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High-Frequency and Integrated Design Based on Flip-Chip Interconnection Technique (Hi-FIT) for High-Speed (>100 Gbaud) Optical Devices

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SUMMARY We developed a high-frequency and integrated design based on a flip-chip interconnection technique (Hi-FIT) as a wire-free interconnection technique that provides a high modulation bandwidth. The Hi-FIT can be applied to various high-speed (>100 Gbaud) optical devices. The Hi-FIT EA-DFB laser module has a 3-dB bandwidth of 59 GHz. And with a 4-intensity-level pulse amplitude modulation (PAM) operation at 107 Gbaud, we obtained a bit-error rate (BER) of less than 3.8×10^{-3}, which is an error-free condition, by using a 7%-overhead (OH) hard-decision forward error correction (HD-FEC) code, even after a 10-km SMF transmission. The 3-dB bandwidth of the Hi-FIT employing an InP-MZM sub-assembly was more than 67 GHz, which was the limit of our measuring instrument. We also demonstrated a 120-Gbaud rate IQ modulation.

key words: *flip-chip, EA-DFB laser, Mach-Zehnder modulator, packaging*

1. Introduction

Internet traffic is increasing rapidly thanks to the fast growth of cloud computing and mobile services. 100-gigabit-Ethernet (100GbE) was standardized for data-center networks in 2010 [1]. And a $4\lambda\times25.8$ Gbit/s non-return to zero (NRZ) scheme was employed for a 10-km single-mode-fiber (SMF) transmission. However, a 400-Gbit/s 10-km optical link system is now being standardized by the 100G Lambda Multi-Source Agreement (MSA) Group [2], and a promising candidate is a $4\lambda \times 53.2$-Gbaud 4-intensity-level pulse amplitude modulation (PAM) system. As for long-haul networks, a 100G/λ system was standardized in 2010 by the Optical Internetworking Forum (OIF) [3], and it employs a 32-Gbaud dual-polarization multiplexed quadrature phase-shift keying (DP-QPSK) scheme. But, the 400G/λ system is now being standardized, and a 64-Gbaud dual-polarization multiplexed sixteen-level quadrature amplitude modulation (DP-16QAM) is a promising candidate. As described above, regardless of the application, the baud rate has been increasing. And to cope with this increase, we need a high-bandwidth optical module.

An electroabsorption modulator integrated with a distributed feedback laser (EA-DFB laser) is a promising device for use as a high-speed optical transmitter for a data-center network. The 25- and 40-Gbit/s NRZ operation of an EA-DFB laser module has been reported [4]–[7]. A Mach-Zehnder interferometer modulator (MZM) has good potential for use as a high-speed optical transmitter for long-haul applications. Although an MZM requires a higher modulation voltage and has a larger chip size than an EA-DFB laser, it can generate an optical phase-shift-keying (PSK) signal as a QPSK and a QAM. The 25- and 40-Gbaud operation of MZM modules has been reported [8], [9]. In these reported modules, a conventional wire interconnection technique was employed to connect between a chip and a radio frequency (RF) circuit board and between a chip and a terminator. However, the bonding wire degrades the frequency response of the module due to parasitic inductance. Therefore, to fabricate a high-speed (>100 Gbaud) optical module using an EA-DFB laser or an MZM, we need a wire-free interconnection technique.

We developed a high-frequency and integrated design based on a flip-chip interconnection technique (Hi-FIT) as a wire-free interconnection technique [10], [11]. This technique uses an impedance-controlled RF circuit board and gold bumps with a height of less than 30 μm instead of bonding wires, and so provides a higher modulation bandwidth. In this paper, we describe the Hi-FIT and report the 107-Gbaud 4-PAM operation of the Hi-FIT EA-DFB laser module with a 3-dB bandwidth of 59 GHz and the 120-Gbaud QPSK operation of the Hi-FIT MZM sub-assembly with a 3-dB bandwidth of more than 67 GHz.

