Journal of the Microelectronics & Packaging Society
Vol. 18, No. 1, p. 41-47. 2011

# Ultra-Wide-Band (UWB) Band-Pass-Filter for Wireless Applications from Silicon Integrated Passive Device (IPD) Technology

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(Received February 22, 2011: Accepted March 14, 2011)

**Abstract:** Currently, there is widespread adoption of silicon-based technologies for the implementation of radio frequency (RF) integrated passive devices (IPDs) because of their low-cost, small footprint and high performance. Also, the need for high speed data transmission and reception coupled with the ever increasing demand for mobility in consumer devices has generated a great interest in low cost devices with smaller form-factors. The UWB BPF makes use of lumped IPD technology on a silicon substrate CSMP (Chip Scale Module Package). In this paper, this filter shows 2.0 dB insertion loss and 15 dB return loss from 7.0 GHz to 9.0 GHz. To the best of our knowledge, the UWB band-pass-filter developed in this paper has the smallest size (1.4 mm×1.2 mm×0.40 mm) while achieving equivalent electrical performance.

**Keywords:** Integrated Passive Device (IPD), Ultra Wide Band (UWB), Chip Scale Module Package, Flip-chip, Wire-bonding

## 1. Introduction

With the rapid growth of wireless communication markets, silicon is recognized as an especially promising material to meet the demands of low cost, high integration for RF passive devices.[1)] The fabrication of high quality factor (Q) inductors is an important task to be solved imperatively for silicon radio frequency (RF) integrated circuit (IC) applications, but this task is confronted with the question of microwave performance degradation and reliability due to higher substrate losses in silicon than in GaAs materials. In order to overcome this difficulty, various approaches have been tried. In the early development of high quality factor (Q) inductors on silicon substrates, good results have been reported using high resistivity silicon wafer.[2,3)]

RF passive networks are predominantly used in the front end of wireless communication systems (i.e. between the active RFIC and the antenna.) Conventional discrete passive components consume 60%~70% of the footprint area of the system. These components are typically made using ceramic technology,[4,5)] because of ceramic's good electrical and thermal characteristics. However, IPDs based on semiconductor processes offer the advantage of excellent parameter control, and allow simplified and compact module design. IPD processes can be used to make high density capacitors, high Q inductors and large value resistors.[6)]

The general trend in packaging for RF wireless products, especially for consumer applications, is to reduce form-factor and, consequently, cost. This is leading to the adoption of 3-D packaging technology for wireless application.

In this paper, an UWB Band-pass-filter is made using lumped IPD technology on a silicon substrate for CSMP (Chip Scale Module Package).

## 2. IPD Description

Fig. 1 shows a cross sectional view of the passive structure. A specially treated silicon substrate is used to grow dielectric layer and metal layer. There are three metal layers (MCAP, M1, and M2) and two dielectric layers (PI-1, and PI-2) in the cross section. Layer MCAP and M1 are used to form MIM capacitors and two metal layers are

