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A Study of Dual-Mode Bandpass Filter Integrated in BGA Package for Single-Chip RF Transceivers

Y. P. Zhang, X. J. Li, and T. Y. Phang

Abstract—This paper presents a study of a dual-mode bandpass filter integrated in a ball grid array (BGA) package for the single-chip solutions of radio frequency (RF) transceivers. The novel in-package filter, except for the economical advantage of mass production and automatic assembly, has potential benefit to the system-level board miniaturization and the system-level manufacturing facilitation. The simulated and measured performance of the in-package filter is presented. The effects of the different physical parts of the package on the filter performance are investigated. Experimental results show that the in-package filter of size $15 \times 15 \times 1.905 \text{ mm}^3$ achieved 3-dB percentage bandwidth of 14% and insertion loss of 2.07 dB at 5.25 GHz.

Index Terms—Ball grid array (BGA) packages, RF bandpass filters, single-chip radio frequency (RF) transceivers.

I. INTRODUCTION

SIGNIFICANT advances have been achieved in single-chip solutions of RF transceivers for wireless local area network applications at the 5-GHz band in recent years [1]. Single-chip solutions adopt low intermediate frequency transceiver architectures; as such, the difficulty of integration of high-Q analog bandpass filters in deep submicron complementary metal oxide semiconductor (CMOS) technology for image rejection and for channel selection can be circumvented. However, not all integration difficulties can be avoided by proper transceiver architectures. There exists the preselect filter that appears currently impossible to be combined into a single CMOS radio frequency (RF) transceiver chip with the size of several square millimeters. Consequently, it is left external to the single chip (or chips) in virtually all solutions of highly integrated RF transceivers [2]. In order to suit these innovative single-chip solutions of RF transceivers, a number of miniature bandpass filters have been developed as the result of a great effort involving the fabrication of new dielectric materials and the application of sophisticated manufacturing technologies [3]–[7]. Ceramic materials of very high permittivity are preferred for smaller filter sizes. Low-temperature cofired ceramic (LTCC) technologies are widely employed because they allow the use of noble metals in filters to minimize the insertion loss. These small bandpass filters undoubtedly help miniaturize RF transceivers; they are, however, still discrete. Therefore, the embedded solutions of RF bandpass filters in multichip module substrates have received much attention over the past few years. Dalmia *et al.* designed an embedded bandpass filter in a laminated multichip module (MCM-L) substrate [8]. The bandpass filter of the size $1.125 \times 1.5 \text{ mm}^2$

shows a simulated insertion loss of 1.6 dB at the center frequency of 2.1 GHz. Murase *et al.* developed an embedded bandpass filter in a ceramic multichip module (MCM-C) substrate of very high permittivity ($\epsilon_r = 110$). The bandpass filter of the size $1 \times 2 \text{ mm}^2$ shows a measured insertion loss of 2.4 dB at the center frequency of 5.8 GHz [9]. Donnay *et al.* realized two identical RF bandpass filters in a deposited multichip module (MCM-D) substrate. The bandpass filters of the size $2.3 \times 1.4 \text{ mm}^2$ show a measured insertion loss of 2.4 dB at the center frequency of 5.2 GHz [10]. In this paper, we report an integrated bandpass filter. The bandpass filter, in line with the single-chip solutions of RF transceivers, is integrated in a thin 48-ball ball grid array (BGA) package that can carry a single CMOS RF transceiver chip. We call the filter implemented in this manner the integrated circuit package filter or the ICPF for short. The ICPF uses patch resonators rather than LC resonators used in the discrete and embedded bandpass filters [3]–[10]. Thus, there are no narrow lines, the width of which is close to the technology limitations. Also, these patch resonators have smaller resonant frequency uncertainties and easy-to-design layout [11]. The configuration of the ICPF is described in Section II. The effects of the different physical parts of the ICPF on the filter performance are investigated in Section III. Finally, the conclusion is summarized in Section IV.

II. CONFIGURATION OF INTEGRATED CIRCUIT PACKAGE FILTER

BGA packages have been widely used to carry highly integrated RF transceivers because of their excellent performance [2], [12]. Fig. 1(a) shows the ICPF in a cavity-down BGA package format. It consists of four laminated dielectric layers ($\epsilon_r = 9.7$, $\tan \delta = 0.001$), with a cavity formed in the middle. There are three buried metallic layers ($\sigma = 3.7 \times 10^7 \text{ S/m}$) in the construction. The lower buried layer provides the metallization for the signal traces, the middle buried layer for the cavity ground plane, and the upper buried layer for the filter. Fig. 1(a) also shows a bare single-chip RF transceiver attached upside down to the cavity ground plane. The input and output terminals of the bare single-chip RF transceiver are connected to the external solder balls through the bond wires, the signal traces, and the vias. The bare single-chip RF transceiver is shielded from the filter by the cavity ground plane automatically and will be encapsulated in real implementation. The filter is linked to the bare single-chip RF transceiver through a via, a signal trace, and a bond wire. Fig. 1(b) shows the layout of the filter. It is seen that the filter consists of two patch resonators with inset feeding link to each other through a coupling gap [13]. The filter exhibits an elliptic characteristic response. It was found that this new filter structure can achieve lower insertion loss and smaller resonant frequency uncertainties by