2. High-Frequency and Integrated Design Based on Flip-Chip Interconnection Technique (Hi-FIT)

In this section, we describe a high-frequency and integrated design based on a flip-chip interconnection technique (Hi-FIT) by taking the EA-DFB laser sub-assembly as an example. Figure 1 (a) shows the schematic structure of an EA-DFB laser sub-assembly employing a conventional wire interconnection technique. An EA-DFB laser chip, a terminator and an RF circuit board are mounted on the subcarrier. The RF circuit board is connected to the EA-DFB laser chip using bonding wire with a length of about 0.2 mm and the

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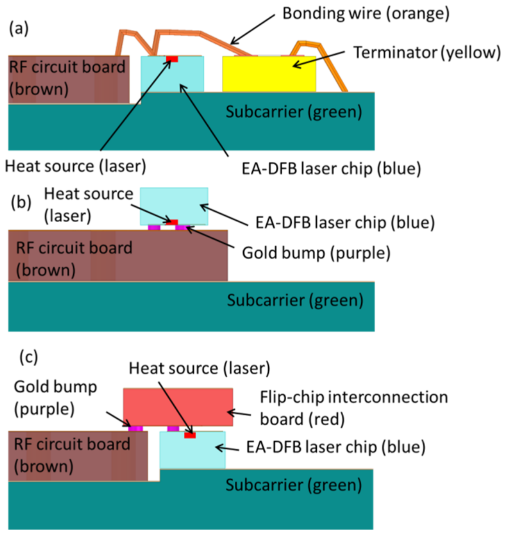
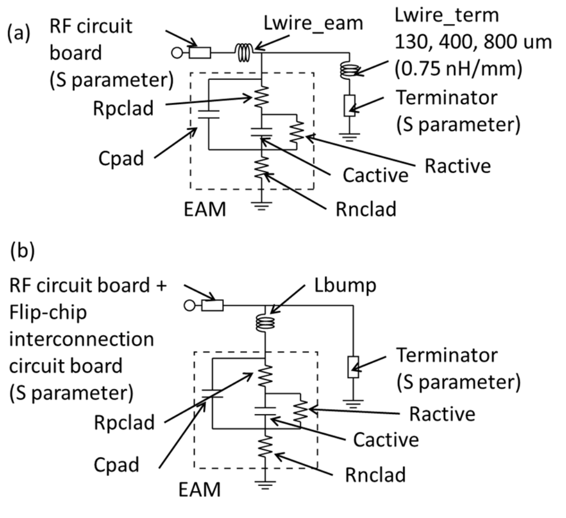


Fig. 1 Schematic structure of (a) wire interconnection, (b) flip-chip mounting and (c) Hi-FIT EA-DFB laser sub-assemblies.



All S parameters were calculated by an HFSS

Fig. 2 Equivalent circuit of (a) wire interconnection and (b) Hi-FIT EA-DFB laser sub-assemblies.

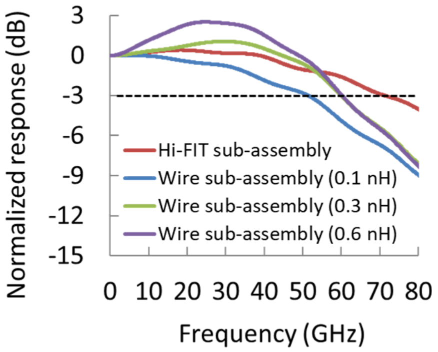


Fig. 3 Frequency responses of wire interconnection and Hi-FIT EA-DFB laser sub-assemblies.

