Parallel-Coupled Microstrip Filters with Over-Coupled Stages for Multispurious Suppression

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Abstract — An inherent zero of a microstrip coupled stage near twice the design frequency \(2f_0\) is found tunable by varying its coupling length. This zero is used to suppress the unwanted response of parallel-coupled line filters at this frequency by using over-coupled end stages. The above idea is extended to design over-coupled middle stages for suppressing the spurious \(S_{21}\) peaks at \(3f_0\) and \(4f_0\) of the filter, so that the upper stopband can be greatly enhanced up to \(5f_0\). The passband preserves a response as good as the traditional design. Measured results have a good agreement with simulation data and show that the idea works very well.

Index Terms — Parallel-coupled microstrip filter, over-coupled, spurious response.

I. INTRODUCTION

Parallel-coupled microstrip filters have been widely used for decades in the RF front end of wireless communication systems. This type of filter is popular since it has many advantages. The design method for parallel-coupled microstrip filters has been well documented in [1], [2]. Its passband response can be synthesized to be maximally flat or a Chebyshev function. However, it suffers from the spurious response at the harmonics of the passband frequency \(f_0\) [2], [3]. At even-order harmonics \((2f_0, 4f_0, \text{ etc})\), unwanted responses arise because \(\beta_e\) and \(\beta_o\), the even- and odd-mode phase constants, respectively, of the coupled-line stages are unequal. In particular, the spurious band at \(2f_0\) causes the passband response asymmetric and greatly reduces the upper stopband bandwidth. Such filters on a dielectric substrate with relative high permittivity will exhibit a considerable difference in \(\beta_e\) and \(\beta_o\), and make this problem more seriously.

Many structures have been proposed to tackle the spurious at \(2f_0\). The design concept includes providing different lengths for the even- and odd-modes and equalizing the modal phase velocities. In [3], [4], an over-coupled resonator is proposed to extend phase length for the odd-mode to compensate different in the phase velocities. In [4], over-coupled stages with increased image impedances are employed in filter design to further effectively suppressing the unwanted response. The structures in [5-6] use capacitors to prolong the traveling path of the odd-mode. The corrugation of the coupled microstrip sections in [7], the suspended substrate structure in [8], and the microstrip circuits with an overlay dielectric [9] are designed to achieve equalization of modal phase velocities.

A parallel-coupled microstrip filter also has spurious responses at \(3f_0\), \(5f_0\) and beyond. These peaks occur repeatedly in frequency spectrum due to distributive nature of resonators and coupled stages. So far, only a limited number of papers address on suppression of multispurious response. Recently, based on electro-magnetic band-gap concepts and coupled-mode theory in nonuniform periodic structures, a method is proposed to effectively reject multiple spurious passbands by employing different periods in which each coupled-line section tuned to the different bands to be rejected [10]. Obviously, the nonuniform structure will have long simulation time due to fine discretization.

In this paper, the approaches in [4] are extended for multi-spurious suppression. The end stages are designed to have over-couplings for tackling the spurious response at \(2f_0\), and the middle stages are designed to locate transmission zeros at \(3f_0\) and \(4f_0\), so that the upper stopband can be extended. The whole filter can be achieved by cascading the coupled stages. In the following, Sec. II explains the technical background of the idea, Sec. III addresses the consideration of entire filter design using the over-couplings, Sec. IV demonstrates the measured responses in comparison with the simulated predictions, and Sec. V draws the conclusion.

