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by

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High Rejection BPF for WiMAX Applications from Silicon Integrated Passive Device Technology

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Abstract — We have developed a balanced band-pass filter using Silicon Integrated Passive Device (IPD) technology. The size of the filter is 2.0 x 1.3 x 0.4 mm$^3$, which is by far the smallest filter achieving similar characteristics, to the best of our knowledge. A hybrid EM-circuit optimization scheme has been adopted for the design. Prototypes are made and measured. Good agreement has been achieved between simulated results and probed data. The measured insertion loss is 2.3 dB, the attenuation at 2.1 GHz is 24 dB minimum, and the attenuations at 2$^{nd}$ and 3$^{rd}$ harmonics are better than 35 dB. This small form-factor WiMAX filter is well suited for SiP applications to replace discrete filters, or to save large areas used to implement such filtering functions on boards.

Index Terms — WiMAX, filter, balun, Integrated Passive Device, System in Package.

I. INTRODUCTION

In a communication system, along with transceivers, ASICs, RF switches, and others, filtering devices are key components for wireless operation. In transmitter channels, filters help to minimize unwanted signal harmonics to meet FCC compliance. In receiver channels, they are used to block unwanted interference and improve signal’s selectivity. In a cellular-WiMAX co-existence environment especially, filtering functions are necessary for a WiMAX system to work properly.

There have been products incorporating individual filters and baluns for RF applications. Most of them are transmission-line types. The limitation of circuits using transmission-line topology is that their sizes are multiples of quarter-wavelength. For most wireless applications, such as for cellular phone, WiFi, and WiMAX, in which the RF frequencies are lower than 6.0 GHz, lumped LC type circuits still provide a dominant advantage from a size perspective.

To date, in most applications, WiMAX or WiFi filters have been implemented on printed circuit boards [1-2]. The good electrical properties of PCB materials enable this type of BPF widely used in many RF applications. There are also discrete filters (mainly from LTCC technology) for these RF applications. Because of their size and thickness, these LTCC filters are most often used outside packages or modules and are implemented on system boards. However, as the markets for mobile devices demand solutions in low cost, small form-factor, and high performance, there is a need for developing lower profile, smaller size WiMAX filters, which can be integrated inside a package/module using System-in-Package (SiP) concepts [4-5].

SAW/BAW filters are good candidates for such co-existence applications, due to their high rejection and narrow band properties. However, SAW/BAW chips are sensitive to package environments, and it is very difficult to implement SAW/BAW bare dies as regular CMOS chips in a package for assembly. The existing solution is using them in package forms specially developed.

In this paper, a WiMAX filter chip working in the 2.46 GHz to 2.69 GHz band with small form-factor, low profile, is developed using silicon-based integrated passive device (IPD) technology. Design procedure, electrical performance, and comparison between simulation and measurement are discussed in detail in the following sections.

II. DESIGN APPROACH

The filter’s circuit topology [6] was selected as shown in Fig. 1, according to a customer’s specifications. Strong attenuations, at WCDMA band (around 2100 MHz) and cellular phone bands (900 MHz and 1900 MHz), are required for this filter in order to co-exist with these other applications. Certain attenuations at the 2$^{nd}$ and 3$^{rd}$ harmonics (better than 35.0 dB) are also required to
are also required to meet compliance requirements.

In the topology, there are three LC resonators with magnetic coupling. The coupling between the coils is weak, and the coupling coefficients are typically less than 0.2, which is significantly lower than a regular balun topology. However, this topology gives excellent balance property with the last resonator center-tapped.

**Table I. LC Values for the Filter Components (in pF or nH) and Coupling Coefficients**

<table>
<thead>
<tr>
<th>$L_A$</th>
<th>$L_B$</th>
<th>$L_C$</th>
<th>$C_A$</th>
<th>$C_B$</th>
<th>$C_C$</th>
<th>$k_{AB}$</th>
<th>$k_{BC}$</th>
<th>$k_{AC}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.46</td>
<td>2.6</td>
<td>1.1</td>
<td>8.5</td>
<td>1.7</td>
<td>3.6</td>
<td>0.13</td>
<td>0.13</td>
<td>-0.04</td>
</tr>
</tbody>
</table>

Given reasonable Q-factors for the inductors and the capacitors used in the filter, an electrical response from the circuit model may predict the actual filter’s behavior (Fig. 2) to a large extent. The component values and the coupling coefficients between coils for the balanced BPF are listed in Table I. The component layout is based on these values.

First, a layout without co-planar ground was generated according to the L, C and k values. To characterize this device, a co-planar ground is then added to facilitate subsequent G-S-G probing measurement. The layout without co-planar ground has a simulated response similar to the ideal schematic circuit. However, after adding a co-planar ground, the response is altered significantly, as shown in Fig. 4.