EA-DFB laser is also connected to the terminator using the bonding wire. This wire has a parasitic inductance and degrades the modulation bandwidth. Figure 1 (b) shows a conventional flip-chip mounting EA-DFB laser sub-assembly. An RF circuit board is integrated with a terminator. An EA-DFB laser chip is mounted face down on the RF circuit board via gold bumps about 30 μm high and about 60 μm in diameter. This technique requires no bonding wire at all and makes it possible to increase the modulation bandwidth. However, this approach has a thermal flow problem. The bottom surface temperature of the subcarrier is controlled with a thermo-electric cooler (TEC). In Fig. 1 (a), the heat generated by the laser chip is dissipated through the laser chip and the subcarrier. On the other hand, in Fig. 1 (b), the heat is dissipated through the gold bumps and the subcarrier. The gold bumps are only 60 μm in diameter and so the chip temperature increases. Therefore, we proposed the Hi-FIT EA-DFB laser sub-assembly shown in Fig. 1 (c). A flip-chip interconnection circuit board, which is integrated with a 50-ohm terminator, is connected to an RF circuit board and an EA-DFB laser chip through gold bumps about 30 μm high. This circuit board also includes controlled high-impedance coplanar line. This proposed technique also requires no bonding wire at all and makes it possible to increase the modulation bandwidth. And the thermal path of this sub-assembly is nearly the same as that of the wire interconnection EA-DFB laser sub-assembly as shown in Fig. 1 (a), because the EA-DFB laser chip is mounted face up. As a result, this proposed technique has no thermal problem.

The frequency response of the conventional wire interconnection and Hi-FIT EA-DFB laser sub-assemblies were estimated with equivalent circuits. Figure 2 (a) and (b) show the equivalent circuit of the wire interconnection and the Hi-FIT EA-DFB laser sub-assemblies, respectively. The RF circuit board and the flip-chip interconnection circuit board were made of aluminum nitride and their signal lines are a coplanar waveguide. We estimated the frequency responses of these circuit boards and of the terminator using a three-dimensional electromagnetic field simulator (ANSYS HFSS) [12]. Rpclad, Ractive and Rnclad are the parasitic resistances of the electroabsorption modulator (EAM) p-cladding layer, the active layer and the n-cladding layer, respectively. Cpad and Cactive are the parasitic capacitances of the EAM pad and the active layer, respectively. Lbump, Lwire_eam and L_wire_term are the parasitic inductances of the gold bump, the wire between the EA-DFB laser and the RF circuit board and between the EA-DFB laser and the terminator, respectively. Ractive, Rpclad, Rnclad, Cpad, Cactive, Lbump, and Lwire_eam were set at 110, 18.2, 2 ohms, 0.05, 0.085 pF, and 0.03, 0.15, respectively.

Figure 3 shows the simulated frequency responses of the conventional wire interconnection and Hi-FIT EA-DFB laser sub-assemblies. For the wire interconnection sub-assembly, as the inductance of the termination wire (Lwire_term) increases, the peak level of the frequency response increases. However, the frequency response of the wire interconnection sub-assembly degrades rapidly and the

3-dB bandwidth was lower than 60 GHz. On the other hand, the frequency response of the Hi-FIT sub-assembly has no rapid degradation. And the 3-dB bandwidth exceeded 70 GHz. These results indicate that the Hi-FIT contributes to an increase in the modulation bandwidth.

3. Hi-FIT EA-DFB Laser Module

We fabricated an EA-DFB laser module incorporating the Hi-FIT. The fabricated module includes the Hi-FIT EA-DFB laser sub-assembly, which is mentioned in Chapter 2, and has a V connector as an RF connector. The RF circuit board was connected to the package with a 100 μm long ribbon wire. Figure 4 (a) and (b) shows the equivalent circuit of the Hi-FIT EA-DFB laser module and the lasing spectrum, simulated frequency response and measured E/O response of this module, respectively. The chip temperature, laser diode current and EA bias voltage were 25°C, 100 mA and −2.0 V, respectively. The peak wavelength was 1305.4 nm and the side-mode suppression ratio (SMSR) exceeded 50 dB. The simulated frequency response was estimated by using the same parameters in Chapter 2. And the S parameter of the package is measurement value. The measurement result fits the simulation result. And the measured 3-dB bandwidth of the module exceeded 59 GHz.

