Technology of Embedded Ultra-High Frequency Power Amplifier ICs in the Print Circuit Boards

Masanori Itoh **Shinichi Hoshi**
Hiroshi Iinaga

Along with miniaturization process of CMOS using Si material, recently there have been active studies and developments of wireless transceiver ICs operating at ultra-high frequency millimeter bands[1) 2)]. Especially by combining the manufacturing with peripheral circuits including the baseband IC and through integration, ultra-high frequency transceiver ICs can be provided at low cost. What was once expensive and demanded only for specialized applications, ultra-high frequency transceiver ICs are beginning to see use in home appliances. In the 60GHz band, 7GHz bandwidths have been set aside for use as unlicensed bands, 57~64GHz in Europe and North America and 59~66GHz in Japan. Standardization activities such as Wireless HD[3)] and EEE802.15.3C[4)] are underway.

Compared with existing 2.4GHz and 5.8GHz wireless bands, the use of ultra-high frequency has the advantages of employing an extremely wide transmission bandwidth and cutting back on encoding/decoding delays and power consumption. However, output power from IC based on Si material is insufficient and not even capable of transmitting a distance of 1m. Therefore, a high output power amplifier is necessary. Additionally, implementation of antennas and other external circuitry will be required. The short wavelengths associated with ultra-high frequency make circuit designing, implementing and evaluating difficult, and that has been a major obstacle for engineers.

To solve these problems, ultra-high frequency power amplifier IC using compound semiconductor was embedded in the printed circuit board lowering the cost of packaging and implementation. Furthermore, the handling of ultra-high frequency IC was simplified (modularization) by incorporating the ultra-high frequency design into the printed circuit board.

Embedded ultra-high frequency IC printed circuit board

In order to embed the ultra-high frequency power amplifier IC, ultra-high frequency signal must be transmitted before and after the IC. For this, a low dissipation factor is required from the printed circuit board. As shown in **Figure 1**, the printed circuit board material chosen for the task was graft polymer[5)], which similar to Teflon® *1) has a dielectric constant of 2.2 and dissipation factor of 0.0005. During the manufacturing process, Teflon boards for conventional high frequency use utilizes metallic sodium, which is difficult to handle. On the other hand, graft polymer has the benefit of using the same manufacturing process as traditional printed circuit boards (FR4, etc.)

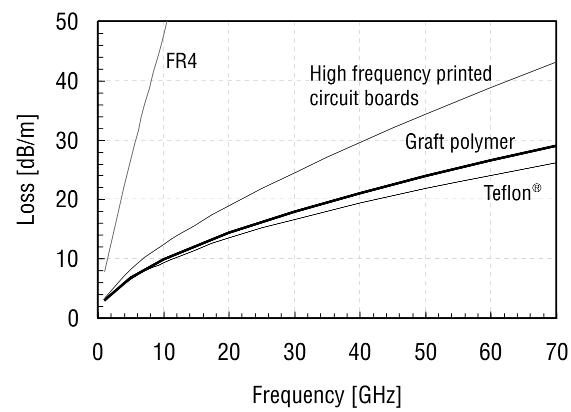

Figure 1. Loss Comparison of Printed Circuit Boards

An InP-MMIC (Indium Phosphide Monolithic Microwave IC) thinned to a thickness of 200μm was used for the embedded power amplifier IC[6)]. The following two problems need to be considered when embedding ultra-high frequency power amplifier IC into the printed circuit board.

① Most power amplifier ICs are designed with input/output characteristic impedance (hereinafter, Zo) of 50Ω. Therefore, the printed circuit board must also be designed with the same Zo=50Ω transmission lines to connect the IC, otherwise power reflection at the connection point becomes too large and transmission performance will significantly degrade. However, the widths of the transmission lines vary greatly from the IC for the same Zo=50Ω due to differences in dielectric constant, design and manufacturing between the IC and printed circuit board.

* 1) Teflon is a registered trademark of DuPont.

② Power amplifier IC is generally mounted on the package that has a heat sink after the IC substrate has been thinned. The printed circuit board into which the IC will be embedded has low thermal conductivity, and the material has difficulty dissipating heat. It is anticipated that the heat generated by the IC will degrade reliability and electrical characteristics.

These issues were examined in advance.

Electrical and thermal design of embedded IC printed circuit board

(1) Transmission characteristics

To embed the ultra-high frequency power amplifier IC into the printed circuit board, a strip transmission line must be formed in the middle layer of the printed circuit board as shown in **Figure 2**. It is possible to design fairly accurate transmission lines using the latest high-frequency circuit simulator. Additionally, width of Zo=50Ω was adopted for the transmission line due to its proven manufacturing and evaluation results. In this case, the line widths were 400μm. Oppose to this, the widths for Zo=50Ω transmission lines on the IC were 16μm and dimension for the bonding pad was 80μm☐ making direct connections impossible. Since it is not possible to change dimensions on the IC, line widths on the printed circuit board must be made narrower. Due to the bonding pad dimension and the board manufacturing requirements, the line width at the connection point with the IC was set to 100μm. To reduce the input/output reflections to a negligible level, an impedance matching circuit as shown in **Figure 3** was designed.