For this balanced BPF, the center-tap at the output coil is a virtual ground, with no current flowing on it in differential-mode operation. At the single-end side (input), the ground return current flows only within its local area. The main reason

**Fig. 2.** Ideal circuit response.

**Fig. 3.** Initial layout. Top: without co-planar ground. Bottom: with co-planar ground.

**Fig. 4.** Electromagnetic (EM) response from the layout in Fig. 3. Solid: without co-planar ground. Triangle: with co-plane ground.

**Fig. 5.** EM response with distance change (d1) between coils A and B.
a co-planar ground structure which is close to the inductor coils.

There are three coils in this design. The outermost coil (the largest one) is impacted most by the co-planar ground structure, and should be adjusted accordingly. The proximity effect reduces this coil’s inductance, so it is necessary to enlarge the coil. The two inner coils (smaller ones) are only weakly impacted, as they are relatively farther from the co-planar ground structure.

The response from an initial/preliminary layout with the co-planar ground does not agree with the ideal circuit’s response expected from the schematic, due to parasitic, coupling and added trace interconnection. Blindly tuning the layout is nearly impossible from an EM simulation point of view. We have found some performance trends of the device under different circumstances, and they were used efficiently in the fine tuning stage to meet the electrical specifications.

In the fine-tuning stage for the IPD, the coupling strength between coils is the major factor altering its performance. As can be seen in Fig. 5, as the distance ‘d1’ increases, the coupling between coils A and B reduces, resulting in a narrower pass-band response, particularly at the high frequency edge of the response. The input return loss is also especially sensitive to his parameter.

As the distance ‘d2’ between coils A and C decreases, the coupling between these two coils increases, and the attenuation pole at the lower side of the pass-band moves to high frequency. This also results in a narrower bandwidth, with better rejection at 2.1 GHz (Fig. 6).

When the distance ‘d3’ between coils B and C changes, the response is not affected as strongly (Fig. 7). However, for good return loss at both input and output it is generally desirable for the coupling coefficient between coils B and C to match the coupling between A and C.

We have adopted a hybrid EM-circuit optimization scheme in all our IPD design. Detail of the optimization method can be found in [3]. For the design of this WiMAX filter, it took less than one week from a circuit concept to the final layout whose response meets the specifications.

III. MEASUREMENT AND COMPARISON

The designed IPD was manufactured in STATS ChipPAC IPD process. A micrograph of the device is shown in Fig. 8. There are probing pads added for probe measurement (G-S-G probes with 150 µm pitch). Short interconnection is added for the G-S-G transition. For a direct comparison, these transitions are also included in EM simulation.

Fig. 9 shows the response uniformity of the IPDs located at different sides on a wafer. Responses from three IPDs are plotted together in this figure. At the 2.1 GHz where it has very sharp attenuation response, the rejection range is from -24.0 dB to -33.0 dB, resulting in 9.0 dB variation. In other words, to meet the rejection requirement, a design should have at least 9.0 dB rejection.
9.0 dB margin at this frequency.
In the pass band, the insertion-loss variation from the same
design is about 0.3 dB, which is pretty acceptable for this
application. The frequency shift due to the wafer process is about
2.6%, which is well with the variation specification 3.5%.
In Fig. 10, the data from measurement is plotted together with
the simulation data. The simulation can be seen to be in very
good agreement with the measurement data. From the
measurement data, the insertion loss is 2.3 dB, and the attenua-
tion at 2.1 dB is 24 dB minimum. Meanwhile, the IPD also has
good attenuations at cellular bands (larger than 30 dB attenua-
tion).

The fabricated IPD has excellent balance properties. The
measured amplitude-imbalance is better than 0.1 dB, and the
measured phase-imbalance is better than 1.0 degree, with re-
spect to 180 degree.

IV. CONCLUSION
Integrated passive device technology through silicon process
has very tight tolerance, and is a very promising technology in
terms of electrical performance, repeatability, and size. We have
described a filter implemented in this technology using
magnetically-coupled resonator architecture. The size of the
balanced BPF (with high rejection) is 2.0 x 1.3 x 0.4 mm$^3$. To
the best of our knowledge, the IPD is the smallest one with
similar functionality. This small from-factor filter may be used
very efficiently in SiP applications.

ACKNOWLEDGEMENT
The authors thank YinYen Bong, Yaojian Lin, Hin Hwa Goh,
Phoo Hlaing, and Badakere Guruprasad for their contributions
in the manufacturing, assembly, and measurement of the IPD.

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