# Integrated Optical Link on Si Substrate Using Membrane Distributed-Feedback Laser and p-i-n Photodiode

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***Abstract*—On-chip optical interconnection is a promising technology for wiring future large-scale integrated circuits, as a means to mitigate the considerable power dissipation of traditional wiring layers. Here, we fabricate an integrated optical link using a membrane distributed-feedback (DFB) laser and a p-i-n photodiode (PD) in a butt-jointed built-in coupling geometry. The optical link is formed on a Si substrate by benzocyclobutene bonding. The integrated DFB laser shows a low-threshold current of 0.48 mA. Light transmission between the DFB laser and the p-i-n PD is confirmed with static measurements of the optical link. The optical link has a 3-dB bandwidth of 11.3 GHz at a 2.73 mA DFB laser bias current and a –3 V p-i-n PD bias voltage. A data transmission experiment of the optical link is performed, using a nonreturn to zero, pseudorandom-bit-sequence with a word length of $2^{31}$-1 signals. With a DFB laser bias current of 2.5 mA, 10 Gbit/s data transmission with a bit-error-rate of $6 \times 10^{-7}$ is successfully achieved.**

***Index Terms*—Distributed-feedback laser, lateral current injection, membrane laser, optical interconnection, semiconductor laser.**

## I. INTRODUCTION

The wiring layer of large-scale integrated circuits is responsible for a large fraction of the total chip power dissipation [1]–[3]. To mitigate this problem, new interconnection technology is required. Novel type on-chip electrical interconnection technologies such as carbon-nanotubes [4] and high-speed transmission lines [5]–[7] have been proposed as approaches capable of achieving energy efficient wiring with small transmission delays. On-chip optical interconnection—in contrast with electrical approaches—has also been recognized as a promising candidate for future wiring schemes [8]–[10]. As in fiber optic communications, on-chip optical interconnection consists of light sources, passive waveguides, and detectors. There are two main approaches to implement on-chip optical links: on-chip light sources, and external light sources with on-chip modulators. As an external light source approach, on-chip optical links have been demonstrated on silicon photonic platforms with an external laser and ring modulators [11]–[14]. Although silicon ring modulators can operate at high-speed and with low-energy consumption, they require heater tuning to change their operation wavelength to that of the external laser [14], because the operation wavelength of the ring modulator is easily affected by temperature changes and fabrication tolerances. Even though the energy consumption of the ring modulator is itself very small (several fJ/bit [15]), that of micro-heaters is much higher than that, and has been reported to be as high as 192 fJ/bit [14]. An optical link implemented on a III-V/silicon-on-insulator (III-V/SOI) platform using an electro-absorption modulator achieved high-speed operation with a 3-dB bandwidth of 13 GHz [16]. A twin-guide laser and a uni-carrier travelling photodiode integrated with InP-membrane circuit were demonstrated [17]. By employing a directly modulated on-chip light source, a reduction of the laser current results in a reduction in the total consumed link energy. A key challenge concerning on-chip light sources is to obtain ultra-low energy consumption semiconductor lasers [18]. Vertical-cavity surface-emitting lasers (VCSELs) can operate with low-threshold and high-speed direct modulation [19], [20]. The VCSEL structure is suitable for vertical fiber coupling (rather than horizontal integration) and requires a 45° total reflection mirror to make an in-plane optical link [21]. Ring lasers [22] and microdisk lasers [23], [24] have been used in III-V/SOI optical links. Even though these lasers are capable of low-threshold and high-speeds, the evanescent coupling between the laser and the passive waveguide prevents an efficient light coupling. Photonic crystal lasers exhibited 4.8-$\mu$A threshold operation [25], and optical links using photonic crystal waveguides and p-i-n photodiodes (PDs) have been demonstrated [26]. Ultra-low energy signal transmission was reported, but the transmitted signal of this optical link structure (laser and PD integration) was not evaluated in terms of

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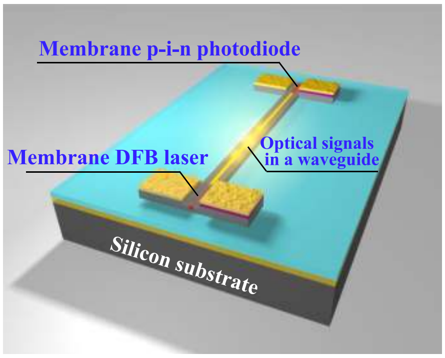


Fig. 1. Schematic of a membrane optical link on a silicon substrate.

