Millimeter-Wave Low Noise Amplifiers Suitable for Flip-Chip Assembly

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The E-band (71–86 GHz) is highly expected recently, because of the available wide frequency range, to support backhaul systems for cell phone and mobile communication systems at much higher data rate. The performance and cost of the E-band wireless equipment strongly depend on not only the available devices but also the assembly form. Sumitomo Electric Device Innovations, Inc. (SEDI) and Sumitomo Electric Industries, Ltd. have newly developed so called three-dimensional wafer level chip size package technology (3-D WLCSP) in order to mass produce microwave and millimeter-wave devices and also assemble them simply in the flip-chip fashion. In this paper, we present a low noise amplifier WLCSP-MMIC and some of its design detail in comparison with conventional wire-connected planar low noise amplifier MMIC.

Keywords: WLCSP, millimeter-wave application, flip-chip, low-noise amplifier, mounting capability

1. Introduction

With the dramatic expansion of communication capacity, the E-band is drawing attention as a backhaul frequency band for high-speed large-capacity communication. Among E-band applications, safe driving assistance radars are ahead of communication equipment. The market has been growing every year and is expected to reach several million units per year in 2016. Since the performance and cost of E-band wireless equipment heavily depend on the mounting technology as well as the devices forming the equipment, a low-cost and easy to mass-produce millimeter-wave mounting technology has been sought. Sumitomo Electric Device Innovations (SEDI) and Sumitomo Electric Industries, Ltd. have established Wafer-Level Chip Size Package (WLCSP), which is an advanced form of 3-D GaAs MMIC technology.[(1)-(4)] WLCSP technology enables surface mounting with micro solder balls on the surface of a chip that is covered with a ground conductor. Therefore, neither packaging nor a wire connection is required. Moreover, the adjustment process after mounting can be eliminated, achieving a significant reduction in mounting costs and suitability for mass-production. Devices based on WLCSP technology have been commercialized for inter-base station wireless communication in the quasi-millimeter band (13 to 38 GHz) and transmission amplification for onboard radars (77 GHz).

This paper describes an E-band communication LNA using 3-D WLCSP technology by comparing it with conventional wire mounting LNA.

2. Wire Bonding and Flip Chips

Figure 1 shows conventional wire bonding technology and 3-D WLCSP technology. With mounting based on wire bonding technology, the bonding pads at the edges of an IC chip and the lead electrodes on the package are electrically connected with thin gold wires. In the millimeter band, a significant loss occurs in the package. Therefore, several chips are mounted on a substrate having transmission lines and the entire circuit is hermetically sealed. Variations in the length of each thin gold wire and placement of the chips greatly affect its high-frequency characteristics. In addition, electromagnetic emissions from the wires and other chips can cause unstable operation within the package. To support the solder reflow process, an additional interposer for surface mounting is required.

On the other hand, 3-D WLCSP technology uses moisture-proofing and packaging is not required. As the outer surface of the chip is covered with a ground conductor, emissions from external components never cause operational instability of the circuit on the chip unlike wire-mounting. The ground, input/output, and power supply pads are covered with barrier metal,*[1] on which micro solder balls are placed. Chips are mounted

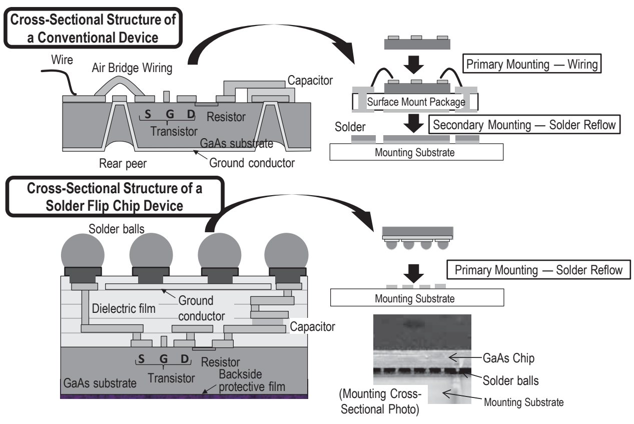

Fig. 1. Wire Bonding Technology and 3-D WLCSP Technology

on a PCB by placing them upside down and reflow-soldering them. As small displacements are corrected by self-alignment during reflow, mounting variations have little effect on the characteristics of the circuit. As with devices such as LNAs, in which the impedance between the mounting substrate and connection part affects the circuit's characteristics, a mounting technology that reduces displacements has great advantages.

