Design of Bandpass Filters Using Three Parallel Coupled-Lines with Open Stub Resonator*

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Abstract — Bandpass filter with equal-ripple response in the passband and four transmission zeros in the stopband is synthesized in this letter. Equivalent circuit model is proposed. Based on even- and odd-mode theory, design formulas are derived to provide relationship between filtering characteristics (center frequency, bandwidth, and transmission zeros) and circuit parameters for the filter. To verify the design concept, a bandpass filter with a fractional bandwidth of 26.7% (ripple level 0.01dB) at the center frequency of 3.9 GHz is designed and fabricated. The measured insertion loss is less than 0.6 dB, and return loss is higher than 19.4 dB in the passband. The stopband extends to 10.4 GHz with the rejection level of 20 dB. Measured results show good agreement with simulations.

Key words — Bandpass filter (BPF), Even- and odd-mode, Three parallel coupled-lines.

I. Introduction

Wideband Bandpass filters (BPFs) are essential building blocks for communication systems. Many efforts have been made to develop BPFs, such as two sections of coupled-lines connected with a stub[1]. BPFs using coplanar-waveguide, microstrip to slotline and defected ground are proposed in Refs.[2-4]. However, etching pattern on ground plane can increase the fabrication difficulty and radiation loss. By using interdigital-hairpin[5] and LTCC technology[6], multilayered BPFs are designed with complicated fabrication procedures. A novel double loop dual-mode BPF is proposed in Ref.[7], unfortunately, the return loss is not ideal.

Three parallel coupled-lines are attractive for realizing wideband BPFs with low fabrication tolerance and planar structure[8,9]. Nevertheless, the selectivity of the mentioned BPFs is bad and the stopband is narrow. So an open stub is added to three parallel coupled-lines to improve the performances of selectivity and stopband in this paper. It offers wide bandwidth and four transmission zeros.

In this paper, a synthesis procedure based on equivalent circuit model is proposed, which designs BPFs consisting of three parallel coupled-lines and a resonator. Design formulas are deduced to determine the circuit parameters for BPFs from filtering characteristics. As a result, a BPF is designed and fabricated, which exhibits equal-ripple response in the passband and four transmission zeros in the stopband.

II. Filter Theory and Design

1. Filter theory

Fig.1(a) shows the proposed filter configuration. The coupling between \( l_{inc1} \) and \( l_{inc3} \) is relatively weak, so the effect of it can be neglected in our design and the actual parameters of the filter can be obtained through readjustment. The circuit model of the filter is presented in Fig.1(b). Since the model is symmetrical with respect to the plane \( A - A' \), transfer functions can be derived from Fig.1(c), by using even- and odd-mode theory:

\[
S_{21} = \frac{Z_0(Z_{inc}(\theta) - Z_{ino}(\theta))}{(Z_{inc}(\theta) + Z_0)(Z_{ino}(\theta) + Z_0)} \quad (1)
\]

\[
S_{11} = \frac{Z_{inc}(\theta)Z_{ino}(\theta) - Z_0^2}{(Z_{inc}(\theta) + Z_0)(Z_{ino}(\theta) + Z_0)} \quad (2)
\]

where

\[
Z_{inc}(\theta) = \frac{j(Z_{inc} - Z_0)^2}{2(4Z_a + Z_{inc} + Z_{inc})\cos \theta \sin \theta - \frac{1}{2}(Z_{inc} + Z_{inc})\cot \theta}
\]

\[
Z_{ino}(\theta) = -2\csc \theta Z_{inc}Z_{inc}^2
\]

To exhibit Chebyshev response with ripple constant (\( \varepsilon \)) in the passband, transfer functions can be expressed as:

\[
\begin{align*}
|S_{11}(\theta_c)| &= \varepsilon, \\
|S_{21}(\theta_c)| &= 0
\end{align*}
\]

(3)

where \( \theta_c \) and \( \theta_a \) are electrical lengths at lower cutoff and transmission zero frequencies. Using Eqs.(1) and (2), the transfer function in Eq.(3) can be expanded as:

\[
Z_{inc}(\theta_c)Z_{inc}(\theta_c) - Z_0^2 \pm \varepsilon jZ_0(Z_{inc}(\theta_c) - Z_{inc}(\theta_c)) = 0
\]

\[
\cos^2 \theta_a = \frac{Z_{inc} + Z_{inc}^2}{Z_{inc} + Z_{inc} + 4Z_a}
\]

(4)

(5)