We performed a 107-Gbaud 4-PAM (214-Gbit/s) signal transmission experiment using the fabricated Hi-FIT EA-DFB laser module. Figure 5 shows the measurement setup for a 214-Gbit/s operation. Two 107-Gbit/s NRZ $2^{15} - 1$ pseudo-random bit sequence (PRBS) signals were generated by using 2:1 multiplexers (MUXs) with different bit delays. The output from one of the MUXs was attenuated by 6 dB, and then both signals were combined with an analog combiner. We obtained clear eye opening for the electrical 107-Gbaud 4-PAM signal, as shown in the figure. The 4-PAM signal was amplified by using an electrical amplifier with a bandwidth of more than 65 GHz. The amplified signal voltage was 1.2 Vpp. The chip temperature, LD bias current and EA bias voltage were set at 25°C, 100 mA and −2.57 V, respectively. The average output power was +4.4 dBm at point A in this figure. A praseodymium-doped fiber amplifier (PDFA) was used after an SMF transmission. A high-speed photodiode (PD) with a 3-dB bandwidth of more than 50 GHz [13] converted the optical signal to an electrical signal. We sampled and digitized the electrical signal from the PD using a real-time digital storage oscilloscope (DSO) with a sampling rate of 160 GSample/s and a bandwidth of 62 GHz. The received electrical signal was demodulated by offline digital signal processing. And the resampled signal was equalized by using a blind feed-forward equalizer (FFE) with a half-symbol-spaced (T/2-spaced) adaptive finite impulse response (FIR) filter controlled by a decision-directed least-mean-square (DD-LMS) algorithm.

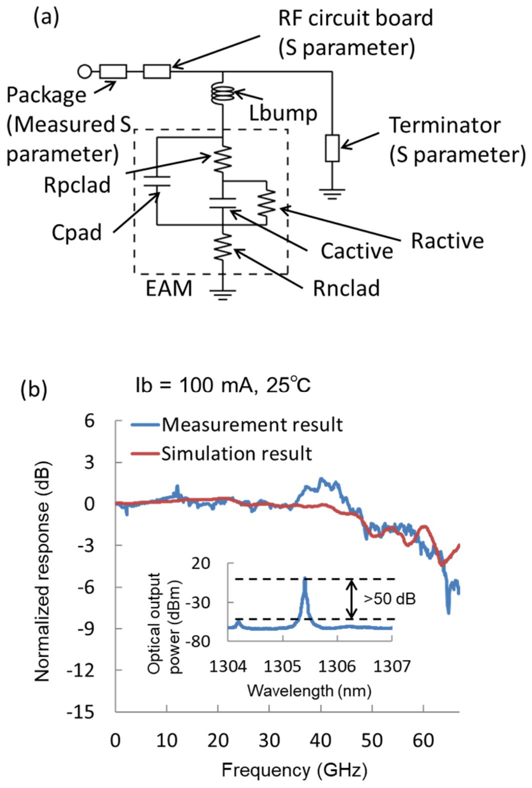


Fig. 4 (a) Equivalent circuit of Hi-FIT EA-DFB laser module and (b) lasing spectrum, simulated frequency response and measured E/O response of module.

Figure 6 shows a digitally interpolated eye diagram after offline FFE with 41 taps. After the offline FFE, clear eye opening was obtained. Figure 7 shows the bit-error-rate (BER) characteristics for a back-to-back (BtoB) con-

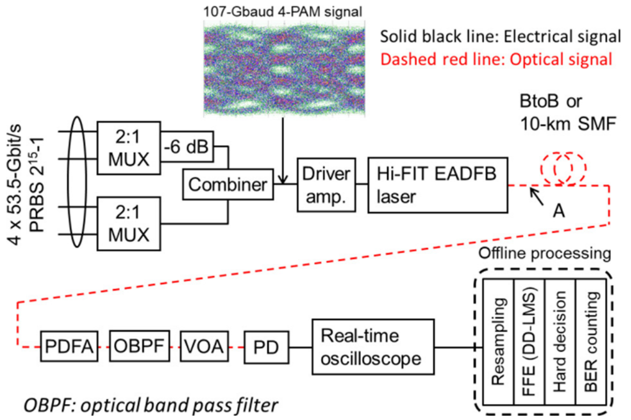


Fig. 5 Measurement setup for 107-Gbaud 4-PAM signal transmission experiment and electrical eye diagram.