II. TRANSMISSION ZERO OF AN OVER-COUPLED STAGE

A. Design at \(2f_0\)

For the coupled-line stage shown in Fig. 1, through derivation of its two-port \(Z\) parameters and enforcing \(Z_{21} = 0\) or \(S_{21} = 0\), it can be shown [3] that a transmission zero can be determined by

\[
\frac{Z_{oo}}{Z_{oe}} = \frac{\sin \beta_e \ell}{\sin \beta_o \ell} = 0
\]

(1)

where \(Z_{oo}\) and \(Z_{oe}\) are the characteristic impedances of the odd- and even-modes, respectively. Referring to the coupled stage in Fig.1, it can be seen from (1) that the inherent transmission zeros can be tuned by simply varying the coupling length \(\ell = L + L_{ov}\.\)
Suppose we are designing circuits on a substrate with \( \varepsilon_r = 10.2 \) and thickness \( h = 1.27 \text{ mm} \). Such a high dielectric substrate is purposely chosen to demonstrate performance of our approach. Fig.2(a) examines the frequency responses of an over-coupled stage near \( 2f_o \) with different over-coupling lengths \( L_{ov} \). The length \( L = \lambda_o/4 \) is chosen based on geometric mean of \( \beta_e \) and \( \beta_r \) at the design frequency \( f_s \). As indicated in Fig.2(a), frequency of the zero decreases as the coupling length is increased. For the particular structure, if the zero is tuned at \( 2f_o \), \( L_{ov} = 0.3L \) will be required. The simulation data are obtained by using the full-wave software package IE3D [11]. In this example, the line width \( W = 1.2 \text{ mm} \) and gap size \( S = 0.6 \text{ mm} \). The structure at \( 2f_o \) has \( Z_{oc} = 60.88 \Omega, Z_{oo} = 37.00 \Omega, \beta/k = 2.79, \) and \( \beta/k = 2.44, \) where \( k \) is the wave number in free space. These values can be used to validate (1).

**B. Design at 3\( f_o \) and 4\( f_o \)**

The transmission zeros can also be tuned at \( 3f_o \) and \( 4f_o \) by making \( L = \lambda_o/6 \) and \( L = \lambda_o/8 \), respectively, and adjusting the over-coupling length \( L_{ov} \). The results are shown in Fig.2(b) and Fig.2(c). It is found that, although the microstrip structure is dispersive, the zeros at \( 3f_o \) and \( 4f_o \) can be accurately obtained by directly scaling down \( L \) and \( L_{ov} \), i.e., \( L_{ov} = 0.3 \times L \) for \( L = \lambda_o/6 \) or \( L = \lambda_o/8 \) for the particular structure. Note that when \( L_{ov} \) is added the coupling levels at \( f_o \) are increased.

**C. The Design Data**

For tuning the zeros, required \( L_{ov}/L \) values depend not only on structure parameters of the coupled microstrip but also on the target tuning frequency. This can be seen from (1) that values of dispersive \( Z_{oc}, Z_{oo}, \beta_e \) and \( \beta_r \) are functions of \( W \) and \( S \). Fig.3(a), Fig.3(b) and Fig.3(c) plot the design data of \( L_{ov}/L \) of a coupled stage for tuning the zeros at \( 2f_o, 3f_o, \) and \( 4f_o \) respectively, for the chosen substrate. It can be seen from the plots that at a given strip width the required \( L_{ov}/L \) value increases as \( S/h \) is increased. When \( W/h = S/h = 0.1 \), the \( L_{ov}/L \) ratios are only 5%, 7% and 9% for \( 2f_o, 3f_o, \) and \( 4f_o \) cases, respectively. If \( W/h \) is kept small, \( L_{ov}/L \) can be as large as 0.4 when \( S/h = 2.0 \). With \( W/h = 2.0 \) and \( S/h = 0.1 \), the required \( L_{ov} \) values are about a quarter of \( L \) as indicated in the three plots. Given \( S/h = 2.0 \), the required \( L_{ov}/L \) values decrease from 40% at \( W/h = 0.25 \) approximately linearly to 35% at \( W/h = 2.0 \) for tuning zero at \( 4f_o \).