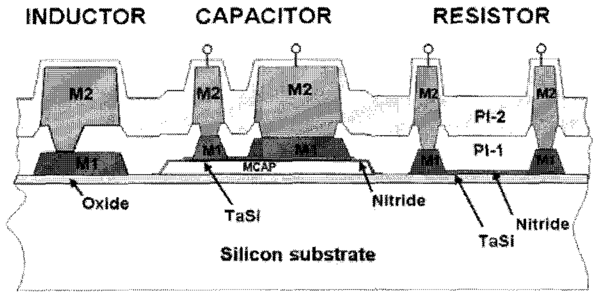


**Fig. 1.** Thin film IPD structure (not in scale).

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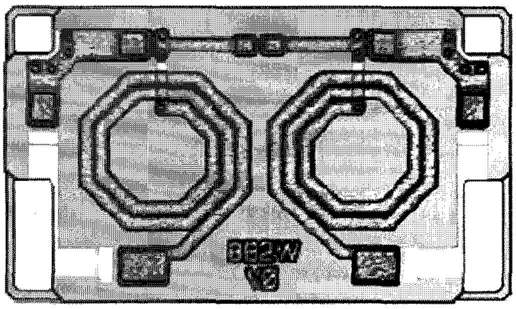
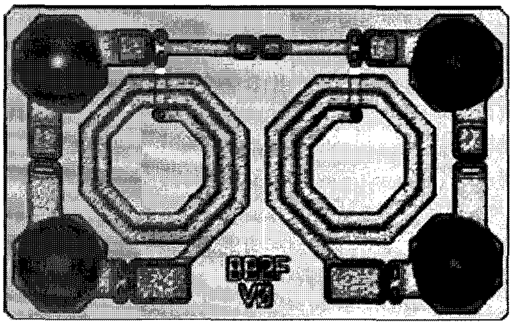


**(a) WIRE BOND ( 1.5mm X 0.9mm)**



**(b) FLIP CHIP (1.5mm X 0.9mm)**

**Fig. 2.** Micrographs of example discrete IPD band-pass filters.

aluminum. The layer M2 is made of thick copper, and inductors are implemented in this layer. The TaSi is used to obtain sheet resistance for resistor.

Both wire-bonding and flip-chip type IPDs can be made from this process.

### 2.1. 3D module Structures

Fig. 2 shows two band-pass filter designs for 802.11b/g band applications (2400~2500 MHz). These devices are designed as stand-alone discrete circuits. They have the same circuit architecture, similar component values and characteristics. The only substantial difference between the two is the method of attachment. For flip-chip (Fig. 2(a)) attachment the component is mounted face-down on a system board or SiP assembly, whereas for wire-bond (Fig. 2(b)) the IPD is mounted face-up with connections to the underlying system board being made by bond wires. These two attachment methods have different parasitic impedance characteristics, leading to some minor differences in the device performance.

Three common 3-D module structures are shown in Fig. 3. All of these package types use a silicon substrate to fabricate the IPDs required for the front-end. These circuits are generally balun transformers (used to convert signals from single-ended to differential or vice-versa), band-pass filters (mainly used in receivers to pass only the desired band and block undesired out-of-band interference) and low-pass

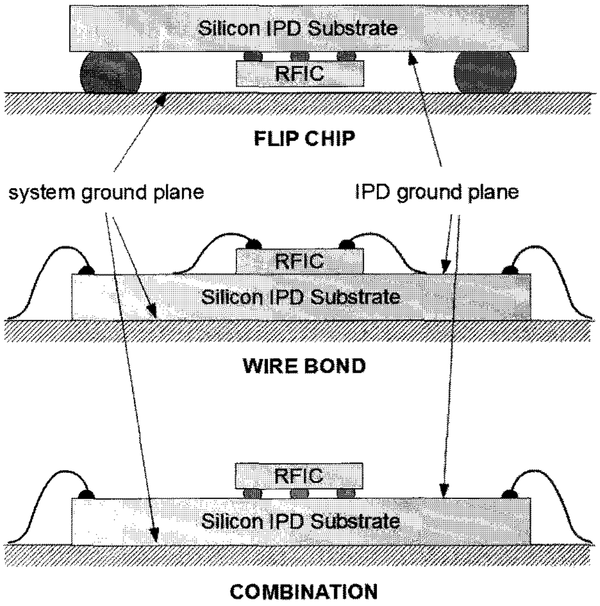



**Fig. 3.** Chip-Scale Module Package (CSMP) assembly alternatives.

filters (mainly used in transmitters to eliminate harmonics from the output spectrum.) Active RFICs are electrically connected to the silicon substrate by either flip-chip solder bumps or by wire bonds.

In 3D module structures like the examples shown above, it is usually desirable to add a secondary ground plane on the IPD substrate. Since the silicon substrate does not have a thru-via, local connections to the main system ground are not possible. (Emerging TSV technologies may change this, but at present this is not in widespread use.) Instead, the local ground plane on the IPD is connected to the system ground around its periphery, either by wire-bond or flip-chip connections.

