A 100-GHz Distributed Amplifier in Chip-size Package

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Abstract — **We developed a new millimeter-wave plastic chip size package (CSP) to operate up to 100 GHz by using a thin-film substrate. It has a flip-chip distributed amplifier with inverted microstrip lines that has a bandwidth of beyond 110 GHz. The CSP amplifier achieved a gain of 7.8 dB and a 3dB bandwidth of 97 GHz, and operated up to 100 GHz as an amplifier. To our knowledge, this value is the highest operating frequency reported to date for a distributed amplifier sealed in a plastic CSP.**

I. INTRODUCTION

The urgent demands to reduce the cost of MMIC modules in commercial millimeter-wave (MMW) applications, such as those for radar and communication systems, are increasing. The flip-chip bonding (FCB) technique shows promise in meeting these demands due to small connection inductance, reduced package size and its potential for high-volume production [1-3]. Many FCB MMICs with coplanar wave-guides (CPWs) have been reported [4-6]. However, their packages are hermetically sealed, metal-wall or ceramic types that are still very expensive due to material costs and complex assembly processes [7-8]. Although non-hermetic plastic packages are the best solution to reducing these expenses, the mold resin that seals the MMICs significantly degrades their electrical performance because of the parasitic capacitance of the transistors and transmission lines on the chip. In addition, mold resin seriously affects the performance of the transmission line on the package substrate, in the form of insertion loss and isolation of coupled lines, since the mold resin's dielectric constant and loss tangent are larger than those for air. Therefore, when using plastic packages for FCB MMICs, we have to take into account the changes in transistor and line characteristics. However, that complicates not only to design FCB MMICs accurately but also to assure a known good die (KGD). The purpose of this paper is to overcome these difficulties and to provide the most cost-effective millimeter-wave chip size package (MMW-CSP) operating at up to 100 GHz. To achieve this purpose, we first developed a distributed amplifier with a 3-dB bandwidth of more than 110 GHz by using inverted microstrip lines (IMSL) [9]. The performance of the MMIC did not change after molding, theoretically due to electromagnetic shielding by the top ground layer of the chip. Second, we propose the use of a cost-effective polyimide film as a package substrate. Techniques to suppress the influence of the mold resin and secure high isolation of couple lines are described in terms of using a thin-film substrate. The fabricated CSP demonstrated record bandwidth performance, which has not yet been reported for any CSP amplifier. In addition, we investigated the role of electrical characteristic of lead-free SnZnAl solder bumps [10] in providing an accurate design for broadband CSP MMICs operating at up to 110 GHz.

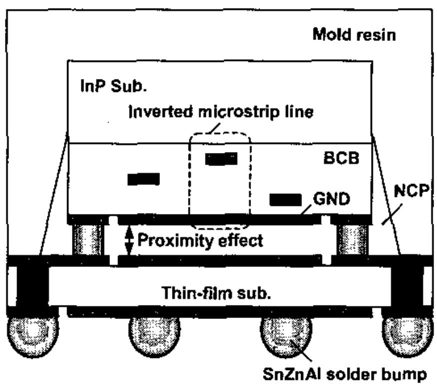

Fig. 1 Schematic cross-section of MMW plastic CSP structure.

II. Millimeter-wave Chip Size Package Structure

Figure 1 is a schematic cross-section of the proposed MMW-CSP structure. The multi-layer MMIC chip is mounted by FCB with pillar on a polyimide thin-film substrate. We used the non-conductive paste (NCP) FCB to mount the MMIC on the substrate. This technique has a shorter assembly time and lower assembly temperature than the gold-tin eutectic reaction method [11], and does not require underfill between the chip and assembly substrate after FCB because this underfill is done with FCB. There is a cross-sectional microphotograph of the connecting pillar in Fig. 2. The MMIC was attached to the thin-film substrate with NCP.

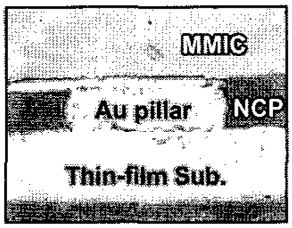

Fig. 2 Microphotograph of pillar connecting MMIC and thin-film substrate by NCP FCB method.

The multi-layer transmission lines on the MMIC chip are formed with BCB (Benzocyclobutene) films. The top layer of the MMIC chip is covered with ground metal (GND) that screens face-down ICs from the underfill resin, and prevents line parameters from changing from those before to those after underfill. The IMSLs for matching circuits are formed with a signal line at the first layer and a ground plane at the top of the chip, as indicated by a rectangle circumscribed by dashed lines in Fig. 1. The thin-film substrate interposes to widen the pad pitch of the signal lines to simplify assembly and to ensure signal lines are effectively isolated. The chip is sealed with mold resin

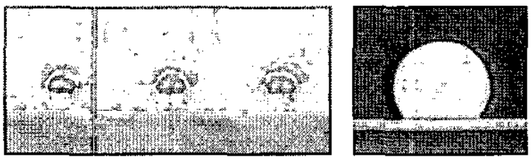

Fig. 3 Microphotographs of lead-free SnZnAl solder bumps on thin-film substrate. Solder bump diameter is 130 μm.

to increase mechanical strength and reliability. The rear of the CSP has arrayed solder bumps that connect to the printed circuit boards (PCBs), as Fig. 3 shows. The bumps are lead-free SnZnAl solder that has a lower melting temperature of 199 °C than conventional lead-free solder such as SnAgCu. Their diameter is 130 μm.