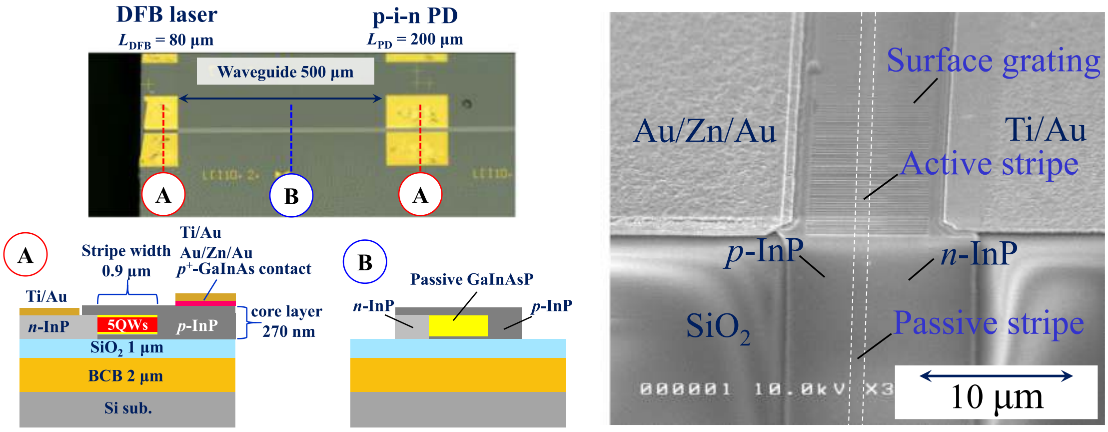
bit-error-rate characteristics, because of the small output power of the photonic crystal laser.

As discussed above, on-chip optical interconnections require low-power consumption lasers and efficient coupling structures. Membrane distributed-feedback (DFB) lasers—DFB lasers fabricated in thin semiconductor layers—are promising candidates as light sources for on-chip optical interconnection [27]. A schematic of an optical link using a membrane DFB laser is shown in Fig. 1. The edge-emitting structure of the DFB laser is well suited for in-plane integration, and is widely used as the light source in photonic integrated circuits [28], [29]. The typical operating current of DFB lasers is of several tens of milliamperes due to its large active volume [30], [31]. The membrane structure has an ability to reduce the operating current of DFB laser as following reasons. A thin semiconductor layer sandwiched by dielectric claddings enhances the optical confinement factor of the active layers [32]. A large refractive-index difference between the core and cladding layers results in strong grating index-coupling [33]. These properties make the membrane DFB laser a candidate for use as a low-power consumption light source [34]. In our early works, optically pumped operation has revealed low-threshold and strong index-coupled characteristics [35]–[37]. By adopting a lateral-current-injection (LCI) structure [38]–[41], LCI-membrane lasers were operated with both pulsed [42] and continuous-waves (CWs) [43], [44]. Many integration schemes are available, such as butt-jointed built-in (BJB) structures [45], quantum-well intermixing [46], offset quantum wells [47], and so on. We adopted a BJB structure to integrate the membrane DFB laser with a passive waveguide section [48]; a low threshold current of 0.23 mA was achieved with the BJB waveguide [49]. Integration with a distributed-Bragg reflector enhanced the output efficiency [50]. Recent works showed the high speed modulation properties of membrane DFB lasers at low-bias currents [51], [52]. Optical transmission has been performed using monolithically integrated membrane DFB lasers and p-i-n PDs [53]. However, the dynamic characteristics of the membrane optical link have not hitherto been investigated.

