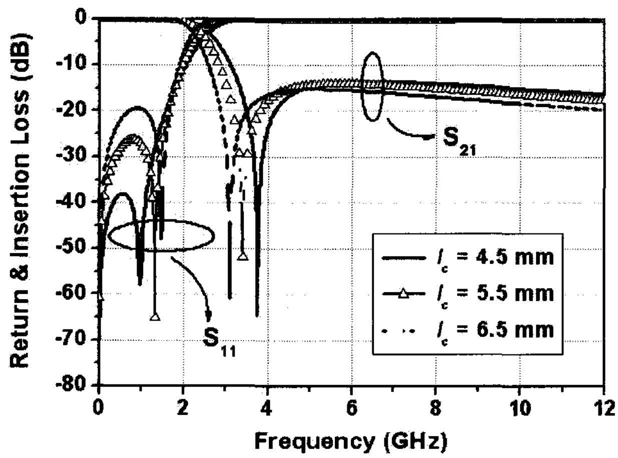


Fig. 6 Low-pass filters with different parallel coupled-line length

As shown in Fig. 4, the simulated results of the proposed microstrip low-pass filter by ADS momentum simulator agree quit well with those of its equivalent circuit. By comparison, the proposed low-pass filter is very much improved on the skirt characteristics than the conventional stepped-impedance one as a finite attenuation pole near the stopband cutoff frequency is available. Furthermore, the finite attenuation pole can be adjusted by simply tuning the electrical parameters of the open-stub and symmetrical parallel coupled line. As illustrated in Fig. 5 and Fig. 6, the attenuation pole shifts to the higher frequency as Cs or the lengths of the parallel coupled-line decreases. Therefore, we can find the optimum values for this kind of low-pass filter design by tuning the circuit electrical parameters.

3. Fabrication and Measurement

In order to validate the proposed design approach, a microstrip low-pass filter under Cs = 1.20 pF is fabricated based on a 1.524 mm thickness Taconic substrate with relative dielectric constants of εr = 3.5. The low-pass filter is measured with Anritsu 37369D network analyzer. A photograph of the fabricated filter is shown in Fig. 7, and the measured results are compared with the simulation study for Cs = 1.20 pF. As shown in Fig. 8, the measured and simulated results agree very well. A finite attenuation pole appears at 3.5 GHz up to 53 dB to improve selectivity characteristic of low-pass filter. The return loss within passband is less than -20 dB from DC to 1.8 GHz. The insertion loss is very low and it is almost less than 0.25 dB from DC to 1.75 GHz. The rejection level within stopband is greater than 20 dB from 3.1 to 9.5 GHz, which is a very broad rejection band.

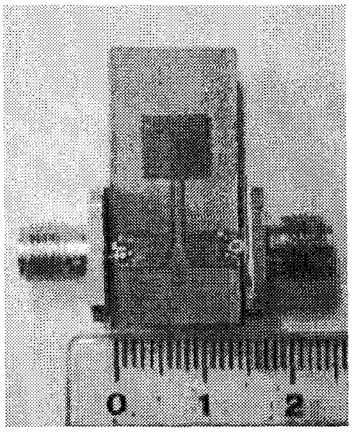


Fig. 7 Photograph of the proposed low-pass filter

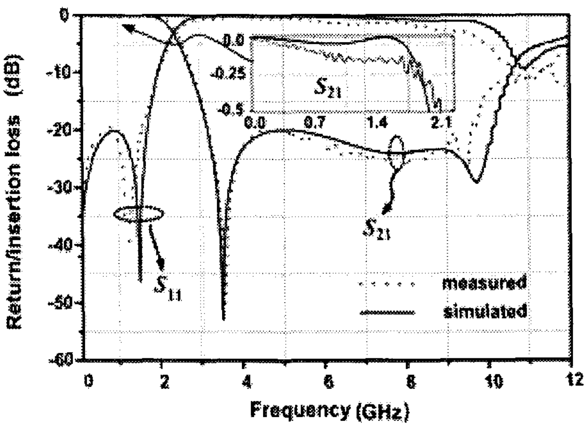


Fig. 8 Measured and simulated frequency responses

4. Conclusion

A new compact low-pass filter with very simple structure and its equivalent-circuit model have been developed in this paper. Based on our observations on simulation performance and measurements, this new type of compact low-pass filter demonstrated many desirable features: low passband insertion loss, sharp skirt characteristics and broad rejection bandwidth. Also, our design can be further extended and used in more high order design process to achieve more sharp skirt characteristics and deeper rejection band. The microwave circuit using this kind of low-pass filter can be applied to marine communication system.

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