In addition to the non-ideal characteristics of coplanar ground structures, the peripheral connection of the IPD ground to the system ground is imperfect. The inductance of wire-bond connections in particular, and flip-chip connections to a lesser extent, causes the connection to be progressively worse at higher frequencies. This is not a major problem for small IPD at low frequencies, like the example shown in Figure 2. These circuits are so small that they do not have their own secondary ground plane, but instead make local connections to the main system ground.

### 2.2. UWB Band-Pass-Filter for Flip Chip IPD

In the circuit-level simulation that was done using ADS, a perfect performance of the UWB band-pass-filter is expected since there are no parasitic effects or losses in circuit-level simulation. In the actual circuit design, layout for the inductors and capacitors is implemented using a proprietary

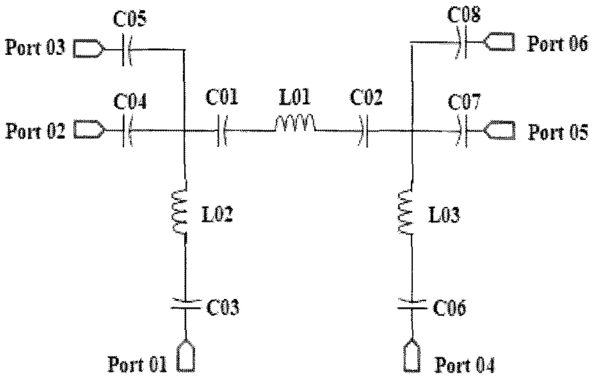



**Fig. 4.** Circuit topology for UWB band-pass-filter (BPF).

RCL generation tool which complies with the design rules. But, in the case of high frequency from 7 GHz to 9 GHz, the added inductances from the interconnection traces in the IPD layout have to be taken into account. The approach used was to first use EM simulation to model the traces as well as the individual passive components. Component values were determined based on these models. These values were then used in the full layout. Fig. 4 shows a circuit topology for the band-pass filter.

Adjustments to the layout were made in circuit simulation, using a combination of EM simulation models and ideal circuit elements. The response from the initial layout departs from the schematic circuit's predicted response, due to the parasitic effect of the added traces for interconnection. A number of internal ports between electrodes of the capacitors were assigned to allow for tuning (using ideal capacitors in circuit simulation) to obtain a desired response in our design process. The resulting values of these ideal components represent incremental changes to the circuit that were subsequently implemented as changes in the layout. Through iteration and optimization, the simulated performance of the UWB band-pass filter, taking into consideration of all of

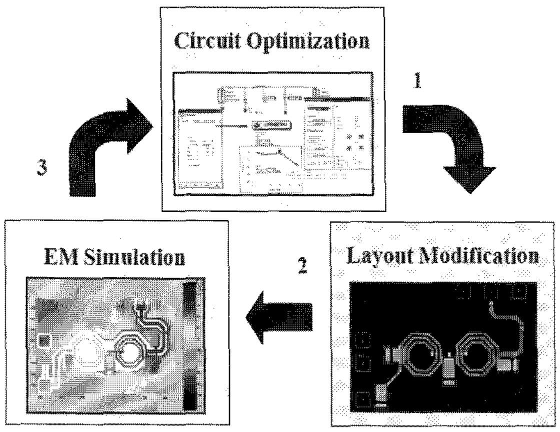



**Fig. 5.** Design methodology of integrated passives.

traces and passive components, can be made to approach the desired specifications. Details of this EM based optimization method can be found in.[7)]

To meet electrical performance and size target a general design methodology (Fig. 5) was followed. This consists of the following steps: 1) Create circuit model for IPD: 2) Generate physical layout to fit available space, and perform EM simulation: 3) Optimize as required to meet specifications.

Fig. 6 shows the layout of the UWB band-pass-filter for EM simulation. There are six bumps in the flip-chip IPD Layout. Two bumps are for UWB band-pass-filter input and output, and four bumps are just for electrical ground.