In this paper, we fabricated an integrated optical link consisting of a membrane DFB laser, a p-i-n PD, and a passive waveguide. Fabrication procedure of the membrane optical link is shown in Section II. The static characteristics of the optical link are characterized in Section III. The small-signal modulation measurements are performed in Section IV. Finally, a large-signal data transmission through the optical link is presented in Section V.

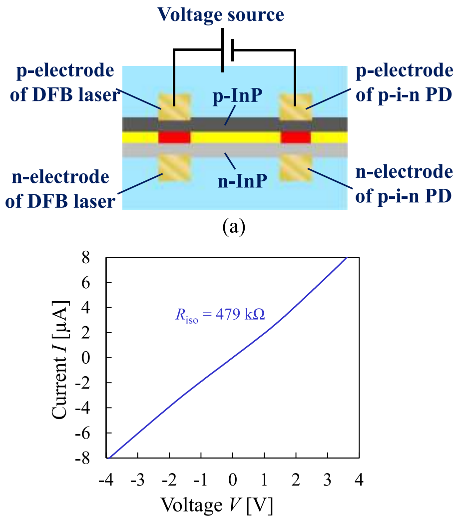
## II. MEMBRANE OPTICAL LINK FABRICATION PROCEDURE

A membrane optical link was fabricated by three-step organometallic vapor-phase-epitaxy (OMVPE) regrowth and benzocyclobutene (BCB) adhesive bonding. The detailed process is described in [49]. The initial wafer consisted of a 270-nm-thick core layer including a five-quantum-well (5QW) active layer, a $p^{++}$-GaInAs contact layer, and sacrificial etch stop layers. The active region had a photoluminescence peak at a wavelength of 1520 nm. The fabrication was started with the three-step OMVPE regrowth. First, a passive GaInAsP waveguide layer was regrown. The fabrication procedure for BJB structure of the active and passive sections was described in [53]. Subsequently, n-InP and p-InP layers were regrown, for the lateral p-i-n diode structure. A $SiO_2$ cladding layer was deposited on the regrown InP substrate by a plasma-enhanced chemical vapor deposition. After BCB adhesive bonding of the initial wafer onto a silicon substrate, the InP substrate was removed by chemical polishing and selective wet chemical etching. Au/Zn/Au (25/50/300 nm) was deposited as the p-side electrode by thermal evaporation, and annealed at 350 °C in $N_2$ ambient for one minute. Ti/Au (25/200 nm) was then deposited on both n-side and p-side electrode regions by electron beam evaporation. A surface grating pattern was defined by electron beam lithography. The grating design was uniform first order grating with period of 295 nm and duty ratio of 0.43. The pattern formed on a $SiO_2$ mask was transferred to an InP cap layer by wet chemical etching. The etching for 50-nm-depth grating was performed using chemical etchant of $H_2O$: $H_2O_2$: HCl: $CH_3COOH = 92: 1: 2: 20$ at 10 °C for 8 s. The etching rate for an InP was approximately 6 nm/s. Finally, stripe-shaped photoresist for protecting both an active and a passive waveguide region was formed by photolithography. The unnecessary InP region was then removed by wet chemical etching, to enhance the electrical isolation between the devices. Fig. 2(a) shows an optical microscopy image of the fabricated membrane optical link and cross-sections at the active and passive regions. The DFB laser and the p-i-n PD had lengths of 80 and 200 $\mu$m, respectively. The absorption layer of the p-i-n PD was the same as that of the active region of the DFB laser. These devices were connected by a 500-$\mu$m-long passive waveguide. The coupling efficiency between the active and passive section was calculated to be 98% [48]. The propagation loss of the passive waveguide was measured to be more than 8 dB/cm by the Fabry-Perot resonance method using the waveguide with both cleaved facets. The propagation loss for a 500-$\mu$m-long waveguide was at least 0.4 dB. The output of the DFB laser on the opposite side to the p-i-n PD was cleaved, for measuring the lasing characteristics. Fig. 2(b) shows a scanning electron microscopy image of the DFB laser region. As shown, the surface grating pattern was successfully formed on the InP cap layer. The electrical isolation between the DFB laser and the p-i-n PD is important to ensure independent device driving and to suppress crosstalk in



(a) (b)

Fig. 2. (a) Optical microscopy image and cross sections of the optical link fabricated using a membrane DFB laser and a p-i-n PD. (b) Scanning electron microscopy image of a joint region of the DFB laser and the passive waveguide.



