80-GHz Bandwidth and High Responsivity of InP Coherent Receiver PIC with Butt-joint waveguide PDs

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Abstract: An InP-based coherent receiver PIC with waveguide PDs demonstrates 80-GHz bandwidth and high responsivity of 0.156 A/W at a wavelength of 1.55 μm. A coherent receiver module with PICs and TIAs performs sufficient characteristics for 128-GBaud transmission.

1. Introduction

The development of data center application has accelerated increasing transmission capacity for long-haul and metro networks. The digital coherent transmission technology is a certain scheme to satisfy this demand, due to its high sensitivity and spectrally efficient modulation formats. To realize long-reach coherent networks with a transmission capacity of more than 1 Tbps/λ in near future, an increase of symbol rate is desirable rather than that of modulation order, because the high order modulation formats bring about a limitations of optical signal-noise-ratio (OSNR) [1] and an elevation of power consumption in digital signal processing (DSP). Towards beyond-1-Tbps/λ coherent transmission, exceeding 100-GBaud operation which requires a 3-dB bandwidth of more than 70 GHz is an indispensable factor.

In 2021, optical internetworking forum (OIF) released an implementation agreement (IA) for high bandwidth coherent driver modulator (HB-CDM) 2.0, which covers 128 GBaud transmission [2], and the same symbol rate is also required in intradyne coherent receivers (ICRs). In addition, a high responsivity is another requirement to reduce power consumption of local oscillator (LO) on the receiver side. A photonic integrated circuit (PIC) chip integrated with waveguide photodiodes (PDs) and 90° hybrids is a key component to achieve them. A silicon PIC with germanium (Ge) PDs is a candidate for the PIC chip, owing to its wide 3-dB bandwidth and high-density integration [3, 4]. On the other hand, an InP-based PIC is also attractive [5], because it has established wide 3-dB bandwidth and high responsivity, and exhibited high reliability with mature technologies. Furthermore, its wide wavelength range operation thanks to the GaInAs absorber is very valid to double the coherent network capacity using both the C- and L-bands. Since 2013, we have fabricated InP-based PICs integrated with Butt-Joint (BJ) coupled waveguide PDs. This BJ structure has overcome the tradeoff between responsivity and 3-dB bandwidth utilizing its advantages for 100 GBaud ICRs [6].

In this paper, we report a 3-dB bandwidth as wide as 80 GHz and a high responsivity of 0.156 A/W at a wavelength of 1.55 μm of our latest InP PIC employing a waveguide PD structure with a thin-film-cladding layer. We have also assembled an ICR with the PICs and achieved sufficient characteristics for 128 GBaud transmission.

2. Device Structure and Characteristics

Fig. 1 (a) shows an overview of our fabricated InP-based PIC chip consisting of an optical 90° hybrid and 4-channel

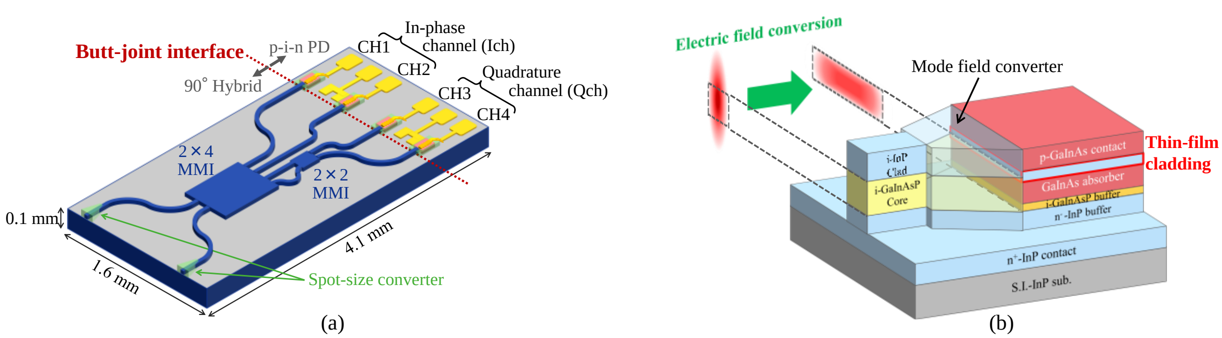


Fig. 1. Schematic diagrams of a perspective view of (a) an InP-based PIC and (b) a waveguide PD with thin-film-cladding.