The simulated characteristics of the UWB band-pass-filter are shown in Fig. 7. The insertion loss from 7 GHz to 9 GHz is 1.8 dB and the return loss is greater than 15 dB in EM-simulation. Depending on the specifications of the module these characteristics may be adjusted by the values of the capacitors and inductors.

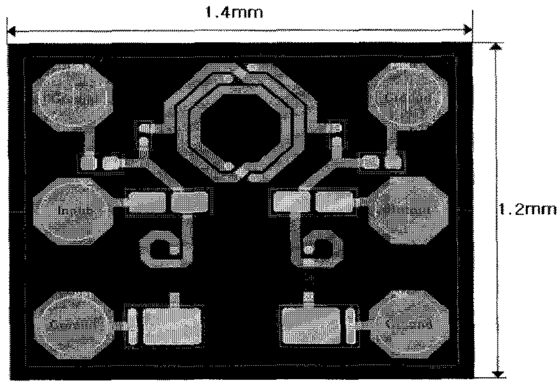



**Fig. 6.** Flip-chip IPD layout of the UWB band-pass-filter for EM simulation.

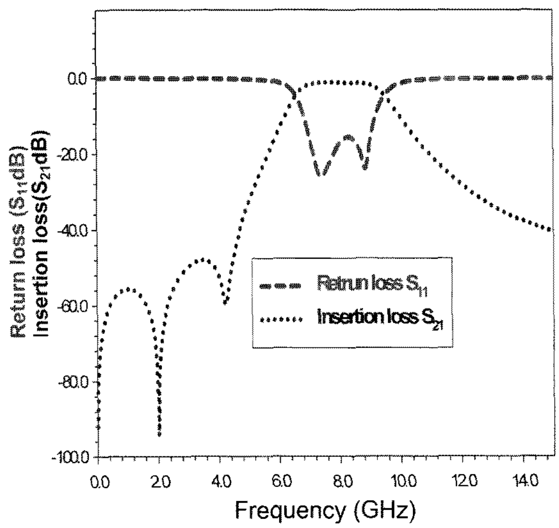
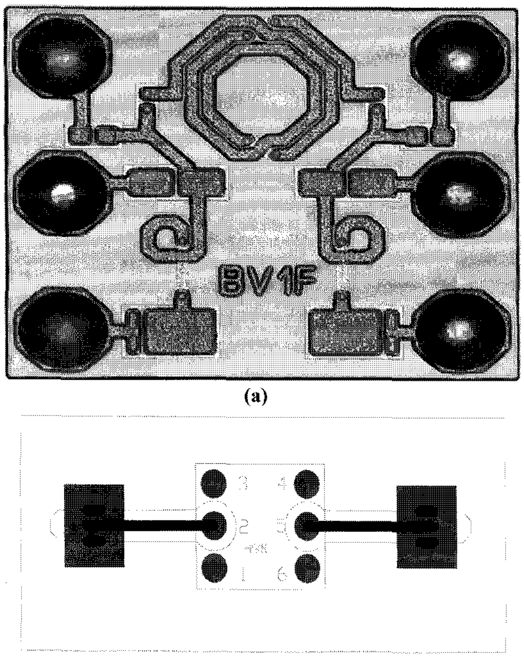