(a)

(b)

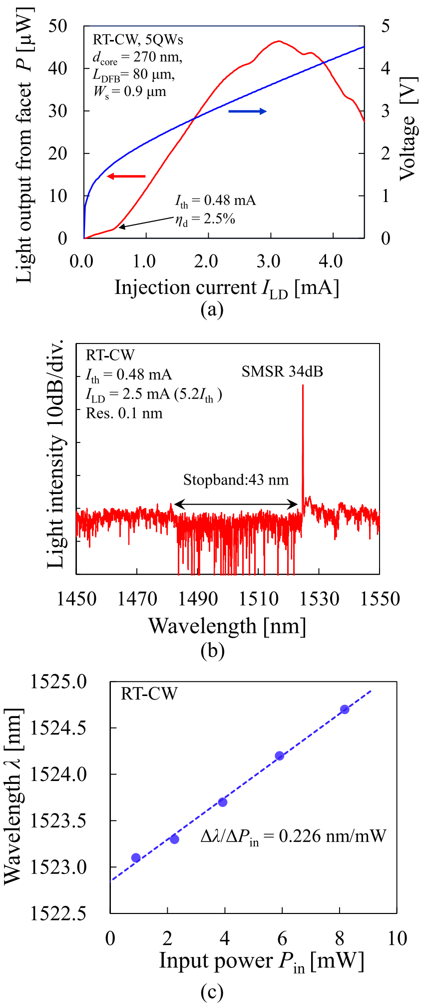
Fig. 3. Electrical isolation measurement. (a) Schematic of the measuring configuration. (b) Current–voltage characteristics.

the integrated structure. The electrical isolation resistance $R_{\mathrm{iso}}$ between the p-side electrodes of the DFB laser and the p-i-n PD was measured, as shown in Fig. 3(a). Given that the n-electrodes will be set to common ground during the optical transmission measurement, the isolation resistance between the n-side electrodes becomes not a serious problem. Fig. 3(b) shows the obtained current–voltage characteristics. The isolation resistance $R_{\mathrm{iso}}$ was measured to be of approximately 479 kΩ; at the device operating voltage, the leakage current was therefore expected to be under 10 $\mu$A, which implies that sufficient electrical isolation was obtained in the fabricated structure.

## III. STATIC CHARACTERISTICS

Prior to evaluating the fabricated optical link, the static characteristics of the integrated membrane DFB laser were measured. The DFB laser was characterized by measuring the light output from the cleaved facet formed on the side opposite to the p-i-n PD. The light output was detected by a commercial p-i-n PD. Fig. 4(a) shows the light output versus current and the applied voltage versus current characteristics. The obtained threshold current $I_{\mathrm{th}}$ was 0.48 mA, and the corresponding threshold current density $J_{\mathrm{th}}$ was 667 A/cm$^2$ for the 5QW active layer. The external differential quantum efficiency $\eta_{\mathrm{d}}$ was 2.5% (facet output). It should be noted that even though the output efficiency from the facet was small, the facet output was not used in the optical transmission measurement to be shown later. Fig. 4(b) shows the lasing spectrum measured at a bias current of 2.5 mA; in these measurements, the lasing wavelength was 1525 nm and the sub-mode suppression-ratio was 34 dB. The stopband width— which can be defined as the wavelength range with very low intensity level—was 43 nm, corresponding to an index-coupling coefficient of 2000 cm$^{-1}$. Same values of stopband width were observed for the different devices on a same chip. The slight difference of Bragg wavelength was observed between the devices, which was attributed to the variation of stripe width or non-uniformity of regrowth thickness. Fig. 4(c) shows input power versus lasing wavelength characteristics. The slope $\Delta\lambda/\Delta P_{\mathrm{in}}$ was 0.226 nm/mW.