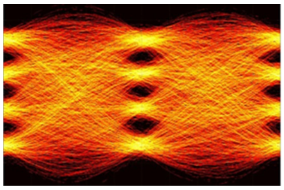


Fig. 6 107-Gbaud 4-PAM eye diagrams after offline FFE.

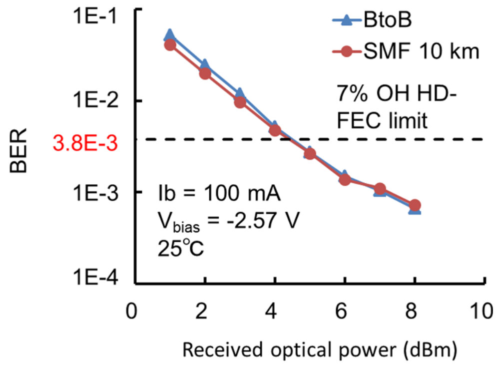


Fig. 7 BER characteristics under107-Gbaud 4-PAM operation.

figuration and 10-km SMF transmission. With 41 taps, we observed a BER of less than 3.8×10^{-3}, which is an error-free condition using a 7%-overhead (OH) hard-decision forward error correction (HD-FEC) code [14], even after 10-km SMF transmission. The receiver sensitivity was +4.3 dBm for a BtoB configuration, and the power penalty was negligible compared with that for the 10-km SMF transmission.

4. Hi-FIT MZM Sub-Assembly

We have already reported a high-speed InP-MZM chip [15]. The new n-i-p-n heterostructure and the capacitively loaded traveling wave electrode enable us to achieve high-speed operation. We applied the Hi-FIT to this InP-MZM. Figure 8 (a) and (b) show MZM sub-assemblies, which employ the conventional wire interconnection technique and the Hi-FIT, respectively. For the wire interconnection sub-assembly, terminators were mounted face up beside an InP-MZM chip and connected to the InP-MZM chip by wires. However, the reflection characteristic degrades due to the parasitic inductance of these wires. On the other hand, for the Hi-FIT sub-assembly, the terminators were mounted face down on an InP-MZM chip through gold bumps 60 μm in diameter and only 30 μm high. Therefore, the Hi-FIT enables us to improve the reflection characteristics because this technique requires no wire.

To confirm the advantage of the Hi-FIT, we measured the small-signal frequency characteristics of the Hi-FIT and the ideal termination InP-MZM sub-assemblies as shown in Fig. 9. With the ideal termination sub-assembly, the 50-ohm RF broadband terminator is connected to the InP-MZM chip through an RF probe. This approach is generally utilized to realize an ideal termination. The DC bias voltage of the MZM was −8 V. As shown in Fig. 9, the E/O responses and reflection characteristics (S11) of the Hi-FIT sub-assembly were almost the same as those of the ideal termination sub-assembly. The measured 3-dB bandwidth of the Hi-FIT sub-assembly exceeded 67 GHz, which was the limit of our measuring instrument. And its electrical reflection was less than −10 dB below 67 GHz. These results indicate that the Hi-FIT provides an ideal high-frequency interconnection.

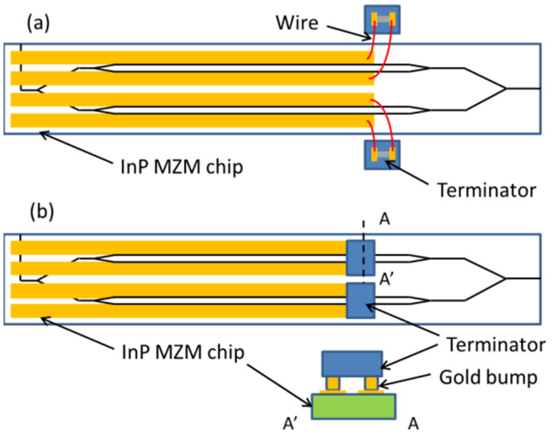


Fig. 8 Schematic structure of (a) conventional wire interconnection and (b) Hi-FIT InP-MZM sub-assemblies.