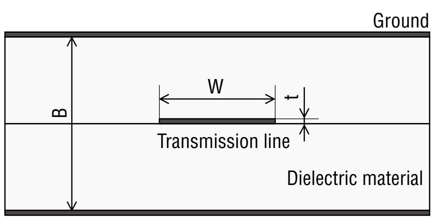

Figure 2. Overview of Strip Line

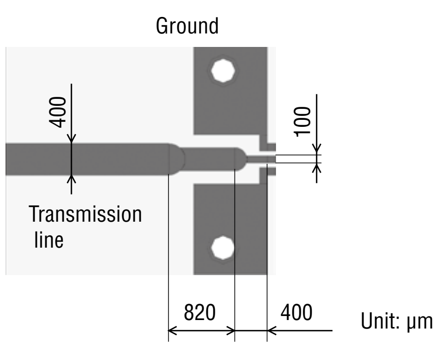

Figure 3. Impedance Matching Circuit

As shown in **Figure 1**, the graft polymer used for the printed circuit board has good high frequency characteristics, but it is extremely soft and weak against high temperatures.

This weakness can lead to variations in transmission line width and spacing of the manufactured printed circuit board. To compensate for this fact, the dependence of the transmission characteristics on line widths was examined using a simulator. According to the results, for ±10% variation in transmission line width, loss difference was about 0.05dB/cm and standing wave ratio was less than 1.5. It was determined that the values were comparable to components used for ultra-high frequency. In actual usage, the lines will be made shorter and manufacturing variations will be corrected, so no problems are expected in production.

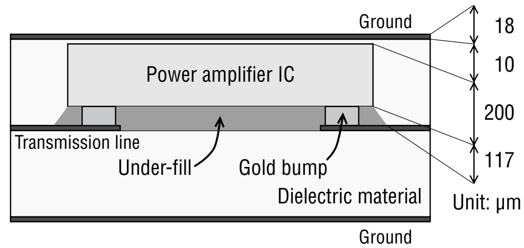

Figure 4. Cross-section of Embedded IC Printed Circuit Board

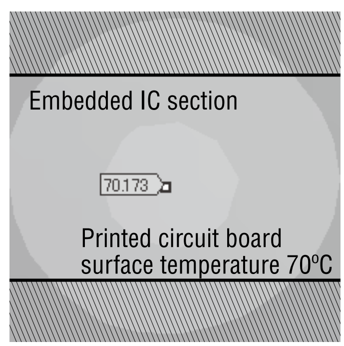

Figure 5. Simulation Results of Printed Circuit Board Surface Temperature

(2) Thermal characteristics

The power amplifier IC embedded in the printed circuit board is InP-MMIC with a maximum output power of about 60mW. Efficiency is approximately 10%, and about 600mW is emitted as heat. As shown in **Figure 4**, the IC is mounted as flip-chip (reverse) against the transmission line placing the IC's heat generating part on the under-fill side. Under-fill is required to hold the chip. It also serves to relieve the stress on the chip when bonding to the printed circuit board. However, main ingredient of the under-fill is resin, so the IC is surrounded by the poor thermal conductivity of resin.

The indium phosphide used for the IC substrate is brittle. Therefore, to prevent the IC from cracking when it is handled or being bonded to the printed circuit board, the thickness was limited to under 200μm. If only an 18μm thick copper foil is present on the printed circuit board surface facing the IC backside, bonding stress may again crack the IC. To prevent this, about 10μm of resin is left on the structure. Heat generated on the topside of the IC will travel upwards through the IC substrate that has a higher thermal conductivity than the resin.

Copper foil can be bonded to the IC underside allowing heat to escape thus lowering the IC temperature. Instead, the resin left on the structure was made as thin as the manufacturing allows, but thick enough to prevent the IC from cracking. Height of gold bumps were adjusted several μm, and the result is the structure shown in **Figure 4**.

Figure 5 shows the surface temperature results of the thermal simulation conducted on the structure of **Figure 4**. When the bottom side temperature of the printed circuit board was fixed at 60ºC, the surface temperature was about 70ºC. The maximum temperature on active area of the IC at that time was 83ºC. Since the IC temperature rise is only 13ºC, it is assumed there are no issues with the IC specification or usage. During production, aluminum and other metallic substrates will be connected to the printed circuit board further improving heat dissipation.

Prototype of the embedded IC printed circuit board

Figure 6 shows an overview of the embedded IC printed circuit board manufacturing process.