3. Noise Figure of an Amplifier

When an amplifier amplifies a signal, it also generates and amplifies noise. The noise performance of an amplifier is represented with a Signal-to-Noise (S/N) ratio. The ratio between the S/N ratio of the input wave and the S/N ratio of the output wave is called a Noise Figure (NF).*2

The noise figure of an amplifier is described in **Equation (1)** using the admittance (Ys) of the signal source.

$$F = F_{min} + \frac{r_n}{Re(Y_S)}|Y_S - Y_{OPT}|^2 \quad \cdots\cdots (1)$$

Where r_n is called the equivalent noise resistance of the FET. Y_{OPT} is the optimal input admittance, which is the signal source admittance that provides the lowest NF. F_{min} has a dependence on frequency, which increases with the frequency, as indicated by **Equation (2)**.

$$F_{min} = 1 + a(f/f_T) + b(f/f_T)^2 \quad \cdots\cdots (2)$$

The NF of a cascade connection of amplifiers is determined by **Equation (3)**.

$$F = F_1 + \frac{F_2 - 1}{G_1} + \cdots + \frac{F_n - 1}{G_1 G_2 \cdots G_{n-1}} \quad \cdots\cdots (3)$$

Eq. (3) indicates that the noise characteristics of a multistage amplifier is largely determined by the NF and gain of the first two stages.

In summary, when designing an LNA, it is important to implement an input matching circuit in conjugation with Y_{OPT}, and to suppress noise contamination in the third stage and after by increasing gains in the first and second stages. This applies to all general LNAs. In the design of a millimeter band LNA it is also necessary to consider the impedance between the mounting substrate and the interface, and the loss in the input matching circuit including those components. These factors can almost be ignored in low-frequency circuits. However, in high frequencies such as the E-band, a very small inductance for each wire or solder ball has a significant effect on impedance and loss in the matching circuit. The capacitance of a metal pad on which a wire and solder ball is attached also affects the characteristics of the circuit.

A WLCSP circuit has a larger earth parasitic capacity compared to a wire mounted circuit, which reduces the gain of an HEMT*3 and increases noise contamination in the following stages. To cope with this, the HEMT structure, which will be discussed later, and amplifier design have been improved to minimize the reduction in gain.

4. Design of an Amplifier

Figure 2 shows the outer appearance of an E-band LNA and its block diagram. The chip sizes of the wire mount device and WLSCP device are 2.0 mm × 1.0 mm and 2.1 mm × 1.1 mm respectively. The solder balls have a diameter of 130 µm and are spaced with a pitch of 300 µm. The LNA consists of two current-reuse amplifiers—one with four 40 µm-gates and the other with six 50 µm-gates. Each amplifier in the second stage comprises two stages of HEMTs. However, the first-stage amplifier is built with two HEMT stages in wire mounting, and three HEMT stages in WLCSP due to a smaller gain per stage.

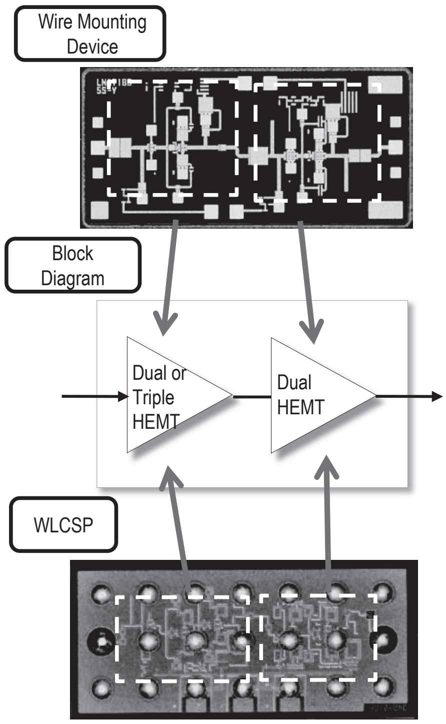

Fig. 2. Outer Appearance and Block Diagram of the LNA

Figure 3 briefly describes a current-reuse amplifier. The current supplied to the drain of the second HEMT flows also draws into the first HEMT through the source of the second HEMT.(5) The gate bias of each HEMT is determined by resister R_S. With an extremely simplified direct current bias circuit, and the total current to the amplifier reduced by half, the bias wires can be made thinner. Different from normal amplifiers, the section between the HEMT stages is high-impedance/voltage-driven, and it follows that gain S_{21}^{DUAL} of the part surrounded by the dashed line is:

$$S_{21}^{DUAL} = \frac{(2g_m Z_0)^2/2}{(Y_{ds}+Y_{RL})Z_0 \cos\theta + j(1+Y_{ds}Y_{RL}Z_0{}^2)\sin\theta} \quad \cdots\cdots (4)$$