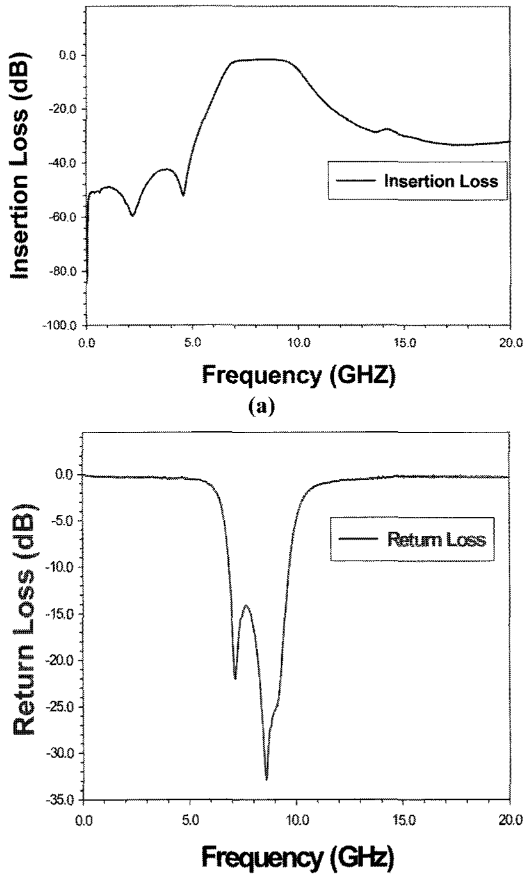

**Fig. 7.** $S_{11}$ and $S_{21}$ parameters for the UWB band-pass-filter in simulation.




(a)

(b)

**Fig. 8.** UWB band-pass-filter flip-chip die (a) and RF test board layout (b).




(a)

(b)

**Fig. 9.** Typical characteristics of the manufactured UWB band-pass-filter. The insertion loss (a) and return loss (b).

### 2.3. UWB Band-Pass-Filter Results for Flip-Chip IPD

The manufactured UWB band-pass-filter has low pass-band insertion loss and small size. It is composed of 8.0 um Cu-plated inductors and Metal-Insulator-Metal capacitors which are fabricated on a silicon substrate using IPD process. The bump size and pitch of the UWB BPF are selected so that the device can be mounted directly on a PCB or laminate substrate using conventional surface mount techniques.

Fig. 8(a) shows the photomicrograph of fabricated UWB band-pass-filter IPD. The device was fabricated on a silicon substrate using thin film IPD process and input/ output signal are connected by using the solder bumps. S-Parameters were measured with the test board loss. The use of the test board adds an insertion about 0.5 dB at 8 GHz, and shifts the harmonic rejections slightly. The UWB band-pass-filter of flip-chip die has a size of 1.4 mm×1.2 mm×0.40 mm (including bump height).

Fig. 8(b) shows an UWB band-pass-filter die with flip-chip bump to input pad (#2) and output pad (#5). The four ground pads (#1, #3, #4, #6) are also connected with flip-chip bump pads. S-Parameters were measured with flip-chip IPD die through probing on the G-S-G patterns on the test board.

The characteristics of the UWB band-pass-filter are shown in Fig. 9. The insertion loss is 1.7 dB (Minimum) in

**Table 1.** Typical characteristics for the flip-chip UWB band-pass filter.

| | Original Specification | EM-Simulation | Measured Results |
|---|---|---|---|
| Passband Frequency | 7000~9000 MHZ | 7000~9000 MHZ | 7000~9000 MHZ |
| Passband Insertion loss | <2.0 dB | <1.8 dB | <2.0 dB |
| Passband Return Loss | >10 dB | >15 dB | >15 dB |
| Attenuation (824~915 MHZ) | >55 dB | >55 dB | >50 dB |
| Attenuation (1710~1910 MHZ) | >35 dB | >60 dB | >53 dB |
| Attenuation (2400~2500 MHZ) | >30 dB | >55 dB | >55 dB |
| Attenuation (4900~5900 MHZ) | >15 dB | >16 dB | >18 dB |
| Attenuation (12000~15000 MHZ) | >15 dB | >30 dB | >21 dB |

Fig. 9(a) and return loss is 15 dB in Fig. 9(b). Table 1 shows the typical characteristics of the UWB band-pass-filter. In simulation of the UWB band-pass-filter, it is very difficult to predict the return loss very accurately at high frequency because the return loss is very sensitive to small layout features. In high frequency applications, our simulation scheme is very suitable for designing IPD products.

### 2.4. UWB Band-Pass-Filter for Wire Bonding IPD

The circuit design and fabrication of the wire-bond UWB band-pass-filter IPD are similar to those described above for the flip-chip device. The pad size and pitch of the UWB band-pass-filter are selected so that the device can be mounted directly on a PCB or laminate substrate using conventional wire-bonding techniques.

