An Over 110-GHz InP HEMT Flip-chip Distributed Baseband Amplifier with Inverted Microstrip Line Structure for Optical Transmission Systems

S. Masuda, T. Hirose, T. Takahashi, M. Nishi*, S. Yokokawa*, S. Iijima, K. Ono, N. Hara, and K. Joshin

FUJITSU LABORATORIES LTD.
*FUJITSU QUANTUM DEVICES LTD.
10-1 Morinosato-Wakamiya, Atsugi 243-0197, Japan

Tel.: +81-46-250-8244 Fax: +81-46-250-4337
E-mail: masuda@flab.fujitsu.co.jp

Abstract

We successfully developed state of the art InP HEMT distributed amplifiers by using inverted microstrip line technology. For one, we achieved a gain of 14.5 dB and a 94-GHz 3-dB bandwidth resulting in a gain-bandwidth product of 500 GHz, and for the other we achieved a gain of 7.5 dB and a 3-dB bandwidth of over 110 GHz. This technology also demonstrates the capability of fabricating ultra-broadband packaged IC's with flip-chip assembly for operation up to the W-band. To our knowledge, these results represent the highest gain bandwidth product and the widest bandwidth for distributed amplifiers reported to date.

Keywords

Inverted microstrip line, flip-chip, distributed amplifiers, InP HEMT.

INTRODUCTION

Distributed baseband amplifiers are key components for optical fiber communication systems. Kimura *et al*. reported a 0-90-GHz amplifier with a 10-dB gain by using InP HEMTs [1]. Baeyens *et al*. demonstrated a 70-GHz bandwidth amplifier with a gain of 17 dB, resulting in a gain bandwidth product (GBW) of 495 GHz by using InP HBTs [2]. However, when employing these IC's for future systems beyond 40 Gbit/s, chip assembly is a big challenge because the parasitic wire inductance affects ICs' performance significantly due to short signal wavelength. Flip-chip bonding (FCB) is a most important technique since it can be used to connect a chip and an assembly substrate with a much shorter length than can be achieved with ribbon or wire bonding. When designing FCB circuits with coplanar waveguides (CPWs), however, the proximity effect between chips and substrates seriously influences their face down circuit performance because it changes transmission line parameters, such as characteristic impedance, compared with those before and after FCB [3]. Therefore, designing FCB IC's precisely is difficult, and determining a good die before FCB by performing an RF on-wafer measurement is also difficult. To overcome these challenges, we developed distributed amplifiers based on inverted microstrip line (IMSL) technology. In addition, we examined the technology's capability for accurate design of broadband FCB ICs and easy assembly on substrates of chips designed for operation at up to 110 GHz.

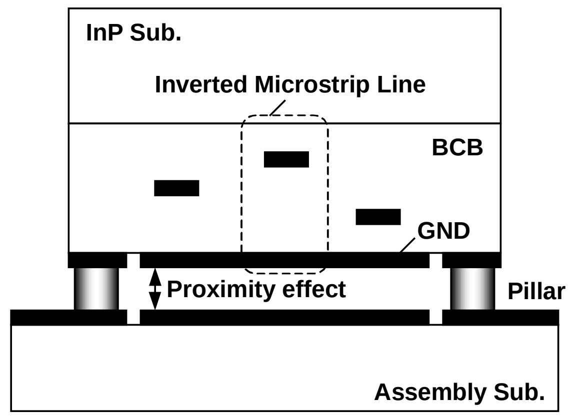

Figure 1. Schematic cross section of FCB multi-layer transmission line structure.

CIRCUIT DESIGN

Figure 1 shows a schematic cross section of the FCB multi-layer IC's structure. The chip is mounted on the as-

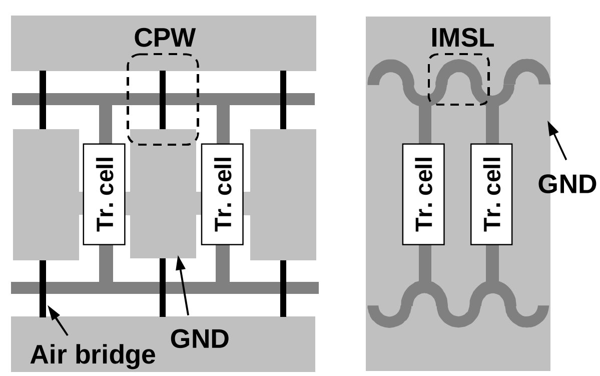

Figure 2. Comparison of schematic layout of distributed amplifiers designed with CPW and IMSL.

sembly substrate with bonding pillars. The multi-layer transmission lines are formed with BCB (Benzocyclobuten) films, which have a low dielectric constant (ε_r=2.6). The top layer of the chip is covered with ground metal (GND) that screens face-down ICs from assembly substrates and prevents changing of line parameters between those before and those after FCB. 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 the dotted circles in Figure 1. Unlike a CPW, using an IMSL provides precise circuit design because the ground plane is everywhere above signal lines, and we can make accurate line models in circuits such as T-junctions. Moreover, an IMSL is sutable for designing broadband circuits such as distributed amplifiers because its transmission line characteristics have little frequency dispersion.

