Design of Zigzag Parallel-Coupled Microstrip Bandpass Filter at 500 MHz

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ABSTRACT
Coupled filter design uses the basic knowledge of odd and even wave coupling of transmission lines, which results in odd and even characteristic line impedances. Cascading the parallel coupled-line sections gives rise to bandpass filter structures that are designed easily with the aid of RF circuit simulation packages. This paper shows the design, simulation, and implementation of a 500 MHz zigzag parallel-coupled microstrip filter.

Keywords: wave coupling, coupled-line section, parallel-coupled microstrip filter.

1. INTRODUCTION
In electronics, RF and microwave telecommunication, filters are vital components in a variety of electronic systems. They are used to detect the desired frequency or signal which is called pass-band also to reject the undesired frequency or the stop-band. Filter operates by providing a large attenuation for stop-band frequencies, and a minimum attenuation (ideally zero) for passband frequencies. Filters can be designed using either active devices such as transistors and operational amplifiers or passive devices which are inductors and capacitors. However, at RF and microwave that is relatively high frequency, passive devices are preferable. RF and microwave telecommunication devices such as cordless phones, cellular communication, local area network (LAN), and personal communication systems (PCSs), become an important role in our daily life. The present rate of growth in RF and microwave technology is trended to be raised continuously. Thus, it is interesting to investigate the design of microstrip filter basing on the principal of coupled strip line.

Traditionally, microstrip bandpass filters designed from coupled line have been widely used in many microwave and millimetre-wave systems. This kind of filter is popular since it has a planar structure, a simple synthesis procedure, and good repetition [1]. There are many various designs basing on parallel-coupled line, for instance, cascaded parallel-coupled, zigzag parallel-coupled, hairpin-line, etc. These designs can be determined from the odd and even modes of each coupled section [2] and [3]. Some concepts are used in the design of cascaded parallel-coupled microstrip filter on a dielectric substrate [4]. Conceptually, zigzag filters can be obtained by bending the resonators of the parallel-coupled lines. The field-theoretical study indicates the design and simulation techniques for the microstrip filter with low insertion loss and return loss better than 16 dB [5]. The zigzag parallel-coupled filter is introduced and shown that odd order zigzag filters are more efficient than even order [6]. Since the image impedance of each coupled stage deviates from 50 Ω, the design parameters for the filter have to be modified accordingly. In the experiment, Ansoft Designer SV program is used to design and simulate the parallel-coupled microstrip filters [7].

This paper is organized as follows. Section 2 explores and formulates the basic of coupling microstrip filter. Section 3 shows the design of zigzag parallel-coupled microstrip filter. Section 4 presents the simulated and measured filter responses, Section 5 is a conclusion, Section 6 draws an acknowledgement, and Section 7 shows references.

2. COUPLING MICROSTRIP FILTER
Our works based on the odd and even wave coupling of transmission lines through a common ground plane, which results in odd and even characteristic line impedances. This sets the stage to an understanding of the coupling between two strip lines and their input/output impedances as part of a two-port chain matrix representation. Cascading these elements gives rise to bandpass filter structures that are most easily designed with the aid of RF circuit simulation packages. A simple modelling approach of coupled microstrip line interaction is established when considering the geometry depicted in Fig. 1.

![Fig. 1: A coupled microstrip line](image)

A coupled microstrip line consists of two lines separated over a distance $S$ and attached to a dielectric medium of thickness $d$ and dielectric constant $\varepsilon_r$. The strip lines are $w$ wide, and the thickness is negligible compared with $d$. The capacitive and inductive coupling phenomena between the lines and ground is given in Fig. 2. The even mode voltage $V_e$ and an odd mode voltage $V_o$ in terms of the total voltage at terminals 1 and 2 [2] and [3].
Fig. 2: Equivalent circuit diagram and appropriate voltage and current definitions for a system of two lossless coupled transmission lines

\[ V_e = \frac{1}{2} (V_1 + V_2) \]  

\[ V_o = \frac{1}{2} (V_1 - V_2) \]

The circuit in Fig. 2 can be further described by the characteristic line impedances \( Z_{oe} \) and \( Z_{oo} \) for the even and odd modes which can be defined in terms of even and odd mode capacitances \( C_e, C_o \), and the respective phase velocities, \( v_p \) as follows:

\[ Z_{oe} = \frac{1}{v_p C_e} \]  

\[ Z_{oo} = \frac{1}{v_p C_o} \]

For the bandpass filter section, the geometric arrangement with input and output ports and open-circuit conditions and the corresponding transmission line representation are shown in Fig. 3.