III. Millimeter-wave Chip Size Package Design

At high frequencies, the transmission line loss from the dielectric loss tangent is a serious problem. Mold resin increases loss in the transmission line on a thin-film

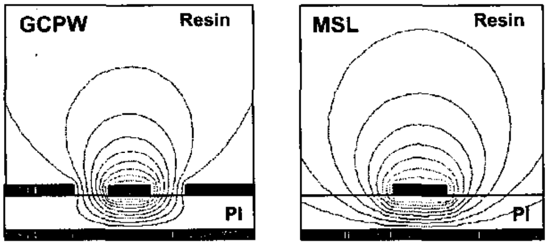

Fig. 4 Cross-sectional potential profile of GCPW and MSL on thin-film polyimide substrate with mold resin. GCPW prevents electric field from expanding more than MSL.

substrate because the resin's loss tangent is larger than that for air. Furthermore, it is essential to isolate signal lines, because cross-talk degrades the MMIC's electrical performance due to feedback oscillations. Mold resin increases the coupling between transmission lines because it has a higher dielectric constant than air. Consequently, we focused on how to decrease transmission line loss and how to ensure effective isolation. First, we fabricated ground plane at the rear of the thin film substrate to concentrate electric field into it because the loss tangent of polyimide is smaller than that of mold resin. The ground

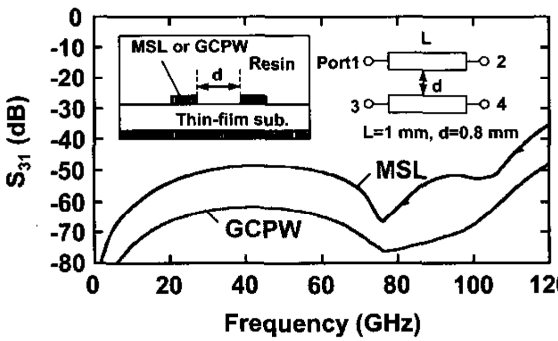

Fig. 5 Comparison of calculated isolation characteristics for coupled MSL and GCPW using electromagnetic simulator. Space (d) is 0.8 mm and length (L) is 1 mm.

plane also screens transmission lines from the PCB so they are not affected by it. We then compared various kinds of transmission lines on the substrate. We found a grounded CPW (GCPW) concentrated electric field into the thin-film substrate more than microstrip lines (MSLs). Figure 4 shows the constant potential of a GCPW and MSL on a thin-film substrate simulated by electromagnetic simulator. We can clearly see that GCPW prevents electric field from expanding near the signal line more than MSL does. This creates better isolation characteristics than those obtained by MSL. Figure 5 compares calculated isolation for coupled lines for GCPW

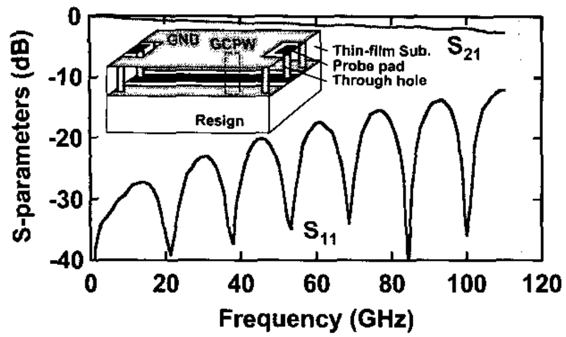

Fig. 6 Through line characteristic of fabricated MMW-CSP. Through line consists of molded GCPW and two through holes. GCPW is 5-mm long.

and MSL. The S_{31} of GCPW is 10 dB less than that of MSL. Therefore, a GCPW structure with a thin-film substrate is best for fabricating a MMW-CSP.

Figure 6 shows measured S-parameters for the through line test element group (TEG) expressed in the graph. The GCPW was formed with both CPW between the thin–film substrate and resin, and the ground plane on the surface of the TEG, as a rectangle circumscribed by dashed lines in Fig. 6 shows. The GCPW is connected to probe pads by through holes. The GCPW is 5-mm long. The S_{11} is less

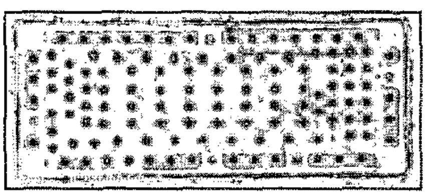

Fig. 7 Microphotograph of IMSL distributed amplifier. Chip is 2.5 x 1.1 mm.

than –15 dB up to 90 GHz, and less than –10 dB up to 110 GHz and over. The S_{21} is -1.7 dB, equal to an insertion loss of 0.34 dB/mm at 80 GHz. Therefore, our technique, to design a package with GCPW, shows promise at high frequencies.