The optical link was then statically characterized, by measuring the optical transmission properties between the DFB laser and the p-i-n PD. The light output of the DFB laser into the passive waveguide section was detected by the integrated p-i-n PD. The obtained photocurrent of the p-i-n PD, $I_{\mathrm{PD}}$, is shown in Fig. 5 as a function of the current injected into the DFB laser, $I_{\mathrm{LD}}$; the light output from the cleaved facet (the same curve shown in Fig. 4(a)) is also shown, for comparison. The threshold current of the DFB laser observed from the photocurrent characteristic was 0.48 mA, which was the same value measured with the external p-i-n PD. The slope of $I_{\mathrm{LD}}$–$I_{\mathrm{PD}}$ characteristics was 68.4 $\mu$A/mA. $\eta_{\mathrm{d}}$ for the p-i-n PD side output can be calculated by assuming the internal quantum efficiency of p-i-n PD of 100% and incorporating the propagation loss of 500-$\mu$m-long waveguide of 0.4 dB. The $\eta_{\mathrm{d}}$ of the DFB laser was calculated to be 7.5% from the slope of the photocurrent by assuming the p-i-n PD responsivity of 1.25 A/W. The higher wall-plug effi-



(a)

(b)

(c)

Fig. 4. Lasing characteristics of a membrane DFB laser integrated in an optical link. (a) Light output versus current. (b) Lasing spectrum at a 2.5 mA bias current. (c) Input power versus lasing wavelength characteristics.

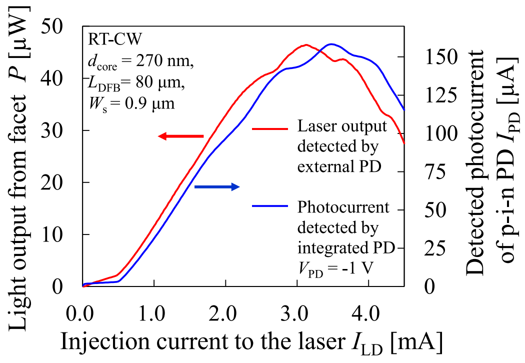


Fig. 5. Photocurrent of the integrated p-i-n PD and light output power of the laser (measured by an external PD) as functions of the laser injection current.

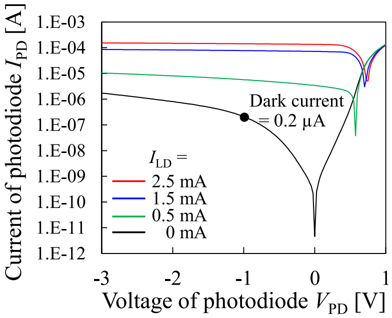


Fig. 6. Current–voltage characteristics of the integrated p-i-n PD, for various injection currents in the DFB laser.

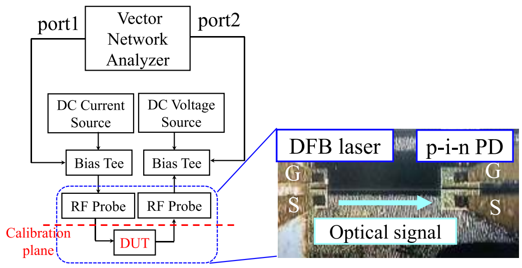


Fig. 7. Setup used to measure the small-signal response of the optical link. The left side image shows the block diagram of the measurement setup. The right side image shows an optical microscopy image of the device under test.