**III. FILTER DESIGN**

In filter design, proper couplings at \( f_o \) between adjacent coupled stages should be determined by bandwidth and element values of the low-pass filter prototype. The line width \( W \) and spacing \( S \) of each stage are determined by \( Z_{oc} \) and \( Z_{oo} \) which depend on inverter value of each stage [1]. When a coupling length is tuning around \( L = \lambda_o/6 \) or \( \lambda_o/8 \), however, the coupling at \( f_o \) deviates from that is anticipated for the quarter-wave case. One can expect that the coupling levels for
$L = \lambda_o/6$ or $\lambda_o/8$ at $f_o$ will be lower than that for $L = \lambda_o/4$. The couplings then must be enhanced by narrowing the $W$ and $S$ sizes. The new values of $W$ and $S$ can be determined as follows. It can be derived [1] that coupling coefficient of a coupled stage with coupling length $\theta$ can be determined by

$$C = C_o \sin \theta$$

(2)

where $C_o$ is the coupling coefficient of the coupled stage with $\theta = 90^\circ$. For example, when a coupled stage requires a coupling coefficient $C$ and is tuned to have a zero at $3f_o$, $\theta = 60^\circ$ ($L = \lambda_o/6$) will be used. The values of $Z_{oc}$ and $Z_{ow}$ should then be chosen by a new coupling coefficient $C_o = C/\sin 60^\circ$. In this way, the fundamental passband response can be preserved when the coupled stages have over-couplings at the same time for suppressing the unwanted responses.

IV. FILTER DESIGN AND MEASUREMENTS

We begin with the traditional design method given in [1]. In a fifth-order parallel-coupled filter, there are six coupled stages. Fig.4 shows the circuit layout. Two circuits are designed and measured on the RT/Duroid 6010 microwave laminate, and their end stages are tuned to suppress the spurious passband at high frequency. Photo of the circuit is shown in Fig. 5(b). In the second circuit, stages 2 and 5 are adjusted for locating a zero at $3f_o$ and the two center stages are trimmed for $4f_o$. The design specifications of the passband are identical to those of the previous one. Fig. 6 compares the measured responses with simulation results. The measured $|S_{21}|$ and $|S_{11}|$ curves show a good agreement with the simulations. In the passband, the best insertion loss is -1.4dB and the best return loss is better than -30 dB. The upper stopband is extended up to 9 GHz where the spurious at $5f_o$ arises. The performance of the measured spurious responses at $2f_o$, $3f_o$ and $4f_o$ are better than -32 dB. In comparison of the high-performance rejections of the two filters in upper stopband, the proposed method is quite flexible, i.e., the target zero can be easily tuned using individual coupled stages.

Fig. 3. Required $L_{ov}/L$ values for tuning the zeros at (a) $2f_o$ with $L = \lambda_o/4$ (b) $3f_o$ with $L = \lambda_o/6$ and (c) $4f_o$ with $L = \lambda_o/8$. The substrate of the coupled microstrip lines has $\varepsilon_r = 10.2$ and thickness = 1.27 mm.
Fig. 4. Layout of a fifth-order parallel-coupled microstrip filter designed with over-coupled stages.

![Image of filter layout](image)

Fig. 5. (a) Measured and simulation responses of the first experimental filter. (b) Photo of the fabricated circuit. The substrate has $\varepsilon_r = 10.2$ and thickness = 1.27 mm.

![Image of measured and simulated responses](image)

Fig. 6. Measured and simulation responses of the second experimental filter. The substrate has $\varepsilon_r = 10.2$ and thickness = 1.27 mm.

V. CONCLUSION

A design technique is demonstrated for multispurious suppression in parallel-coupled microstrip filters based on over-coupled stages. Varying the coupling length of a coupled stage can finely tune zeros at $2f_o$, $3f_o$ and $4f_o$ for suppressing the spurious responses at these frequencies. For various $W/h$ and $S/h$ ratios, design data for tuning transmission zeros of a coupled stage at $2f_o$, $3f_o$, and $4f_o$ are presented. Detailed procedure for filter synthesis incorporating with over-coupled stages is reported. The measurements show that suppression of the unwanted responses achieves a level better than 30dB.

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