Figure 2 shows the circuit layout of two distributed amplifiers, one with a CPW and the other with an IMSL. In the layout with a CPW, the ground plane between transistors is connected to an ideal ground plane by air-bridges that make the ground potential unstable at high frequencies due to the inductance of the air-bridge. On the other hand, the IMSL layout provides stable ground potential even in high frequencies because it can maintain a large ground plane in the circuit.

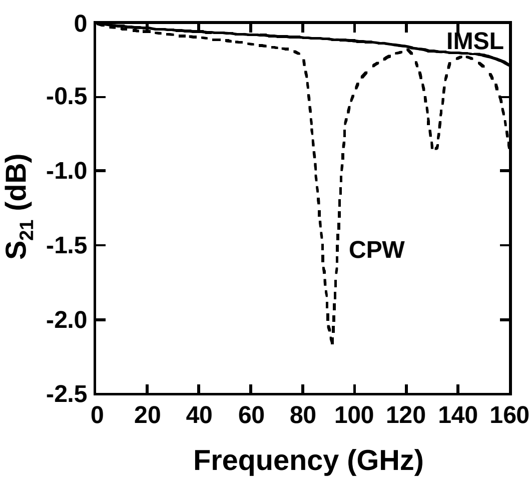

Figure 3. Comparison of simulated S_{21} characteristics of CPW and IMSL in distributed amplifiers. Solid line and dotted line indicate S_{21} of IMSL and CPW, respectively.

Figure 3 shows a comparison of simulated S_{21} for CPW and IMSL in a distributed amplifier with 200-μm line length (shown circled in figure 2). The S_{21} of CPW constantly decreases at frequencies up to 80 GHz, but there are fluctuations above 80 GHz. On the other hand, the S_{21} of IMSL decreases without fluctuations at increasing frequencies up to 160 GHz. Therefore, IMSL is suitable for designing a distributed amplifier for operation at higher frequencies. In addition, we can reduce chip size by using an IMSL because we can easily form meander lines and nar-

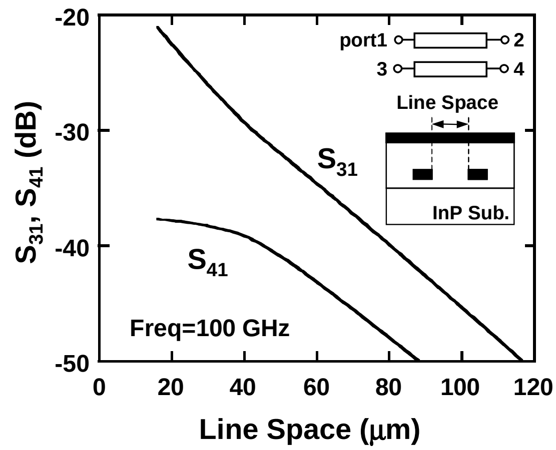

Figure 4. Simulated isolation characteristic of couple inverted microstrip lines at 100 GHz.

row line spaces compared to using a CPW that has ground layers at both sides of signal lines.

When designing distributed amplifiers for high-frequencies range such as 100 GHz, we focused on the isolation of coupled lines to reduce line space for circuit compaction and to suppress the undesired oscillation due to cross talk between transmission lines. Figure 4 shows the isolation characteristic of the coupled IMSL calculated by using an electromagnetic simulator. A 40-μm line space between coupled lines is enough to maintain more than 30-dB isolation at 100 GHz, and this was applied to the circuit design. This IMSL structure is much more effective than CPW structure for reducing circuit size.

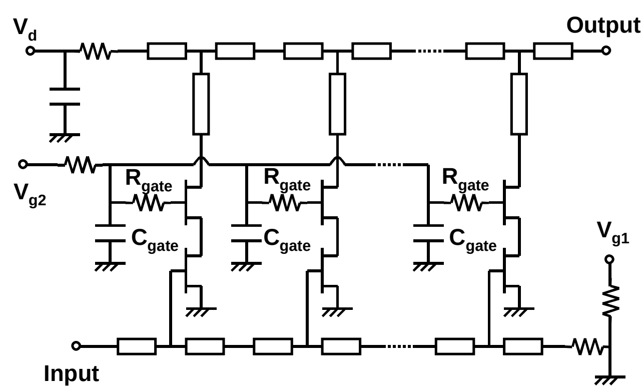

Figure 5. Circuit diagram of distributed amplifier.

