Design of Compact Bandpass Filter Using Transformer-Based Coupled Resonators on Integrated Passive Device Glass Substrate

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Abstract — This paper presents a transformer-based coupled resonator structure for a bandpass filter (BPF) using the integrated passive device technology on a glass substrate. The use of such a transformer-based coupled BPF not only provides the advantage of compact size but also creates extra transmission zeros to enhance the roll-off rate or the desired stopband rejection. The measured results verify the validity of this design methodology and show good agreement with the simulated results. For demonstration purposes, two example filters are designed and implemented. Both good performance and miniaturization are achieved for the proposed filters, and the expected transmission zeros are observed.

Index Terms — Bandpass filter, transformer-based resonators, integrated passive device, transmission zeros.

I. INTRODUCTION

Wireless communications has expanded rapidly in the recent years, as evidenced by the increasing demand for high-performance, low-cost, and compact wireless front-end devices. A bandpass filter is commonly used in a wireless front-end to prevent the interference of RF signals. In the past, considerable research work was conducted, and various design approaches were proposed. Among them, two methods are popular. One of the methods to achieve a bandpass operation is to employ a transmission-line structure, and the other involves the use of lumped LC-type structures adapting to the filter design. Most miniaturized bandpass filters extensively reported in the literature to date are based primarily on the transmission-line structure [1–3]. Filters based on the transmission-line element have encountered difficulty with respect to size-reduction because of the fact that their sizes are in multiples of the quarter-wavelength. Some other studies propose novel structures to reduce the filter size, including stepped impedance resonators (SIRs) [4], defected ground structure (DGS) resonators [5], dual-mode ring resonators [6], and spiral-like resonators [7]. However, the resulting designs are complex and not flexible. On the other hand, the experimental responses of lumped LC-type BPFs cannot match the desired prototype responses because of the distributed parasitic and coupling effects, deviating from their ideal behavior [8]. Furthermore, the LC-type bandpass filter has difficulty in further reducing its size because of the considerable number of element requirements.

In this paper, a novel compact bandpass filter design using the transformer-based coupled resonators, which is compatible with direct feeding structures in I/O ports, is proposed and investigated. The bandpass filter features coupled resonators with magnetic-dominant coupling coefficients. The proposed design technique can realize a compact BPF by precisely calculating the required mutual inductance to couple the primary and secondary coils where each coil resonates with a small capacitor. By appropriately controlling the coupling strength at the transformer, the desirable coupling coefficients at the passband can be obtained, and hence, the filter bandwidth can be easily controlled. In addition, the design skillfully applies parasitic mutual capacitances and modified a parallel resonator to create transmission zeros for enhancing the stopband rejection ratio. On the basis of this concept, two BPFs operating at 2.1 GHz for 3G mobile wireless communication applications are designed and fabricated using the glass-based substrate integrated passive device (IPD) technology with a three-layer metal and polyimide dielectric layer, as shown in Fig. 1. Three layers of plated Cu with thicknesses of 1 μm, 10 μm, and 6 μm were used as metal 1, metal 2, and metal 3, respectively, for the fabrication of the capacitors and transformers used in the filter circuits. Because of the fact that IPDs are generally fabricated using standard wafer technologies such as thin-film and photolithography processing, they can be manufactured at a low cost and with a small size and excellent RF properties [9].

The design methodology and experimental results are presented in the following sections, the proposed filter can easily achieve high performance, with a simple structure and a very compact size.

Transformer MIM capacitor

Glass substrate

metal 1 metal 2 metal 3

Fig. 1. Cross-section of a glass-based substrate IPD technology process.
II. TRANSFORMER-BASED COUPLED RESONATOR FILTER DESIGN

Fig. 2 shows the equivalent circuit of the synchronously tuned coupled resonators with magnetic coupling. A coupled resonator is a basic component and particularly used for controlling the center frequency in the filter design; in addition, a simple resonator often consists of an inductor and a capacitor in parallel, as shown in Fig. 2(a). In addition to the filter size reduction, considerable effort has been made to introduce transmission zeros to improve the filter selectivity and the stopband rejection at the desired frequencies. In particular, a modified parallel LC resonator shown in Fig. 2(b) is proposed and utilized for generating transmission zeros in the bandpass filter design. With the assistance of the proposed resonator, compact bandpass filters with extra transmission zeros can be achieved easily. According to Fig. 2, two types of the proposed transformer-based coupled BPF, denoted as type-I and type-II BPF, are designed by employing conventional and modified parallel LC resonators, respectively. Fig. 3 shows the configuration of the proposed second-order bandpass filters utilizing the transformer-based coupled resonators. Fig. 3(a) illustrates the configuration of the proposed type-I filter, composed of one transformer and two capacitors. Fig. 3(b) shows the schematic representation of the proposed type-II filter. The type-II filter contains one transformer and four grounded capacitors. The designed transformer has a rectangular shape with the two parallel coils that are symmetrically interwound side-by-side on metal 2; further, it has integrated capacitors that consist of two parallel conductor plates (metal 1 and metal 2) separated by a dielectric polyimide material.