(CH) BJ waveguide PD array. The optical 90° hybrid includes a 2×4 and 2×2 multi-mode interference structure (MMI), that is, it has no waveguide crossings which induce crosstalk between channels [8]. This chip has been fabricated through two epitaxial regrowth processes. In the 1st regrowth process to form BJ coupling structures, passive waveguides for a 90° hybrid and p-i-n PDs, which have different epitaxial layers, are monolithically integrated. The 2nd regrowth process selectively deposits InP to fabricate buried heterostructures. In this process, spot size converters (SSCs) at optical input ports and passivation layers to obtain high reliability have been formed simultaneously. As shown in Fig. 1 (b), a core layer of passive waveguides and a GaInAs absorber of PDs have been directly connected at the BJ interface. This structure provides a high responsivity thanks to an excellent optical coupling efficiency between the passive waveguide and PDs, while employing short PD length to minimize the capacitive time constant. Therefore, the BJ coupled waveguide PDs represents both high responsivity and wide bandwidth in contrast with evanescent coupled waveguide PDs.

In order to perform even wider 3-dB bandwidth for 128 GBaud transmission, it is essential to decrease three parameters: carrier transit time, diode capacitance, and series resistance. We have introduced a dual-layer absorber consisting of p- and i-type GaInAs to shorten the carrier transit time of holes, whose effective mass is relatively large [7]. With respect to the reduction of the diode capacitance, i-GaInAsP / n^--InP buffer layers have been inserted underneath the absorber to extend the depletion layer [9, 10]. From the viewpoint of the reduction in the series resistance, thinning of a p-InP cladding layer upon the absorber is an effective approach. However, our previous high-responsivity BJ structures have required thick p-InP cladding layers to enhance optical coupling efficiency to the absorber and avoid mode overlap to a p-GaInAs contact layer which causes optical absorption loss. The carriers generated in the p-contact layer do not contribute to the photocurrent, because they are immediately recombined without extraction by applying electric field. Thus, introducing a thin p-InP cladding layer to conventional BJ structures brings about the degradation of responsivity in return for the reduction of series resistance. Though increasing refractive index of the passive waveguide core layer to enhance optical confinement is a method to avoid optical coupling to the p-contact layer, it causes the increase of optical loss in 90° hybrid waveguides and SSCs. To solve this problem, a mode field converter (MFC) is newly introduced between the 90° hybrid and PD as shown in Fig. 1 (b). At the input facet of MFC, an abrupt change in a waveguide width excites higher-order modes. During propagation in a positively tapered waveguide, a gaussian-like mode is converted to a flat-top shaped beam. The sidewalls of the tapered waveguide are covered by InP passivation with the selective regrowth process to stretch the optical field density horizontally. Through these processes, propagation light is vertically confined in the core layer and effectively coupled to the absorber of PD without optical excess loss in the p-contact layer, resulting in high responsivity even the introduction of the thin p-InP cladding layer. Additionally, it is also helpful to obtain linearity under high optical input power condition by preventing electric field concentration.