ciency of the laser can be expected by adopting reduced doping concentration of p-InP cladding to reduce the absorption loss. To compensate increased resistivity of p-InP, the distance between the p-side electrode and active stripe region should be as short as possible. Given that the maximum value of $I_{\text{PD}}$ was 158 $\mu$A at $I_{\text{LD}} = 3.5$ mA, the output power of the DFB laser into the integrated waveguide was estimated to be above 126 $\mu$W (158 $\mu$A ÷ 1.25 A/W), approximately three times higher than that from the cleaved facet (43 $\mu$W). This asymmetry in the output ratio was attributed to the facet phase of the grating. Fig. 6 shows the current–voltage characteristics of the integrated p-i-n PD for various laser bias currents, from 0 to 2.5 mA. To avoid a leakage current between the DFB laser and the p-i-n PD, only the curve at a laser current of 0 mA was obtained with opened electrode pads at the DFB laser. As shown, the p-i-n PD dark current was 0.2 $\mu$A at a bias voltage of $-1$ V. The dark current normalized by the absorption area was $1 \times 10^{-1}$ A/cm$^2$. This unremarkable dark current density was due either to surface leakage or leakage at the waveguide region. The absorption of p-i-n PD did not reach the saturation region, as can be seen from the fact that the p-i-n PD current in reverse bias conditions was almost independent of the bias voltage.

## IV. SMALL-SIGNAL MODULATION CHARACTERISTICS

The small-signal frequency response $S_{21}$ of the full-optical link was measured with a vector network analyzer (VNA; Anritsu 37397C). The setup for small-signal measurement is depicted in Fig. 7. Ports 1 and 2 of the VNA were connected to bias-tees. A DC source was supplied to each bias-tee. A DC-coupled modulation signal was applied to the DFB laser via a 100-$\mu$m-pitch ground-signal (GS) RF probe (Cascade Microtech ACP40). The modulated optical signals were then transmitted via the optical link. The p-i-n PD electrical output was received by a signal-ground probe. The RF component of the detected signal was separated by a bias-tee, and input to Port 2 of the VNA. The measured device chip was put on a heat sink, whose

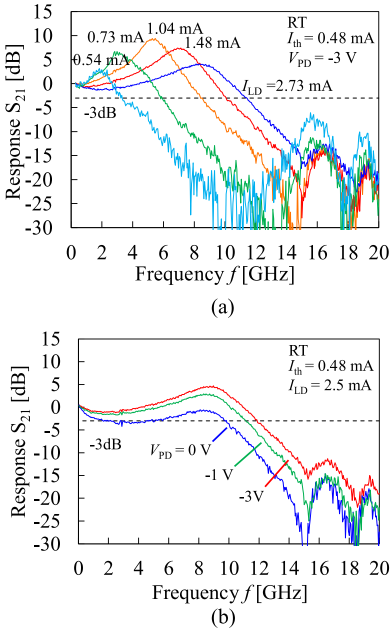


Fig. 8. Small-signal response of the fabricated optical link. (a) Bias current dependence measured at a $-3$ V PD bias voltage. (b) Bias voltage dependence measured at a 2.5 mA DFB laser bias current.

temperature was controlled at 20 °C. In advance of measuring the device, a calibration up to the RF probe tips was performed with an impedance standard substrate (Cascade Microtech, 103-726, GS/SG, up to 67 GHz, pitch: 100 $\mu$m–250 $\mu$m). Therefore, the contribution of measurement system was excluded from the results.