For the synthesis of the transformer-based coupled bandpass filter, the two most important parameters for designing a coupled resonator bandpass filter are the coupling coefficient \( k \) between two resonators and the external quality factor \( Q_e \) [10]. The coupling coefficient mainly depends on the spacing of the interwound turns of the coils in the transformer; the parameters of the transformer, such as the primary inductance \( L \) and the mutual inductance \( M \), as shown in Fig. 2, can be extracted by using the equivalent circuit in [11]. The external quality factor of a single coil-type resonator can be evaluated as a function of the tapped feed position. It is often derived in terms of the normalized input admittance \( (\gamma_m) \) and the group delay \( (\tau) \) with respect to the reflection coefficient at the resonant angular frequency \( \omega_0 \). In order to determine the coil turn spacing and the tapped feed position, one can use the relations of the \( k \) and \( Q_e \) to the second-order filter prototype elements. These relations are given as

\[
\begin{align*}
    k &= \frac{\Delta}{\sqrt{g_1 g_2}} = \frac{M}{L} \\
    Q_e &= \frac{g_0 g_1}{\Delta} = \frac{g_0 g_1}{\Delta} = \frac{\omega_0 \tau_1}{4} \left[ 1 - y_m^2 (\omega_0) \right]
\end{align*}
\]

where \( \Delta \) is the fractional bandwidth and \( g_i \) is the \( i \)th prototype element value. For a Chebyshev bandpass filter design, the passband insertion loss can be further predicted by the formula given in [12] and shown as

\[
IL_{\omega_0} = 4.343 \left( \frac{\omega_0}{\Delta \omega_0} \right) \left( g_1 + g_2 \right)
\]

where \( Q_u \) denotes the unloaded quality factor of a coil-type single resonator at the resonant frequency.

Fig. 4 demonstrates the lumped-element equivalent-circuit model for the proposed second-order filter using the transformer-based coupled resonators illustrated in Fig. 2. The resonant circuit of the type-I and type-II filters includes a primary coil inductance \( (L_a, L_b) \) resonated with the
capacitance $C_i$ and the primary inductance $(L_{i1}, L_{i2})$ resonated with the pair of capacitors of the capacitance $C_{c1}$ and $C_{c2}$, respectively. The magnetic couplings between the two interwound coils of the coupled-resonator pair of the type-I and type-II filters are denoted by the mutual inductance $M_i$ and $M_r$, respectively. The model uses $C_i$ and $C_2$ between two resonant circuits of the type-I and type-II filters to represent the parasitic capacitive coupling of the two interwound coils. It is noted in Fig. 3 that the extension lines labeled with port 1 and port 2 intersected with the interconnect of the coil inductor of $L_{i1}$ and $L_{i2}$, and $L_{r1}$ and $L_{r2}$, indicate the input and output tapped feed positions for the type-I and type-II filters, respectively. Fig. 5 depicts the magnitude $S_{11}$, response of the equivalent circuit for the type-I and type-II BPFs. It can be found that the transmission zero $f_1$ of the type-I filter located at the upper stopband, as shown in Fig. 5(a), was created near the passband and the upper stopband rejection increased significantly. However, two transmission zeros ($f_{1a}$ and $f_{2a}$) of the type-II filter, as indicated in Fig. 5(b), can be obtained at the lower and the upper stopbands, respectively, by using of the modified LC resonator shown in Fig. 1(b).

![Fig. 4. Equivalent circuits of the transformer-based coupled bandpass filter. (a) Type-I. (b) Type-II.](image)