Where, Y_{ds} is the capacitance between the drain and source of the HEMT. If θ and Y_{RL} are adjusted so that the absolute value of the denominator becomes 1/2, gain $|S_{21}^{DUAL}|$ is $(2g_mZ_0)^2$. As gain $|S_{21}^{CSF}|$ of a PHEMT with a single source grounding is $2g_mZ_0$, the gain of a current-reuse amplifier is doubled in the dB representation. It can be further increased by optimizing the conditions. This type of configuration has an advantage over a two-stage amplifier by matching each PHEMT with source grounding in that the matching circuit loss can be reduced by half. Therefore, it is suitable for the millimeter band that accompanies large wiring loss, in particular 3-D WLCSP.

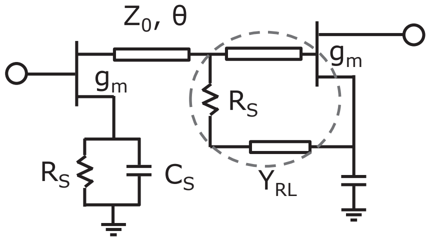

Fig. 3. Current-Reuse Circuit

Figure 4 is the circuit diagram of the first-stage amplifier. To optimize the noise characteristics, the input matching circuit was adjusted so that the impedance on the side of the input terminal from the dotted line matches Y_{OPT} at 86 GHz. The matching circuit includes the solder balls and junctions surrounded by a solid line. The impedance of these parts have been determined with electromagnetic field analysis, and the layout of the solder ball connections have been optimized.(6)