Fig. 8(a) shows the small-signal frequency response (40 MHz to 20 GHz) of the optical link for various bias currents, with a fixed p-i-n PD bias voltage of $-3$ V. A clear relaxation oscillation behavior was observed. In addition, the peak frequency increased with the increase in the DFB laser bias current. Therefore, these responses are not electrical crosstalk between probes, but indeed the transmitted optical signal. The 3-dB bandwidth of the optical link was 11.3 GHz at a DFB laser bias current of 2.73 mA. There were bias-current independent peaks near the 16 and 19 GHz frequencies. Although these peaks were due to the electrical signal being transmitted between the RF probes, we believe that the peaks had little effect on the modulation measurement, because the response magnitude was small compared with that of the optical signal. Fig. 8(b) shows the small-signal response for various p-i-n PD bias voltages, for a fixed DFB laser current of 2.5 mA. Increasing the bias voltage enhanced the 3-dB bandwidth, because the electrical field assisted in charge carrier extraction. The maximum bandwidth was obtained at a bias voltage of $-3$ V. We also determined the modulation efficiency—which is the slope of the relaxation oscillation frequency as a function of the square root of the bias current above threshold—from the small-signal frequency response of the optical link. Fig. 9 shows the 3 dB bandwidth $f_{3\mathrm{dB}}$ and the relaxation oscillation frequency $f_\mathrm{r}$ as functions of the square root of the bias current above threshold. Because the measurements were performed using on-chip p-i-n PD, $f_{3\mathrm{dB}}$ represents bandwidth of the optical link. Modulation efficiencies of 10.8 GHz/mA$^{1/2}$ and 7.6 GHz/mA$^{1/2}$ were obtained for $f_{3\mathrm{dB}}$ and $f_\mathrm{r}$, respectively; the latter was smaller than that obtained in our previous work (11 GHz/mA$^{1/2}$) [52]. However, the active volume of the DFB laser in this work was 2.16 $\mu$m$^3$, which was larger than the previous one (0.9 $\mu$m$^3$). Given that the modulation efficiency is proportional to the square root of the active volume, the value of 7.6 GHz/mA$^{1/2}$ for an active volume of 2.16 $\mu$m$^3$ is in good agreement with the previous result.

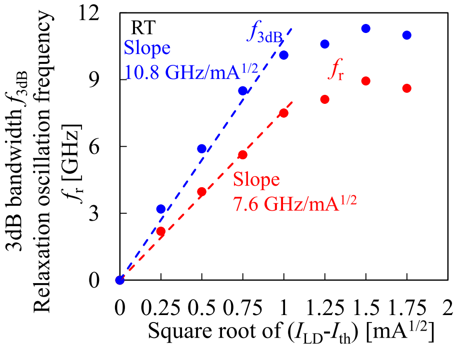


Fig. 9. Relaxation oscillation frequency $f_\mathrm{r}$ and 3-dB bandwidth $f_{3\mathrm{dB}}$ as a function of the square root of the bias current above threshold.

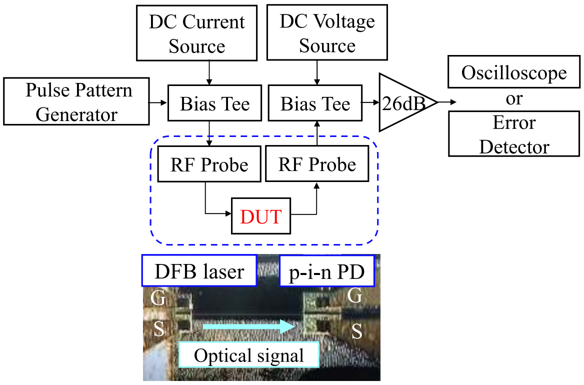


Fig. 10. Measurement setup for evaluation of large-signal transmission through the optical link.

## V. LARGE-SIGNAL DATA-TRANSMISSION

Data transmission via the membrane optical link was performed by large-signal direct modulation of the DFB laser. Fig. 10 shows an experimental setup for data-transmission measurements. The electrical modulating signals were generated by a pulse-pattern generator (Anritsu MP1800A, MU181020B, and MU182021A). Electrical signals were sent to the DFB laser via a bias-tee and a GS probe. The optical signal from the DFB laser was transmitted through the passive waveguide, and detected by the p-i-n PD. The electrical output signal of the p-i-n PD was amplified by a 38 GHz electrical amplifier with a 26-dB gain (SHF806E). The signals were recorded with a sampling oscilloscope (Agilent 86109B) or analyzed with an error detector (Anritsu MP1800A, MU181040B, and MU182041A). In this measurement setup, AC components of the p-i-n PD output

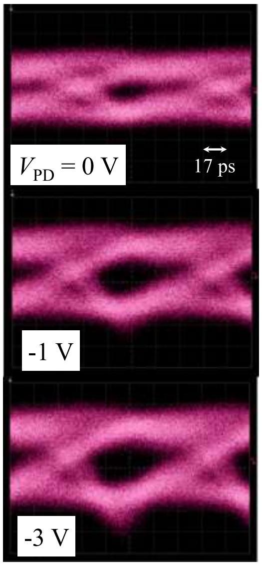


Fig. 11. 10 Gbit/s eye diagrams transmitted through the optical-link for various p-i-n PD bias voltages (0 to −3V). The DFB laser was biased at 2.5 mA, and driven by an NRZ, PRBS ($2^{31}$-1 signals) electrical modulating signal with a voltage swing of 0.75 $V_{pp}$.