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Fig. 1. (a) Cross-sectional view of the ICPF. (b) Filter layout. (c) Signal trace layout. (d) Solder ball layout.

fabrication tolerance as compared with other planar dual-mode filters [14]. Fig. 1(c) shows the signal trace layout. The ICPF employs 48 signal traces, which are taken a symmetric pattern embedded around the cavity. Fig. 1(d) shows the solder ball layout. A solder ball is linked to a signal trace by a via. The ground plane, signal trace layer, and the solder ball layer form the cavity. It is clear that the cavity must be large enough to accommodate a bare single-chip RF transceiver. The typical size of a current bare single-chip RF transceiver in $0.18 \mu\text{m}$ CMOS is $4 \times 4 \times 0.305 \text{ mm}^3$. It is predicted that the size of the bare single-chip RF transceiver will increase as more and more functions are integrated. The advantage of the ICPF is quite obvious. It offers the possibility to combine a filter with a bare single-chip RF transceiver into a standard surface-mounted device. Thus, the system-level board space and the system-level manufacturing can be reduced and facilitated, respectively. Furthermore, the ICPF has much shorter distance to the RF output of the transceiver than a conventional chip filter. This implies a smaller transmission loss, which can be translated as an improvement to the ICPF insertion loss by a few percent.

III. CHARACTERIZATION OF INTEGRATED CIRCUIT PACKAGE FILTER

Having described the configuration of the ICPF, we now proceed to investigate the effects of the different physical parts of the ICPF on the filter performance. This requires a versatile nu-

merical tool. The high-frequency structure simulator (HFSS) was chosen because of its applicability to such problems. To simplify the description, we fix the filter circuit layout as $l = 9.5 \text{ mm}$, $l_c = 1 \text{ mm}$, $l_f = 3.7 \text{ mm}$, $w = 0.6 \text{ mm}$, $d = 3.5 \text{ mm}$, $g = 0.5 \text{ mm}$, and $s = 1.2 \text{ mm}$; we also fix the cover dielectric layer to be 0.2 mm thick and the other dielectric layers to be 0.6 mm thick, 15 mm long, and 15 mm wide. Fig. 2 shows the return and insertion losses as a function of frequency for the cases of laminating dielectric layers. First note that the filter resonates at 5.38 GHz with a 3-dB percentage bandwidth of 10.8% and an insertion loss of 1.4 dB for the case of the filter designed conventionally on the single-layered dielectric substrate. The simulated resonant frequency of 5.38 GHz is quite close to the calculated resonant frequency $f_{010} = (3 \times 10^8) / (2l\sqrt{\epsilon_r}) = 5.35 \text{ GHz}$ of the dominant TM_{010} mode of the filter indicating the accuracy of the simulation. It was found during simulations that the resonant frequency of the filter mainly depends on its length l , the longer the length is, the lower the resonant frequency. In addition, it was also found that the size of the notch next to the inset feeder can be used to fine tune the resonant frequency and the matching condition of the filter. Next, note that the filter still resonates at 5.38 GHz but with improved return losses for the cases of laminating dielectric layers on the filter back. It is expected that the resonant frequency remains at 5.38 GHz because the filter length remains at $l = 9.5 \text{ mm}$ and the effective permittivity of the filter substrate is not changed by the back-lam-

Fig. 2. (a) Return loss versus frequency for the cases of laminating dielectric layers. (b) Insertion loss versus frequency for the cases of laminating dielectric layers.

inated dielectric layers. As for the improvement of the return loss, we conjecture that the filter input impedance is altered to approach 50Ω by the perturbed field distribution of the dominant TM_{010} mode from the back-laminated dielectric layers. Further note that the insertion loss and the 3-dB bandwidth remain almost unchanged by the back-laminated cavity dielectric layers. This is also expected because the back-laminated cavity dielectric layers are isolated from the filter layer by the ground plane. Thus, the quality factor of the cavity does not affect the filter performance. Finally, it is more interesting to note that the simulated resonant frequency reduces to 5.05 GHz, the 3-dB percentage bandwidth to 8.5%, and the insertion loss to 1.0 dB for the case of laminating a dielectric layer on the filter itself. The reduction in the resonant frequency and in the insertion loss can be explained as follows. The cover layer helps concentrate the field distribution of the dominant TM_{010} mode, which is equivalent to an increase in the effective permittivity of the filter substrate, as a result, the resonant frequency reduces. As far as the reduction in the insertion loss is concerned, we believe that it is due to the reduction of the radiation loss by the cover layer. The reduction in the resonant frequency by the cover layer is an attractive feature for the ICPF design as the filter circuit area