Fig. 10 shows the layout of the UWB band-pass-filter for EM simulation. There are six die pads in the wire-bonding IPD layout. Two die pads in triple wire-bonding are for UWB band-pass-filter input and output. Four wire-bonding pads also in triple wire-bonding are just for electrical ground.

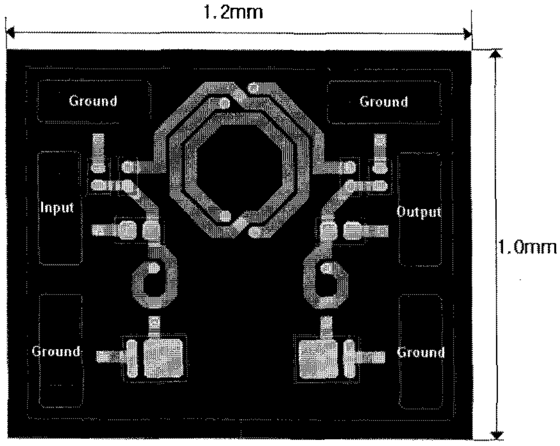



**Fig. 10.** Wire bonding IPD layout of the UWB band-pass -filter for EM simulation.

**Table 2.** Typical characteristics for the UWB band-pass filter.

| | Original Specification | EM-Simulation |
|---|---|---|
| Passband Frequency | 7000~9000 MHZ | 7000~9000 MHZ |
| Passband Insertion loss | <2.0 dB | <1.6 dB |
| Passband Return Loss | >10 dB | >20 dB |
| Attenuation (824~915 MHZ) | >55 dB | >65 dB |
| Attenuation (1710~1910 MHZ) | >35 dB | >60 dB |
| Attenuation (2400~2500 MHZ) | >30 dB | >80 dB |
| Attenuation (4900~5900 MHZ) | >15 dB | >17 dB |
| Attenuation (12000~15000 MHZ) | >15 dB | >20 dB |

Table 2 shows the typical characteristics of the UWB band-pass-filter from simulation. The circuit-level simulation was done using a simple inductance model (0.35 nH) for each of the triple wire-bonds. The simulated characteristics of the UWB band-pass-filter are shown in Fig. 11. The insertion loss from 7 GHz to 9 GHz is 1.6dB and the return loss is greater than 20 dB in EM-simulation. Depending on the specifications of the module these characteristics may be adjusted by the values of the capacitors and inductors.

Fig. 12(a) shows a UWB band-pass-filter die with wire-bonds. S-Parameters were measured with the test board loss. The use of the test board adds an insertion about 0.5 dB at 8 GHz, and shifts the harmonic rejections slightly. The UWB band-pass-filter of wire-bonding die has a size of 1.2 mm×1.0 mm×0.25 mm.

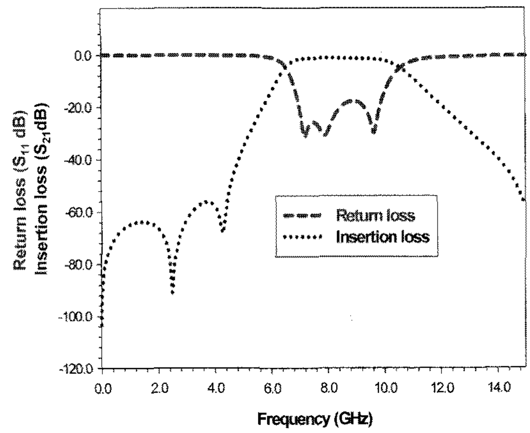
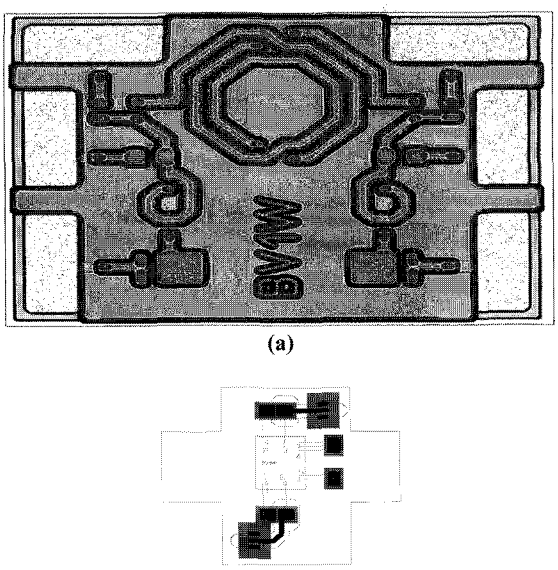