Fig. 3: Bandpass filter element

The input impedance, \( Z_{in} \) responses as a function of the electric length in the range, \( 0 \leq (\beta l) \leq 2\pi \)

\[ Z_{in} = \frac{1}{2\sin(\beta l)} \sqrt{(Z_{in} - Z_{oo})^2 - (Z_{oe} + Z_{oo})^2 \cos^2(\beta l)} \]  

The characteristic bandpass filter performance is obtained when the length is selected to be \( \lambda/2 \) or \( \beta l = \pi/2 \).

3. DESIGN OF ZIGZAG PARALLEL-COUPLED MICROSTRIP FILTER

The first thing to know before starting design microstrip filter is the constant values of the microstrip substrate. In the following designs, DS-7405 with copper clad laminates, that dielectric constant \( (\varepsilon_r) = 4.7 \), copper thickness \( (T) = 0.035 \) mm, tangential losses \( (\tan \delta) = 0.0013 \), and dielectric thickness \( (H) = 1.6 \) mm, is used.

A microstrip filter is made to demonstrate the design of zigzag parallel-coupled bandpass filter with center frequency \( (f_o) \) of 500 MHz. This zigzag parallel-coupled filter is designed and simulated in a simple Ansoft Designer SV program.

As the concept of zigzag parallel-coupled filter is based on bending of the resonators of parallel-coupled lines. Thus, the cascaded parallel-coupled filter is introduced first.

3.1 Cascaded Parallel-Coupled Microstrip Filter

A single bandpass element as discussed before does not result in a good filter performance with steep passband to stopband transitions. However, it is the ability to cascade these bandpass element that results in high-performance filters. Fig. 4 shows a cascaded parallel-coupled or multi-element design.

To design a structure that meets a particular bandpass filter specification, computations have to be performed. The following steps are needed to translate a set of design requirements into a practical filter realization [3].

- Selection of standard low-pass filter coefficients. Depending on whether a Butterworth or Chebyshev design, the standard low-pass filter coefficients \( (g_0, g_1, \ldots, g_{N+1}) \) are used. In this paper, the first-order Butterworth design is chosen. The low-pass filter coefficients are listed in Table 5-2 [2].

- Identification of normalized bandwidth, upper, and lower frequencies. From the desired filter specifications for lower and upper frequencies \( \omega_L, \omega_U \) and the center frequency \( \omega_0 = (\omega_L + \omega_U)/2 \), the normalized bandwidth of the filter is defined as

\[ BW = \frac{\omega_u - \omega_l}{\omega_0} \]  

This factor allows computing the following parameters:

\[ J_{(1)} = \frac{1}{Z_0} \sqrt{\frac{\pi BW}{2g_0 g_1}} \]  

\[ J_{(2)} = \frac{1}{Z_0} \sqrt{\frac{\pi BW}{2g_n g_{n+1}}} \]  

Fig. 4: Multielement configuration of fourth-order parallel-coupled line bandpass filter (N = 4)
\[ J_{j+1} = \frac{1}{Z_0} \frac{\pi BW}{2 \sqrt{S_{j+1}}} \]  
\[ J_{j,N+1} = \frac{1}{Z_0} \frac{\pi BW}{2 \sqrt{S_{j,N+1}}} \]  
which in turn to determine the odd and even characteristic line impedances:

\[ Z_{0o} \big|_{j+1} = Z_0 \left( 1 - Z_0 J_{j+1} + (Z_0 J_{j+1})^2 \right) \]  
(6a)

and

\[ Z_{0e} \big|_{j+1} = Z_0 \left( 1 + Z_0 J_{j+1} + (Z_0 J_{j+1})^2 \right) \]  
(6b)

From (4)-(6), the value of \( Z_{0o} \) and \( Z_{0e} \) of each section are used to calculate the width, length, and space of each coupled line in the Ansoft Designer SV program.