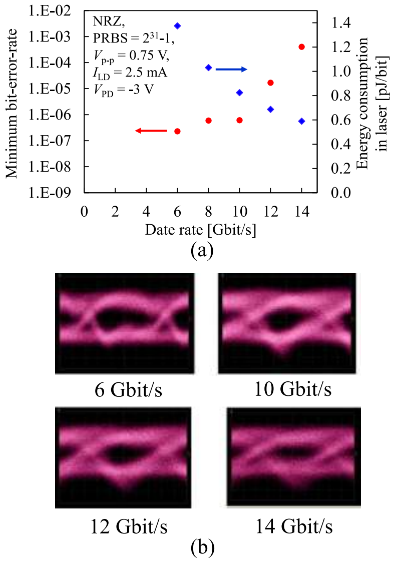


Fig. 12. (a) Bit-error-rate characteristics and energy consumption in the laser of NRZ signal transmission through the membrane optical link; 2.5 mA laser bias current, and −3 V p-i-n PD bias voltage. (b) Eye diagrams for various data rates.

signals were separated from the signals at a bias-tee. Therefore, an extinction ratio of transmitted signal was not obtained.

The input electrical signal to the DFB laser was a non-return-to-zero (NRZ) pseudorandom binary sequence (PRBS) of $2^{31}$-1 signals, with a voltage swing of 0.75 $V_{pp}$. Fig. 11 shows transmitted 10 Gbit/s eye diagrams at a 2.5 mA DFB laser bias current, recorded for various p-i-n PD bias voltages. As the bias voltage of the p-i-n PD increased, larger eye openings were observed, which is consistent with the results of the small-signal measurements. Fig. 12(a) shows the measured bit-error-rate (BER) versus the data-rate and the energy consumption in the laser at each data-rate. All plots were obtained in the same operating conditions (except for the data-rate). A BER in the order of $10^{-7}$ was obtained up to a data rate of 10 Gbit/s. A energy consumption of the laser at 10 Gbit/s was 0.825 pJ/bit. Above 10 Gbit/s, the BER rapidly degraded. The eye diagrams corresponding to the measured BER plots are shown in Fig. 12(b); as shown, the eye diagrams for 12 and 14 Gbit/s are more closed, because of signal distortion.

## VI. CONCLUSION

We described a monolithically integrated membrane optical link fabricated on a Si substrate, which employs a membrane DFB laser and a p-i-n PD. The integrated DFB laser showed a threshold current of 0.48 mA, with a sub-mode suppression ratio of 34 dB at a bias current of 2.5 mA. The integrated p-i-n PD detection of the transmitted light output of the DFB laser was confirmed from static measurements of the optical link. The dynamic characteristics of the membrane optical link were obtained for both small-signal and large-signal modulations. For a DFB laser bias current of 2.73 mA and a p-i-n PD bias voltage of −3 V, the obtained 3-dB bandwidth of the optical link was 11.3 GHz. Data-transmission with NRZ PRBS of $2^{31}$-1 signals was performed. 10 Gbit/s transmission with a BER of $6 \times 10^{-7}$ was achieved at a DFB laser bias current of 2.5 mA. The obtained results show that optical links using a membrane DFB laser are attractive candidates for on-chip optical interconnections.

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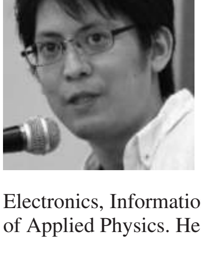

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