In order to investigate and demonstrate the validity of the proposed structure, two BPFs, denoted as the type-I filter and the type-II filter, are implemented on a glass substrate with a relative dielectric constant of 4.6 and a thickness of 700 μm. The type-I bandpass filter with a fractional bandwidth of 12% and the unload quality factor of 26 and the type-II bandpass filter with a fractional bandwidth of 26% and the unload quality factor of 20 are designed at the center frequency of 2.1 GHz for 3G mobile communication applications. The prototype element values of a second-order 0.1 dB equal-ripple filter are $g_u=1$, $g_i=0.843$, $g_c=0.622$, and $g_r=1.3554$. The insertion loss of the type-I and type-II BPFs at the center frequency that can be evaluated by (3) is 2 and 1.2 dB, respectively. In order to obtain the physical dimensions of the filter, the coupling coefficient and the quality factor can be estimated as $k=0.17$ and $Q_e=7.03$ for the type-I bandpass filter design and $k=0.36$ and $Q_e=3.24$ for the type-II bandpass filter design. Hence, the overall design procedure for the filter can be summarized as follows: First, determine the dimension of the transformer-based coupled resonator to meet the center frequency and the bandwidth of the filter, and then, select the feeding position of the resonator from Fig. 3(a) and Fig. 3(b) to meet the specific $Q_e$. Realizable design geometric parameters have been obtained from the layout, as in Fig. 3(a) and Fig. 3(b), that a coil turn spacing of $S_2=20$ μm and a tapped feed position of $P_2=240$ μm for the type-I BPF and $S_2=35$ μm and $P_2=320$ μm for the type-II BPF, respectively. On the basis of the design guide described above, the other dimensional parameters (units: μm) of the fabricated filters are chosen as follows: $W_{i1}=30$, $D_{i1}=300$, $L_{i1}=450$, $W_{i2}=35$, $D_{i2}=200$, $L_{i2}=450$. Therefore, for the dimensions of the type-I filter shown in Fig. 3(a), the corresponding element values of the equivalent-circuit model are $L_{i1}=2.1$ nH, $L_{i2}=1.1$ nH, $C_1=1.2$ pF, $M_i=0.8$ nH, and $C_{c1}=0.8$ pF. For the dimensions of the type-II filter shown in Fig. 3(b), the corresponding element values of the equivalent-circuit model are $L_{i1}=6.85$ nH, $L_{i2}=0.5$ nH, $C_{c1}=1.2$ pF, $C_{c2}=1.2$ pF, $M_i=1.55$ nH, and $C_{c2}=0.025$ pF.

![Fig. 5. Magnitude of $S_{11}$ of the equivalent circuits for the transformer-based coupled bandpass filters. (a) Type-I. (b) Type-II.](image)

### III. RESULT AND DISCUSSION

In order to verify the above-mentioned designs, two filters were designed and simulated by an EM simulator, ANSYS Ansoft HFSS. Fig. 6 illustrates and compares the measured results and the EM simulation of the proposed transformer-based coupled BPFs in the frequency range of 0.1 to 10 GHz. There are some slight discrepancies between the simulated and the measured results, which are primarily due to the fabrication tolerance. Nevertheless, the measured results of the fabricated bandpass filters agree well with the responses of the simulated design. From Fig. 6(a), the measured insertion loss of the type-I BPF in the passband from 1.9 to 2.2 GHz is approximately 2.2 dB, which has a deviation of 0.2 dB from the predicted value, and the return loss in the passband is larger than 18 dB. In addition, it can be obviously observed as expected that there is one extra transmission zero located at 2.9 GHz in the upper stopband. It leads to a stopband rejection level of more than 25 dB in the frequency range 2.8–8 GHz. In the case of the type-II BPF operation, the measured insertion loss and the return loss within the passband shown in Fig. 6(b) are less than 1.5 dB and more than 15 dB, respectively. Although the measured insertion loss is greater than the predicted value, the measurement still shows considerably good correspondence with the simulation. As a result, two transmission zeros of the type-II BPF are generated near the passband edges, which provide a satisfactory rejection level in the stopband and considerably
improved passband selectivity. One of the extra transmission zeros was observed at approximately 0.85 GHz and the other is at 4.2 GHz. As can be seen, the lower and the upper stopband rejections of the type-II filter are better than 28 dB in the frequency range of 0.1 to 1 GHz and 35 dB in the frequency range of 3.7 to 10 GHz, respectively. This implies that the proposed filter not only possesses high selectivity but also has a wide upper stopband. The occupied areas of the designed type-I and type-II filters excluding the outer common ground ring and test pads are $1.7 \times 0.8 \text{ mm}^2$ and $1.6 \times 0.8 \text{ mm}^2$, respectively.

![Type-I](image1)

**Fig. 6.** Measured and simulated results of the proposed BPFs. (a) Type-I. (b) Type-II.

IV. CONCLUSION

In this paper, we proposed compact bandpass filters using novel transformer-based coupled resonators. Based on two different types of transformer-based coupled resonators, a bandpass filter was designed and fabricated using the glass IPD technology. With the assistance of transformer-based resonators, filters with a controllable bandwidth, a compact size, and multiple transmission zeros could be easily achieved. In addition, the proposed filter exhibited a sharp rejection slope and a very wide stopband at the desired frequencies. The measured results were in agreement with the simulated ones. Based on the above-mentioned principle, the proposed bandpass filter is compact, simple, and attractive for 3G mobile communication applications.

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REFERENCES


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