**Fig. 11.** $S_{11}$ and $S_{21}$ parameter for UWB band-pass-filter in EM simulation.



(a)

(b)

**Fig. 12.** UWB band-pass-filter wire-bond die (a) and RF test board layout (b).

Fig. 12(b) shows an UWB band-pass-filter die with 3 wire- bonds to input pad (#3) and output pad (#6). The four ground pads (#1, #2, #4, #5) are also connected with triple wire bonds pads. S-Parameters were measured with wire bonding IPD die through probing on the G-S-G patterns on the test board.

The characteristics of the UWB band-pass-filter of wire bonding die are shown in Fig. 13. The insertion loss is 2.4 dB (Minimum) in Fig. 13-a and the return loss is 7 dB in Fig. 13(b). Compared to the results for the flip chip UWB filter, these results are much worse than expected.

Fig. 14 shows a comparison of the simulated result versus measurement using the simple triple wire bond inductance model. It can be seen that the agreement between the two is poor. Because of the good agreement in the flip-chip case, it was suspected the cause of the discrepancy was in the simple inductance model used for the wire bonds. The simple model does not account for mutual interactions between the wire bonds, which become more important at higher frequencies.

An improved circuit-level simulation was done using the

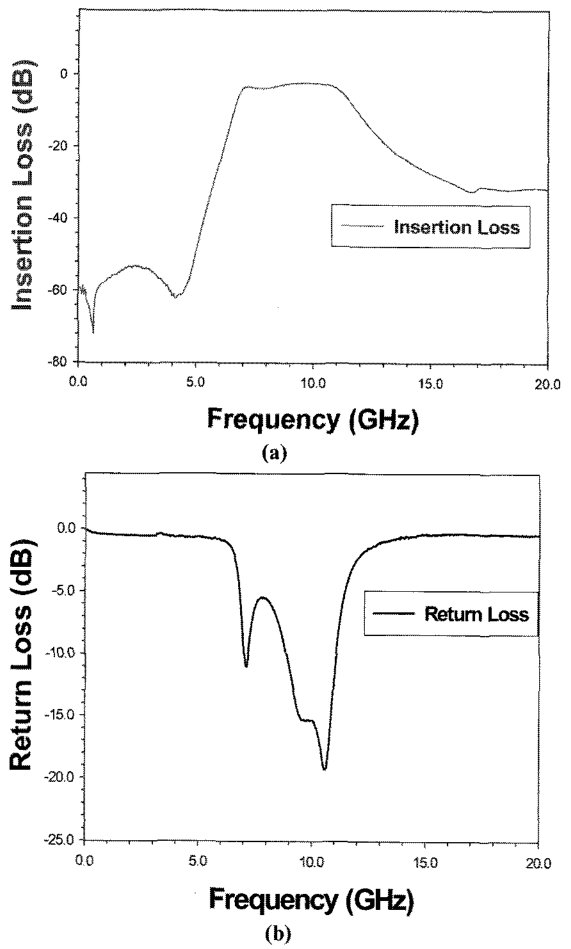



Fig. 13. Measured characteristics of the UWB band-pass-filter of wire bonding die.