Figure 5 shows a schematic diagram of a distributed amplifier. Cascode HEMTs were used to generate negative resistance and to achieve high gain bandwidth product. To enhance the stability of the circuit at high frequency, we inserted a series dumping resistance R_{gate} between the capacitance C_{gate} and the gate of the common-gate transistor [4].

FABRICATION AND CIRCUIT PERFORMANCE

We employed 0.1-µm-class InAlAs/InGaAs/InP HEMT technology with f_T of 160 GHz and f_{max} of 270 GHz. We formed NiCr resistors with a sheet resistance of 50 Ω/square and SiN MIM capacitors. The BCB was coated on wafer by means of a spin coater and cured at 250°C. A bonding pillar was fabricated on the surface of chips by using a wafer process. This pillar was for connecting them to the assembly substrate by using FCB. The pillar's diameter and height were 40 µm and 20 µm, respectively

Figure 6 is a microphotograph of an eight-stage distributed amplifier fabricated by using cascode configuration and using 40-µm gate width HEMTs. The chip size is only 2.5 x 1.1 mm^2. This distributed amplifier achieved a gain of 14.5 dB and a 3-dB bandwidth of 94 GHz resulting in a GBW of 500 GHz, as is shown in Figure 7. The gain ripple was within ±0.7 dB up to 90 GHz.

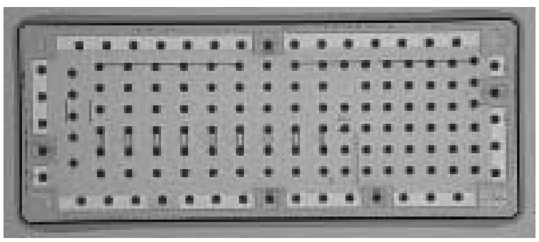

Figure 6. Microphotograph of eight-stage distributed amplifier. Chip size is 2.5 mm x 1.1 mm.

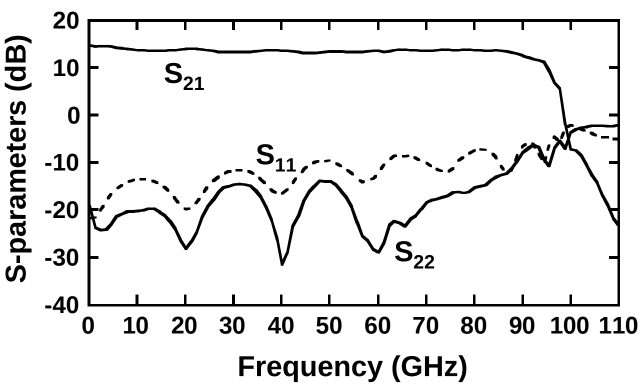

Figure 7. S-parameters of eight-stage distributed amplifier measured on wafer.

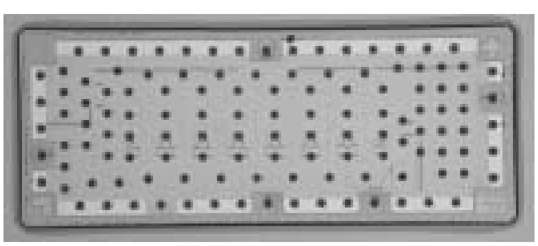

Figure 8. Microphotograph of seven-stage distributed amplifier. Chip size is 2.5 mm x 1.1 mm.

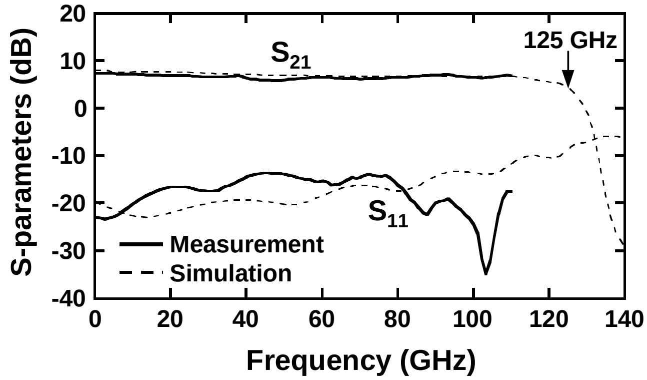

Figure 9. Comparison of measured and simulated S-parameters for seven-stage distributed amplifier. Solid line and dotted line indicate measured and simulated results, respectively.