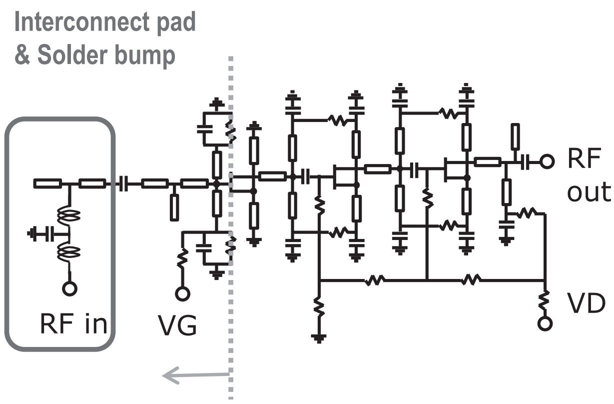

Fig. 4. First-Stage Amplifier

5. Amplification Characteristics

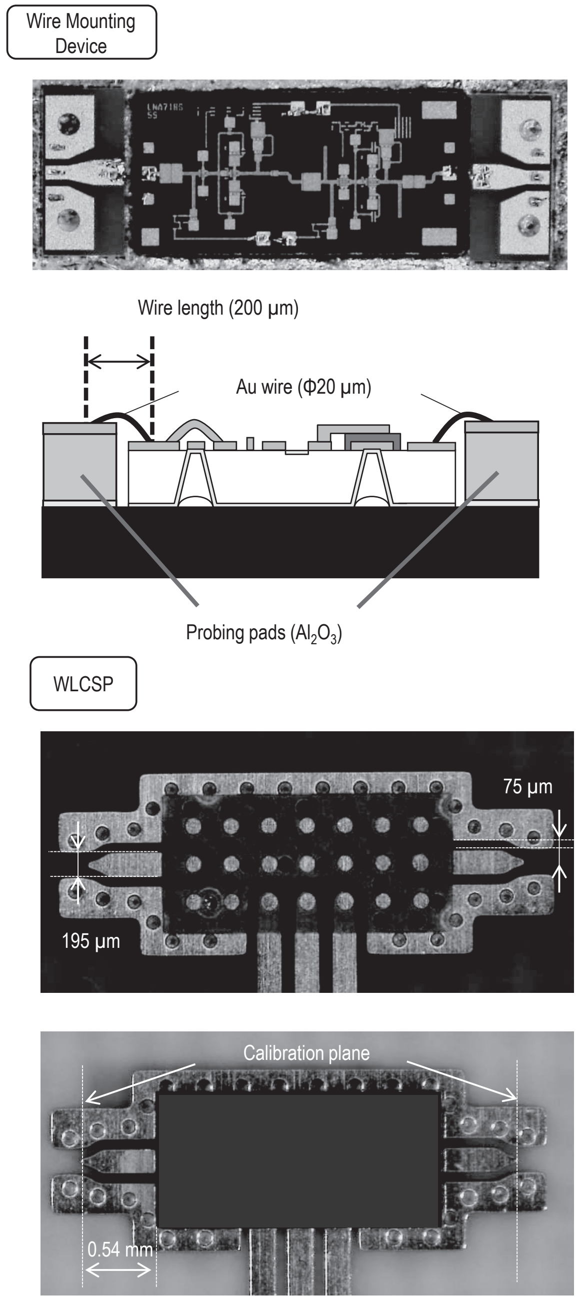

Fig. 5. Outer Appearance after Mounting

Figure 5 shows the outer appearances of a wire mounted device and a WLCSP device. The wire mounted device is attached to a copper plate with AuSn, and its input/output terminals are connected to a G-S-G conversion substrate made of Al_2O_3 with 25 µm Au wires. Each wire is almost straight and approximately 200 µm in length. A wire length of 200 µm is very short and extremely difficult to realize in mass-production assembly. Usually, a wire length of 300 µm or longer is required to make a wire loop with a margin. An approximately 0.3 dB of loss is estimated for the conversion substrate and wires at 86 GHz. The WLCSP chip was mounted on a substrate (RO4450B with a thickness of 100 μm) shown in **Fig. 5** by reflow. The length from the end of the chip to the calibration plane in a probe evaluation was 0.54 mm. The loss in this length is approximately 0.3 dB at 86 GHz.

Figure 6 shows the noise characteristics of the LNA before and after mounting. It also indicates the noise and amplification characteristics with different wire lengths, calculated based on the result of a wire length of 200 μm. In an on-chip evaluation, the LNA for wire mounting has superior noise characteristics by 0.4 dB or more, but the difference is reduced after mounting. With a wire length of 250 μm or longer, the WLCSP device exhibits lower noise characteristics after mounting. This indicates that WLCSP devices are not only easier to mount compared to wire mounting devices, but also superior in reproducibility and suitable for mass-production.

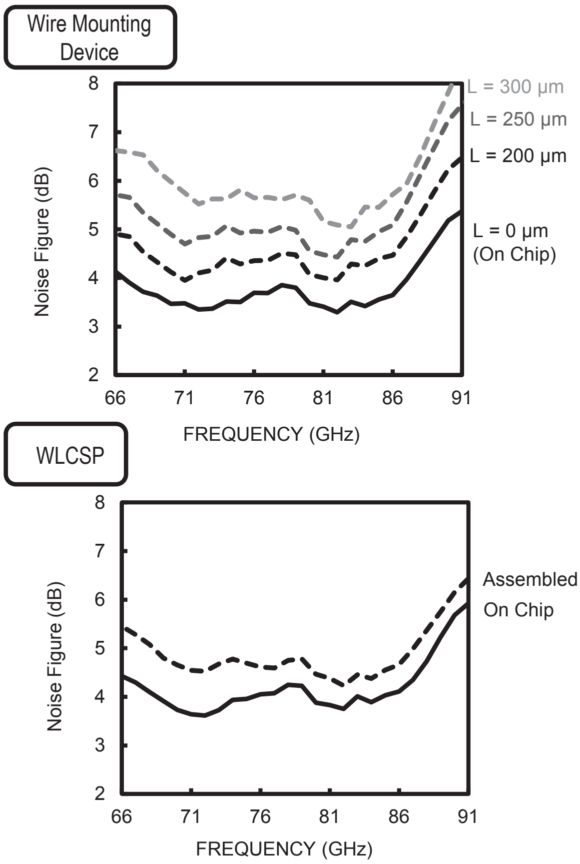

Fig. 6. Noise Characteristics

6. Conclusion

We have designed and prototyped an E-band LNA using the 3-D WLCSP technology of SEDI/Sumitomo Electric. As the noise characteristics of a conventional wire mounting device largely depends on wire length, positioning and bonding require very high precision. On the other hand, a WLCSP device can realize noise characteristics equivalent to or better than a wire mounting device with simple mounting using a normal reflow process. Our development has demonstrated that WLCSP is a technology is suitable for mass-production and superior in reproducibility. We will continue expanding the lineup of millimeter-band products using WLCSP in cooperation with SEDI.

Technical Terms

∗1 Barrier Metal: If a solder ball is connected to a gold pad, it erodes the gold, which substantially degrades reliability. Barrier metal is a metal material that covers the pad to prevent erosion by solder.

∗2 Noise Figure: The ratio between the S/N of the input signal to a circuit and the S/N of the output signal.

∗3 HEMT: High Electron Mobility Transistor. It is a field-effect transistor with a two-dimensional electron gas induced on a semiconductor hetero junction interface. It has superior high-frequency and noise characteristics.

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