Second metal layer is used to form pre-designed transmission lines on top of the lower printed circuit board. In addition, gold bumps are formed on the IC (**Figure 6-1**). IC is flipped and mounted on a lower resin substrate (**Figure 6-2**). After the IC mounting, under-fill material is inserted between the IC and lower printed circuit board to secure the IC and prevent it from cracking when the upper printed circuit board is mounted on top. To embed the IC, a pocket similar in size to the IC is formed in the upper printed circuit board (**Figure 6-3**). The flip-chip mounted board and board with the pocket are bonded together to form an embedded IC printed circuit board. The photo of the embedded IC printed circuit board and X-ray photo of the embedded IC are shown in **Figure 7** and **Figure 8**, respectively. Although there are μm variations in the levels, the board surface is flat. The gold bump array at 150μm intervals can also be confirmed.

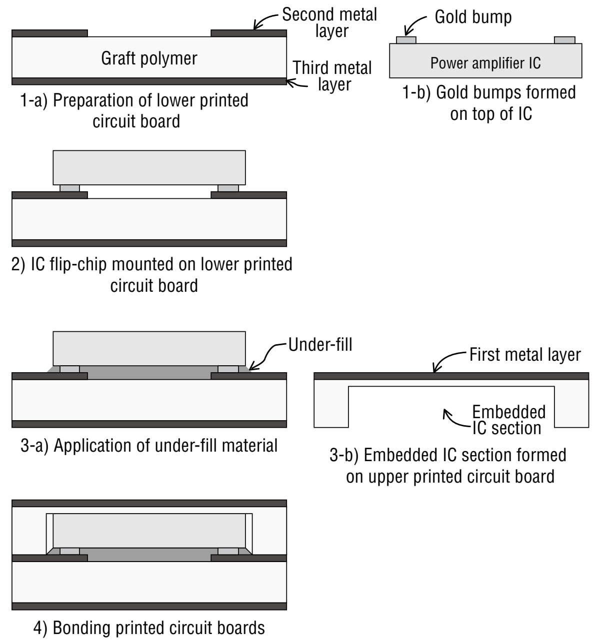

Figure 6. Manufacturing Process

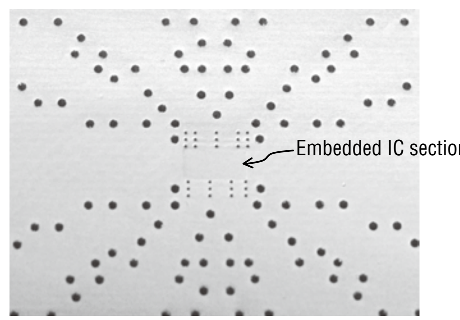

Figure 7. Printed Circuit Board Surface After Mounting

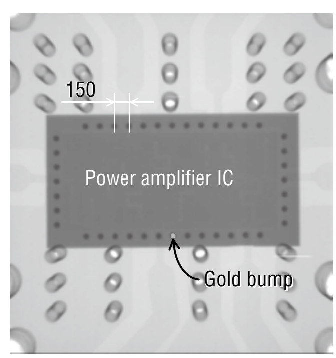

Figure 8. X-ray Photo

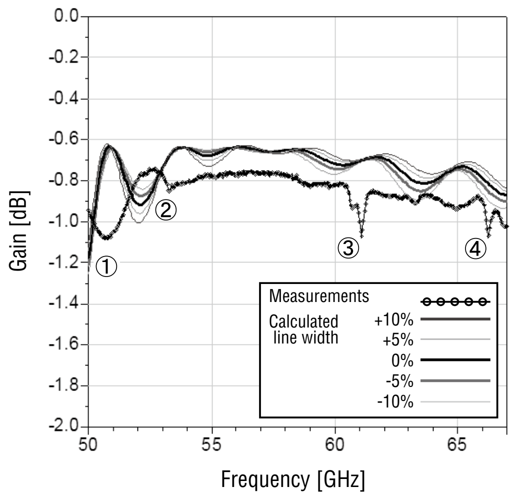

Figure 9. Dependence on Transmission Line Width and Measurement Results

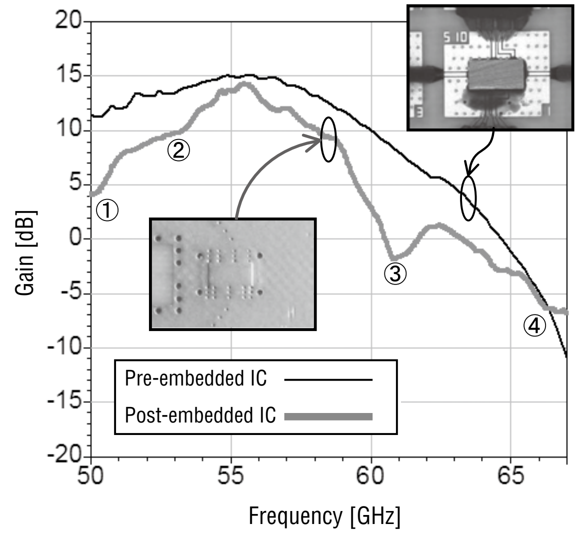

Figure 10. Small-signal Gain Characteristics

Electrical and thermal characteristics of the embedded IC printed circuit board

(1) Transmission characteristics

High frequency circuit simulator calculations and measured values from a 26.6mm long transmission line to determine transmission loss dependency on line width are presented in **Figure 9**. This time, the width of the transmission line manufactured was 380μm against the designed value of 400μm. As **Figure 9** shows, differences between the calculated results and measured values of the 380μm width transmission line were within 0.2dB in the 57~66GHz band used for ultra-high frequency. Position of the standing wave is shifted 2GHz lower than the simulation, but similar results were obtained.

Small-signal gain characteristics of the final prototype are shown in **Figure 10**. Characteristics of the pre-embedded IC were measured with a high frequency probe after the IC was flip-chip mounted and secured to the printed circuit board with under-fill material (top right photo of **Figure 10**). At that time, the peak frequency was 55GHz, and gain was 15dB. Post-embedded IC measurements include passage through transmission lines, impedance converter and waveguide transducer. This time, the peak frequency was 56GHz, and gain was 14dB. The differences in peak frequency and gain were small and considered to be in good agreement. However, there were ripples within the bandwidth, and large drops in gain can be observed. The ripples can be seen in **Figure 9** and **10** at positions indicated by ①~④. The ripples were not observed at the time of flip-chip mounting and appeared after the IC was embedded. The most likely cause is the reciprocal influence of the IC, converters and connections to external circuitry.