Fig. 3. (a) Return loss versus frequency for the cases of building signal traces, vias, and solder balls. (b) Insertion loss versus frequency for the cases of building signal traces, vias, and solder balls.

can be further reduced by shortening the filter length l to make the resonant frequency restore at 5.38 GHz.

Fig. 3 plots the return and insertion losses as a function of frequency for the cases of building the signal traces, vias, and solder balls. The 48 signal traces, vias, and balls follow the current designs of single-chip RF transceivers [16]. It is believed that the number of them will decrease as the level of integration of RF transceivers increases. Therefore, we also consider the cases of 36, 24, and 12 signal traces, vias, and balls. Note that the signal traces, vias, and balls have little effect on the filter performance. For instance, when the number of the signal traces, vias, and balls reduces, the minimum insertion loss remains at 1 dB with slightly shifted skirt and the resonant frequency remains at 5.05 GHz with varied return loss. The return loss varies within the acceptable range between -18 to -26 dB at the resonant frequency of 5.05 GHz. The similar effect was observed when the solder balls were removed and the ICPF was thus in a pin grid array package (PGA) format during the simulations. Furthermore, it was also observed that the signal trace pattern and arrangement slightly affect the filter performance. All these insignificant variations in the filter performance caused by

Fig. 4. Return and insertion losses as function of frequency for the case of loading the ICPF with a bare single-chip RF transceiver.

Fig. 5. Simulated and measured ICPF performance.

the signal traces, vias, and balls can be attributed to the cavity ground plane that sufficiently isolates them from the filter.

Fig. 4 shows the return and insertion losses as a function of frequency for the case of loading the ICPF with a bare single-chip RF transceiver. The bare single-chip RF transceiver is modeled with a piece of silicon ($\epsilon_r = 11.9$). The silicon size is assumed to be $4 \times 4 \times 0.305 \text{ mm}^3$. It is evident that the loading of the ICPF with the dummy chip improves the return loss and slightly increases the 3-dB bandwidth. Once again, the resonant frequency remains at 5.05 GHz. It is thought that the ICPF may have the potential interference to the functionality of the single-chip RF transceivers. Therefore, the ICPF should also be studied from the circuit viewpoint to understand the effect of the ICPF on the signal integrity of the single-chip RF transceiver. This is believed to be a quite useful work and has received our great attention.

For experimental confirmation and demonstration, an ICPF was designed to operate at 5.25 GHz with the Rogers TMM10i ceramic having a relative dielectric constant of $\epsilon_r = 9.8 \pm 0.245$ and a thickness of 0.635 mm. The length and width of the feed lines were $l_f = 3.7 \text{ mm}$ and $w = 0.6 \text{ mm}$, respectively; the notch dimensions were $d = 3.5 \text{ mm}$ and $g = 0.5 \text{ mm}$; the length

of the patch resonator was $l = 10.4 \text{ mm}$ with a cut of $l_c = 1 \text{ mm}$ on a corner; the coupling gap was 1.2 mm. This fabricated ICPF did not have the superstrate layer. The performance of the ICPF was measured using an HP 8510C network analyzer. Fig. 5 shows the simulated and measured results. The ICPF of size $15 \times 15 \times 1.905 \text{ mm}^3$ has a 3-dB percentage bandwidth of 14% and insertion loss of 2.07 dB at 5.25 GHz. The performance of the ICPF can be further improved by using more advanced fabrication technology such as LTCC.

IV. CONCLUSION

This paper has focused on the development of novel integrated circuit package bandpass filters for single-chip solutions of RF transceivers. A compact ICPF has been designed. The effects of the different physical parts of the ICPF on the filter performance have been investigated and discussed. It is found that the ICPF can achieve percentage bandwidth of 14% and insertion loss of around 2 dB. Besides being able to produce good filter response and make full use of the advantages of the planar integration, the ICPF also enjoys economical benefit of mass production, automatic assembly, the system-level board miniaturization, and the system-level manufacturing facilitation. It is therefore anticipated that the results and design details on the ICPF presented in this paper will be very useful for engineers who are interested in filter-package-chip codesign of wireless communication systems.

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