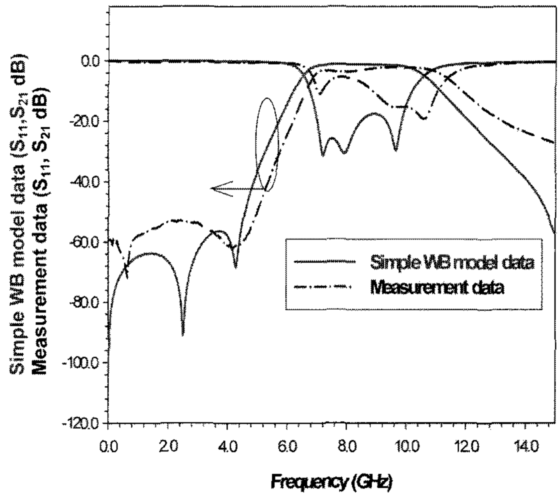



**Fig. 14.** Measurement versus simulation using the simple triple wire-bond inductance models for wire-bonding IPD.

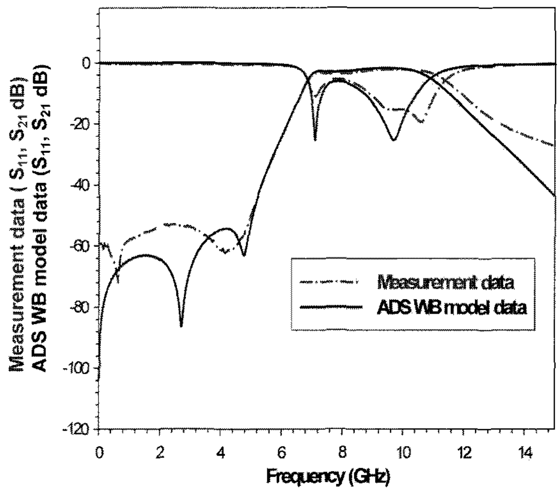



**Fig. 15.** Measurement versus simulation using the Philips/TU Delft triple wire-bond inductance models.

Philips /TU Delft wire-bond models in ADS. These account for a more detailed shape of the wire bond and also account for mutual inductances between all of the wires.

Fig. 15 shows a comparison of the measured data versus simulation using the Philips TU/Delft wire-bond inductance model for wire-bond IPD. With the more accurate wire-bond models, the agreement is much better

The comparison between the IPD characteristics using the simple triple wire bond model and the more accurate Philips/TU Delft model is shown in Fig. 16. The differences between the two indicate that the device characteristics are sensitive to the wire-bonds.

The UWB band-pass-filter operates in the 7 GHz to 9 GHz band. At these high frequencies, the simple wire-bond models are not sufficiently accurate.

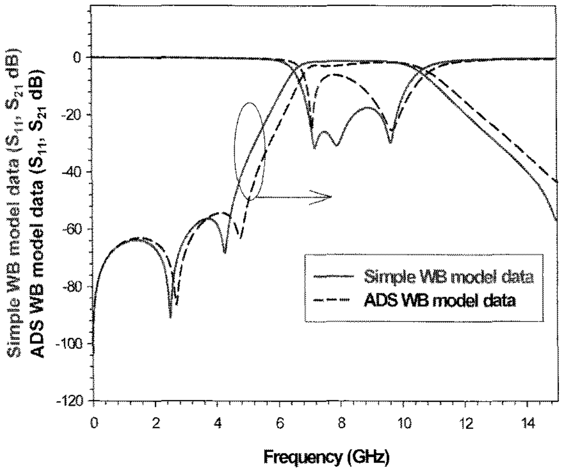



**Fig. 16.** Simulation using the simple triple wire-bond inductance model versus simulation using the Philips/TU Delft triple wire bond inductance models.

## 4. Conclusions

IPD 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. Excellent filter properties are obtained from the UWB band-pass-filter of flip-chip die. For wire bondable IPDs working at high frequencies (such as this UWB filter), simple inductance model for multiple wires is not good enough for designs. More advanced coupled-wire models in ADS have shown better predictions of the wire behaviors. The IPD technology is especially well suited for UWB applications because of its excellent parameter control and enabling smaller from-factors.

## Acknowledgments

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

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