### 3.2 Zigzag Parallel-Coupled Microstrip Filter

The main considerations in the design of the zigzag parallel-coupled microstrip filter are stated as follow [6],

1) The microstrip line width of the zigzag loop resonators is set to be the same everywhere for simplicity of configuration and design of it. 2) Each arm length of the resonator is approximately a quarter of guided wavelength at the frequency of interest. 3) The configurations and lengths of the input and output coupled lines of each resonator are adjusted to obtain enough coupling strength at the operating frequency. 4) The main coupling line (included microstrip bending) between two resonators of the zigzag filter is about a quarter wavelength also.

The zigzag pattern is used to reduce the mechanical length required for a given electrical length as shown in Fig. 5. An empirical method was used to obtain the new coupler layout from the cascaded parallel-coupled design.

**Fig. 5:** Zigzag parallel-coupled filter transformation

Fig. 6a shows the design of first order zigzag parallel-coupled microstrip filter at 500 MHz. A microstrip bending is inserted between two coupled lines. The matching networks are designed to be equal to 50Ω which are used to match with the external 50Ω source. The layout of this designed filter is shown in Fig. 6b.

**Fig. 6a:** Design of 500 MHz zigzag parallel-coupled microstrip filter

**Fig. 6b:** Layout of 500 MHz zigzag parallel-coupled microstrip filter

### 4. SIMULATED AND MEASURED FILTER RESPONSES

A zigzag parallel-coupled bandpass filter is made to simulate and test the design of bandpass filters basing on parallel-coupled line. The fabrication procedure is as follows. First, the DS-7405 with copper clad laminates (\( \varepsilon_r = 4.7, T = 0.035 \text{ mm}, \tan D = 0.0013, \text{ and } H = 1.6 \text{ mm} \)) is used for substrate and ground plane. Next, the centre pins and panel mounts of the subminiature A (SMA) connectors are soldered to the circuit ports and ground plane, respectively. Fig. 7 is the photo of the tested filter.

**Fig. 7:** Photograph of a tested 500 MHz zigzag parallel-coupled filter (filter A in Table I)

A simple Ansoft Designer SV program can perform the simulation of the designed filters well. Anritsu MS4624D Vector Network Measurement System is used
to measure the filter response of a tested filter. The simulation and measured responses are shown in Fig. 8. Table 1 shows the values of centre frequency, passband, insertion loss, and return loss of designed and tested filter.

### Table 1: Simulation and Measured Results of the Fabricated Filter

<table>
<thead>
<tr>
<th>Filter</th>
<th>Order (n)</th>
<th>Simulation</th>
<th>Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Centre frequency, $f_0$ (MHz)</td>
<td>Pass-band (MHz)</td>
</tr>
<tr>
<td>A</td>
<td>1</td>
<td>500</td>
<td>465-539</td>
</tr>
</tbody>
</table>

**Fig. 8a:** Simulation response of 500 MHz zigzag parallel-coupled microstrip filter (filter A)

**Fig. 8b:** Measurement response of 500 MHz zigzag parallel-coupled microstrip filter (filter A).

The measured response of tested filter is not exactly the same as the simulation result, the centre frequency of a tested filter shifted about 20 MHz from what are designed, the insertion loss increased about 1.45 dB and the return loss is reduced by 13 dB. These problems may occur because the substrate used in fabrication is a low-cost material which the constant values, such as $\varepsilon_r$ and $\tan\delta$, can not be guaranteed.

### 5. CONCLUSION

This paper has combined a field-theoretical study on the odd and even modes of parallel-coupled filter and a flexible skill for design of parallel-coupled bandpass filters. The designs are based on a theory of even- and odd-mode of coupled line circuit. A method of designing has been developed for approximately synthesizing parallel-coupled microstrip filters. The simulation and measured results show some differences. This reflects the fact that the material used in microstrip filter design as a substrate pays an important roll on performance of that filter especially the insertion loss, and return loss.

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### 7. REFERENCES