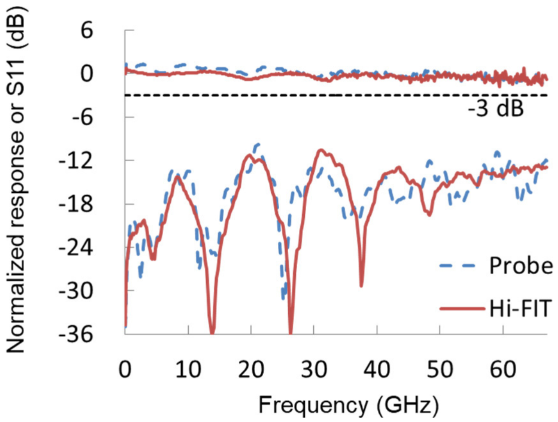


Fig. 9 Measured E/O responses and reflection characteristics of Hi-FIT and ideal termination InP-MZM sub-assemblies.

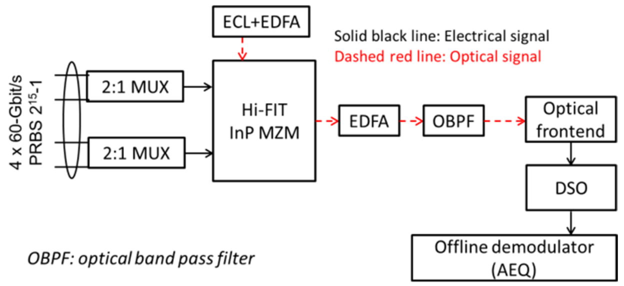


Fig. 10 Measurement setup for 120-Gbaud QPSK signal transmission experiment.

We performed 120-Gbaud QPSK signal transmission experiments using the Hi-FIT InP-MZM sub-assembly. Figure 10 shows the measurement setup for 120-Gbaud QPSK operation. 120-Gbit/s NRZ $2^{15} - 1$ PRBS signals were generated from 2:1 electrical MUXs and the output signal voltages were 0.4 Vpp. An external cavity laser (ECL) with a <30 kHz line width was used as the signal light source. The peak wavelength and power of the optical input were 1550 nm and +16 dBm, respectively. The optical signals were

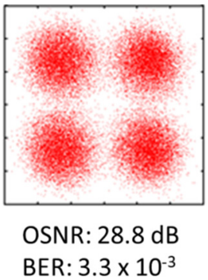


Fig. 11 Constellation diagrams of 120-Gbaud QPSK signal.

amplified by an erbium-doped fiber amplifier (EDFA) and passed through a 100-GHz optical filter. We used a single-polarization offline coherent receiver consisting of an optical frontend. And we sampled and digitized the electrical signal from the optical frontend using a real-time DSO, a sampling rate of 160 GSample/s and a bandwidth of 62 GHz. The digitized electrical signal was demodulated by offline digital signal processing and an adaptive equalizer (AEQ) was used. Figure 11 shows the constellation diagram of a 120-Gbaud QPSK signal. The BER at an optical signal-to-noise ratio (OSNR) of 28.8 dB was 3.3×10^{-3}, which is still below the limit of soft-decision (SD) FEC with a 20% overhead.

5. Conclusion

We proposed a high-frequency and integrated design for a wire-free interconnection technique based on our flip-chip interconnection technique (Hi-FIT). The Hi-FIT EA-DFB laser module had a 3-dB bandwidth of 59 GHz. Using this module, we obtained a BER of less than 3.8×10^{-3}, which is an error-free condition using a 7%-OH HD-FEC code, for 107-Gbaud 4-PAM operation even after a 10-km SMF transmission. The 3-dB bandwidth of the Hi-FIT InP-MZM sub-assembly exceeded 67 GHz, which was the limit of our measuring instruments. We obtained clear IQ modulation signals with a 120-Gbaud rate using this sub-assembly. The proposed Hi-FIT constitutes a key technique for realizing a high-speed optical transmitter operating at beyond 100 Gbaud.

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