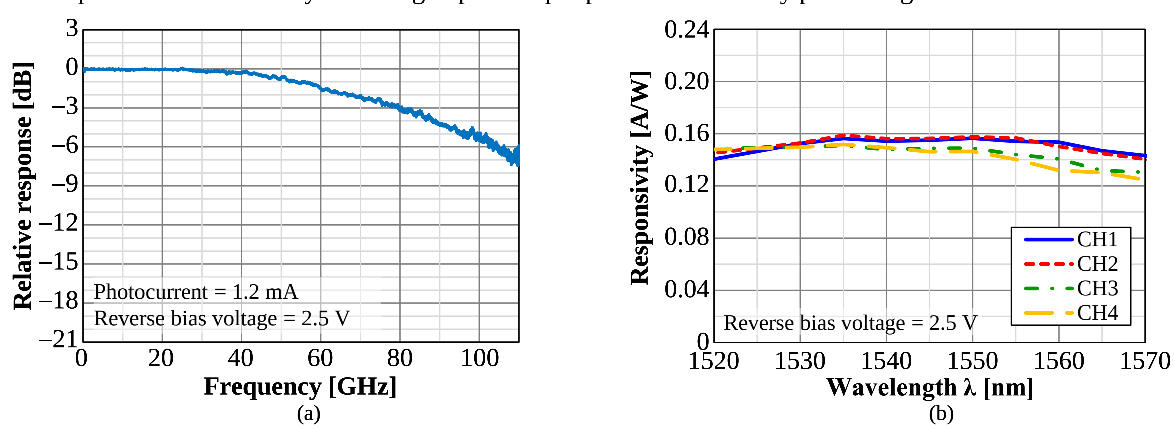


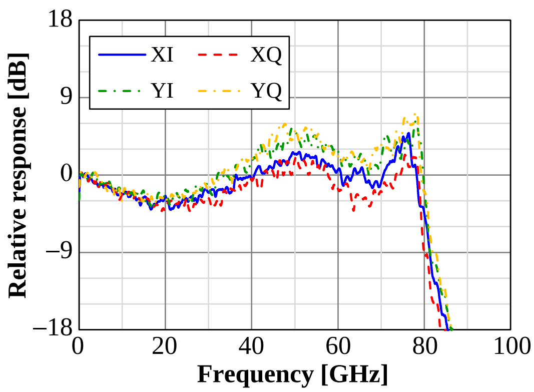
Fig. 2. (a) Optical/electrical frequency response and (b) spectral responsivities for four channels of the PIC integrating waveguide PDs with thin-film-cladding.

With this MFC, we have demonstrated a 128-GBaud PIC integrating waveguide PDs with the thin-film cladding layer which suppresses both of the series resistance and optical loss in the p-contact layer. The series resistance is reduced by 70% without changing the waveguide design of 90° hybrids or SSCs. Fig. 2 (a) shows the optical/electrical frequency response of the waveguide PD with the thin-film cladding layer under a photocurrent of 1.2 mA at a wavelength of 1.55 μm. By attaining the reduction of series resistance with our new PD structure, a 3-dB bandwidth as wide as 80 GHz has been achieved. As shown in Fig. 2 (b), the responsivity in all of 4 channels is higher than 0.12 A/W over the C-band. Due to small optical loss in 90° hybrid waveguides and SSCs, we achieve a high responsivity of 0.156 A/W at a wavelength of 1.55 μm which includes intrinsic loss of 6 dB by a 90° hybrid.

With these results, we have successfully demonstrated both wide bandwidth and high responsivity which are sufficient for 128 GBaud transmission. To our knowledge, this record is one of the highest responsivities among InP PICs for this symbol rate.

3. Performance of coherent receiver modules with 128-GBaud PICs

A coherent receiver module implementing a pair of 128-GBaud PIC chips for X- and Y- polarization has been assembled to evaluate their performance. This module has been comprised of InP-based PIC chips, a trans-impedance amplifier (TIA) designed for 128 GBaud operation, and micro-optic components. The optical signal light and LO light from optical fibers are coupled to the PICs through the micro-optics. The PDs and TIAs have been electrically connected by wire bonding processes. The RF and DC characteristics of the receiver module have been evaluated at a reverse bias voltage of 2.3 V for PDs and TIAs. Fig. 3 (a) shows an optical/electrical frequency response at a medium gain after the effect of evaluation boards and cable losses are de-embedded. We have obtained 80-GHz 3-dB bandwidth in all four channels assigned for X- and Y-polarization (In-phase: XI and YI, Quadrature: XQ and YQ) channels. Averaged responsivities of four PDs for X-polarized light from signal and LO ports have been measured to be higher than 0.060 A/W at a wavelength of 1.55 μm including polarization splitting loss (3 dB) as shown in Fig. 3 (b). From these performances, it is indicated that our InP-based PICs integrating waveguide PDs with the thin-film cladding layer are very useful for 128 GBaud transmission.



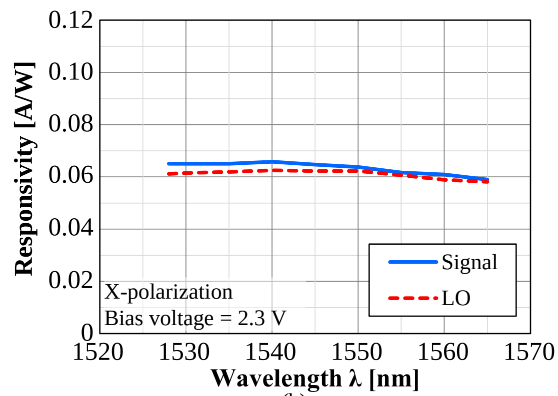


Fig. 3. (a) Optical/electrical frequency response and (b) spectral responsivities of a coherent receiver module with InP-based PICs and TIAs.

4. Conclusion

We have demonstrated the InP-based receiver PIC employing the waveguide PD structure with the thin-film cladding layer and achieved the 80-GHz bandwidth and high responsivity of 0.156 A/W at a wavelength of 1.55 μm. This is one of the highest responsivities of InP-based PICs for 128-GBaud operation. Moreover, From the performance of coherent receiver modules, it is verified that our InP-based PIC chips are very valid towards the realization of 128-GBaud coherent transmission systems.

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