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In order to obtain a unique solution, a variable is introduced:

\[ H_c = Z_{0e} - Z_{0o} \]  \hspace{1cm} (6)

\( H_c \) should be chosen appropriately because too large value of it implies narrow gap between coupled-lines, which results in fabrication difficulty. By solving Eqs.(4)–(6), the following equation can be obtained:

\[
\begin{align*}
q &= -\frac{\cot^2 \theta_e (z_{0e} + z_{0o})^4}{4} + \left[ \frac{H_e^2 (\cos^2 \theta_e + \cos^2 \theta_o)}{4 \sin^2 \theta_e} - z_{0o}^2 \right] \\
\times (z_{0e} + z_{0o})^2 &\pm \frac{2 \epsilon h z_{0e} H_e^2 (\cos^2 \theta_e - \cos^2 \theta_o)}{2 \sin \theta_e \cos \theta_e} (z_{0e} + z_{0o}) \\
- \frac{H_e^4 \cos^2 \theta_e}{4 \sin^2 \theta_e} &= 0
\end{align*}
\]  \hspace{1cm} (7)

Among the parameters \( w_1, l_1, s, w_4, l_4 \) and \( w_2 \), the bandwidth is mainly dependent on \( s \), and the center frequency is significantly affected by \( l_1 \) and \( l_4 \).

2. Filter design

One example is given to design a BPF, which has center frequency at 3.9 GHz, transmission zeros at 2.04 GHz and 5.76 GHz, fractional bandwidth of 26.7% with ripple level \( L_A = 0.01 \)dB. So \( \theta_e \) and \( \theta_o \) are determined as 47° and 78°, \( H_c \) is 203 Ω. According to Eqs.(5)–(7), \( Z_{0e}, Z_{0o}, \) and \( Z_o \) are calculated as 255Ω, 52Ω, and 88Ω respectively.

Then the physical parameters of the BPF can be easily calculated using ADS/Linecalc: \( w_1 = 0.1 \)mm, \( w_4 = 0.4 \)mm, \( l_1 = 12 \)mm, \( l_4 = 11.5 \)mm, \( s = 0.1 \)mm. Fig.3 depicts the responses of the filter with different \( w_2 \). It is observed that the return losses in the passband are \( S_{11} = -27.7 \)dB (\( w_2 = 0.3 \)mm) \( S_{11} = -29.9 \)dB (\( w_2 = 0.2 \)mm) and \( S_{11} = -19.5 \)dB (\( w_2 = 0.1 \)mm) respectively. So the response of filter with \( w_2 = 0.3 \)mm is most close to the specifications.

III. Results and Discussions

The BPF is designed and fabricated on a Rogers RO3003 substrate (\( \varepsilon_r = 3 \), and thickness \( h = 0.508 \)mm). Table 1 summarizes the specifications, simulated and measured results of the filter. Between the feeding line (50Ω) and the three parallel coupled-lines, a short section with triangular shape is inserted to improve the impedance matching.

| Specifications together with simulations and measurements of the filter |
|--------------------------|------------------|------------------|
| Center frequency (GHz)   | 3.9              | 4               | 4               |
| Fractional bandwidth (%) | 26.7             | 26.2            | 24              |
| Transmission zeros (GHz) | 2.04             | 2.05            | 2.08            |
|                           | 5.76             | 5.85            | 5.84            |

Fig.4 presents a photograph of the filter and Fig.5 shows the measured S-parameters together with the EM simulation (ANSOFT HFSS10) results. The measured insertion loss is
less than 0.6 dB, mainly caused by the conductor and dielectric losses, and return loss is higher than 19.4 dB in the passband. There are two transmission zeros with over 50 dB rejection on both sides of the passband, which is benefit for improving the frequency selectivity and out-of-band performance. Furthermore, DC-choke and suppression of harmonic passband are achieved by the existence of transmission zeros at zero frequency and \(2f_0\) frequency (\(f_0\) is center frequency). Indeed, the stopband extends to 10.4 GHz with the rejection level of 20 dB. The first spurious response is at 11.7GHz, which is \(3f_0\).

IV. Conclusion

A synthesis procedure of BPF is proposed in this paper. Design formulas deduced from equivalent circuit model are given, which is useful in determining circuit parameters for the filter. Then a BPF exhibiting equal-ripple response in the passband and four transmission zeros in the stopband is designed and fabricated. Despite the design formulas are for open stub, these formulas can be extended to any resonator. Thus, it provides us with an effective solution in designing this type of BPFs.

References


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