We also assembled an IMSL distributed amplifier in the CSP to verify the FCB MMIC characteristics in the CSP. Figure 7 is a microphotograph of the IMSL distributed amplifier. We employed 0.13-μm InAlAs/InGaAs/InP HEMT technology with an f_T of 160 GHz and an f_{max} of 270 GHz. We formed NiCr resistors with a sheet

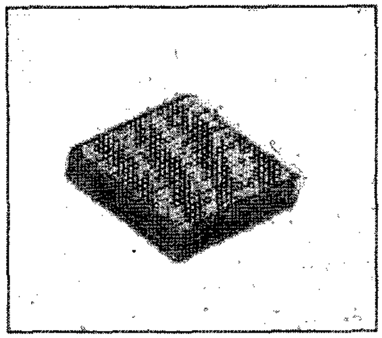

Fig. 8 Photograph of fabricated MMW-CSP with IMSL distributed amplifier. CSP is 5.5 x 5.5 x 1.1 mm (0.033 cc).

resistance of 50 □/square and SiN MIM capacitors. A BCB was coated on the wafer by means of a spin coater. A bonding pillar was fabricated on the surface of the chips with a wafer process. The pillar's diameter was 40 □m and its height was 20 □m. The chip was only 2.5 x 1.1 mm^2.

Figure 8 is a photograph of the MMW-CSP we fabricated and it is only 5.5 x 5.5 x 1.1 mm (0.033 cc). Figure 9 compares the S-parameters of a bare chip and the

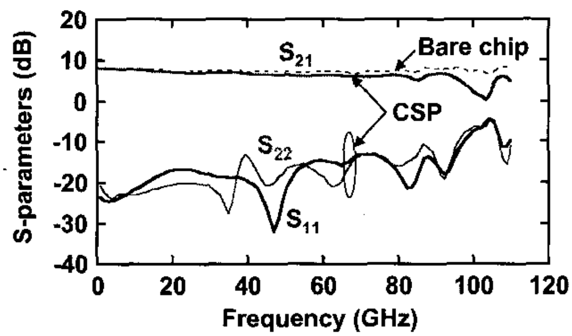

Fig. 9 MMW-CSP performance with IMSL distributed amplifier. S_{21} of bare chip is also plotted. Solid line and dotted line indicate the characteristic of the CSP and the bare chip, respectively.

MMW-CSP. The MMW-CSP amplifier has a gain of 7.8 dB and a 3-dB bandwidth of 97 GHz, which is the highest performance for any distributed amplifier sealed in a molded package that has been reported to date. The return loss was better than 10 dB up to 97 GHz. The gain profile of the MMW-CSP almost corresponded with that of the bare chip up to 100 GHz. A slight difference in the S_{21} resulted from insertion loss in the transmission line on the thin-film substrate. Though the return loss and gain degraded above 100 GHz, these were due to characteristics of the FCB components between the chip and thin-film substrate.

Figure 10 shows through line characteristics of the MMW-CSP mounted on a PCB. The CSP was placed on and attached to the PCB. The S_{11} was better than −10 dB up to 110 GHz. There was some S_{21} ripple from the transmission characteristics of the PCB. These results indicate that our MMW-CSP technology is essential not only for achieving an accurate broadband CSP design but it also reduces the cost of MMIC modules operating up to the W-band.

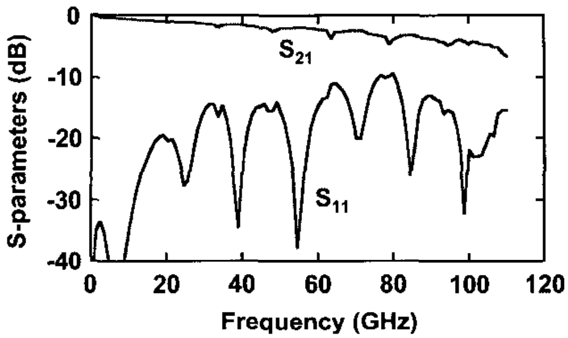

Fig. 10. Through line characteristic of fabricated MMW-CSP mounted on PCB with lead-free SnZnAl solder bumps.

IV. Conclusion

We demonstrated the fabrication of a millimeter-wave CSP by using a thin-film polyimide substrate and an IMSL MMIC. The fabricated CSP amplifier successfully achieved a gain of 7.8 dB and a 3-dB bandwidth of 97 GHz. In addition, we verified that the CSP, mounted on a PCB with SnZnAl solder bumps, had excellent performance up to 110 GHz. It is the most attractive candidate to achieve cost-effective MMIC modules for commercial millimeter-wave applications requiring operation up to the W-band.

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