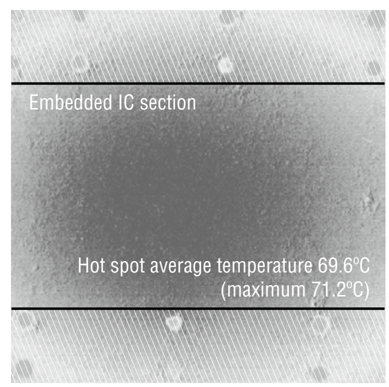

Figure 11. Temperature Distribution of Board Surface

(2) Thermal characteristics

Figure 11 shows the temperature distribution at the board surface when 600mW of heat is generated during operation. Measurements were taken with an infrared microscope while the backside temperature of the board was fixed at 60ºC. Average temperature of the hot spot was 69.6ºC (maximum 71.2ºC), which was the same result obtained with the thermal simulation. From this outcome, the maximum IC temperature is also assumed the same as the simulation rising 13ºC during operation.

Conclusion

Prototype of an ultra-high frequency power amplifier IC embedded in a printed circuit board was fabricated.

After the IC was embedded, big gain drops were observed in transmission characteristics at certain sections due to the ripple effect, but the gain drop was 1~3dB in the 54~59GHz range. If frequency characteristics are also taken into account, the results are considered good for the printed circuit board. Ripples can be remedied through improvement of the transmission lines and adding converters.

The IC temperature rise was only 13ºC confirming that there is no issue regarding thermal characteristics.

From the results described above, it was determined that manufacturing a module with high output power, ultra-high frequency IC embedded in the printed circuit board is possible. Additionally, embedding high frequency analog and passive circuits (antennas, filters, etc.) into the printed circuit board has simplified the connection with external circuits and helped to demonstrate a technology capable of lowering high frequency application costs. ◆◆

■ References

1) Y. Yoshihara, et al., "A 60-GHz CMOS power amplifier with Marchand balun-based parallel power combiner", IEEE A-SSCC, pp.121-1246, Nov. 2008
2) M. Tanomura, et al., "TX and RX front-ends for 60GHz band in 90nm standard bulk CMOS", Int. Solid-State Circuits Conf. Dig., pp.558-559, San Francisco, CA, Feb. 2008
3) http://www.wirelesshd.org/index.html
4) http://www.ieee802.org/15/pub/TG3c.html
5) http://www.nof.co.jp/business/electron/product07.html
6) S. Hoshi, et al., "Double-Recessed 0.1-μm-Gate InP HEMTs for 40Gbit/s Optical Communication Systems", Jpn. J. Appl. Phys. Vol.42 (2003), pp.2367-2370, Part.1, No.4B, April 2003

● Authors

Masanori Itoh, Network Technology Laboratories, Corporate Research & Development Center

Shinichi Hoshi, Network Technology Laboratories, Corporate Research & Development Center

Hiroshi Iinaga, OKI Printed Circuits Co., Ltd.