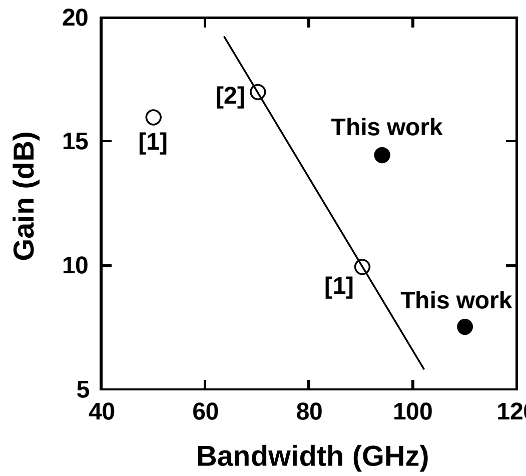

Figure 10. Comparison of gain versus bandwidth for distributed amplifiers.

Figure 8 is a microphotograph of a seven-stage distributed amplifier with 20-µm gate width HEMTs at each stage. The chip size is only 2.5 x 1.1 mm^2. The seven-stage distributed amplifier exhibited a very flat gain of 7.5 dB and the gain ripple was within ±0.8 dB up to 110 GHz, as is shown in Figure 9. The input return loss was less than 13 dB up to 110 GHz. Figure 9 also shows that the simulated result almost corresponded with the measured one, and that it estimated a 3-dB bandwidth of 125 GHz. This result indicates that our design technology provides accurate broadband IC design up to 110 GHz. Figure 10 shows a comparison of our work with distributed amplifiers recently reported. Our distributed amplifiers exhibited the best gain performance at a higher frequency range than any distributed amplifiers yet reported.

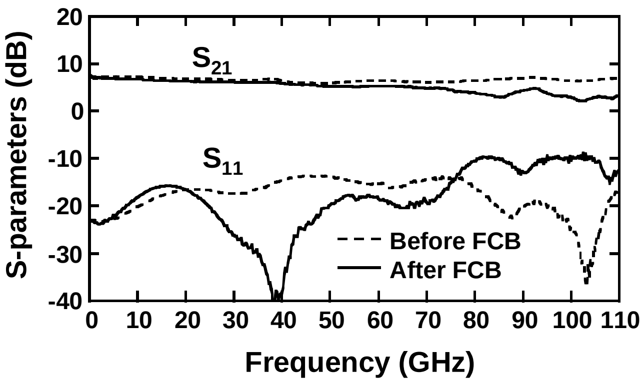

Figure 11. Comparison of S-parameters before FCB and after FCB for seven-stage distributed amplifier. Solid line and dotted line indicate before and after FCB results, respectively

Figure 11 shows a comparison of the S-parameters before FCB and after FCB. The FCB was done on alumina ceramic substrates by using the gold-tin eutectic reaction method [5]. The seven-stage amplifier had nearly the same gain for both before and after FCB up to 110 GHz due to the ground metal at the top of the chip. A little difference of the S_{21} at a high frequency region came from transmission line loss and return loss on assembly substrates. These results show that our multi-layer IC technology is essential not only to achieve precise broadband FCB IC design but it also makes possible both IC assembly without precise pillar height control and testing of FCB ICs by RF on-wafer measurement before FCB.

Conclusion

We fabricated state-of-the-art InP HEMT distributed amplifiers with IMSL. One demonstrated a gain of 14.5 dB and a 3-dB bandwidth of 94 GHz, and another achieved a gain of 7.5 dB and a 3-dB bandwidth of over 110 GHz. We also verified that a chip fabricated with IMSL could provide easy FCB assembly on substrates to achieve operation up to 110 GHz. This technology is a promising means to fabricate high-speed IC modules for future 80- or 160-Gbit/s optical transmission systems.

ACKNOWLEDGMENTS

The authors would like to thank M. Takikawa and Y. Yamaguchi for their encouragement. They also thank M. Shigematsu for his helpful discussions of MMIC design.

REFERENCES

[1] S. Kimura, *et al*., "Loss-compensated distributed baseband amplifier IC's for optical transmission systems, " IEEE Trans. Microwave Theory Tech., vol. 44, pp. 1688-1693, 1996.

[2] Y. Baeyens, *et al*., "InP D-HBT IC's for 40 Gb/s and higher bitrate lightwave transceivers, " *2001 IEEE GaAs IC Symp*., pp. 125-128, 2001.

[3] S. Masuda, *et al*., "A new flip-chip MMIC technology with multi-layer transmission line structure for low-cost W-band transceivers, " *2001 IEEE GaAs IC Symp*., pp. 118-121, 2001.

[4] M. Shigematsu, *et al*., "A 49-GHz preamplifier with a transimpedance gain of 52 dBΩ using InP HEMTs, " *IEEE J. Solid-State Circuits*, vol. 36, pp. 1309-1313, 2001.

[5] S. Aoki, *et al*., "A flip chip bonding technology using gold pillars for millimeter-wave applications," *IEEE MTT-S Digest*, pp. 731-734, 1997.