InP-Based Photonic Integrated Circuits

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Abstract: InP-based photonic integrated circuits are key devices for constructing photonic networks with low cost, low power consumption and small footprint. Many types of components are required to span various application areas, from backbone to on-chip.

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1. Introduction

Photonic integrated circuits (PICs) for the transmitter and receiver in wavelength division multiplexing (WDM) systems have been developed for reducing cost and power consumption [1, 2]. The increase of the transmission rate and distance require advanced modulation formats and highly functional monolithic integrated devices including Mach-Zehnder modulators and delay-interferometers [3, 4].

In addition to these devices primarily targeted for the core network and long-haul transmission, the development of PIC technology is also critical for shorter distances: from metro/metro-core applications down to on-chip (CMOS) interconnects, as illustrated in Fig. 1. The requirements (density, cost, power consumption) for each area are different, and thus the choice of device technology must be carefully considered with the needs of each application in mind.

For the metro, 10-Gbit/s and 100-GbE applications are the dominant drivers, requiring transmitter and receiver arrays which integrate the various components (Fig. 1(a)) [2]. However, the price points are much lower compared to their long-haul counterparts, necessitating high yields which must be facilitated by simplification of the device structure utilized. Extension of the transmission reach is also beneficial for extending the area of use.

For the intra-system application, an optical switch sub-system PIC is illustrated in Fig. 1(b), for use in an optical packet switching router. With the power consumption and size of conventional electrical router technologies becoming unmanageable, optical packet switching technologies are potentially a breakthrough solution to these issues, enabling high-capacity, energy-efficient networks [5]. In particular, the monolithic, N x N optical switch that operates on a per packet basis has attracted considerable attention, allowing dramatic reductions in power and size.

Finally, for on-chip (Fig. 1(c)), a photonic network chip which is integrated with CMOS shows promise for overcoming limits on bandwidth and power faced by electrical interconnects [6]. For this PIC, the density requirement is most severe as several thousand lasers, photodetectors, and switches must be integrated on a single chip. In this context, the development of a laser having a low threshold, low power consumption, and μm-order size is the major challenge. Furthermore, a simple integration technology is increasingly important for higher states of integration, considering the larger number of optical components.

In this paper, we describe novel PIC devices for the three distinct application areas described above: a 4-channel frequency modulated DBR laser array for long distance transmission, a 4-channel wavelength routing switch for optical packet switching, and a photonic crystal laser aimed toward hybrid integration with CMOS technology.

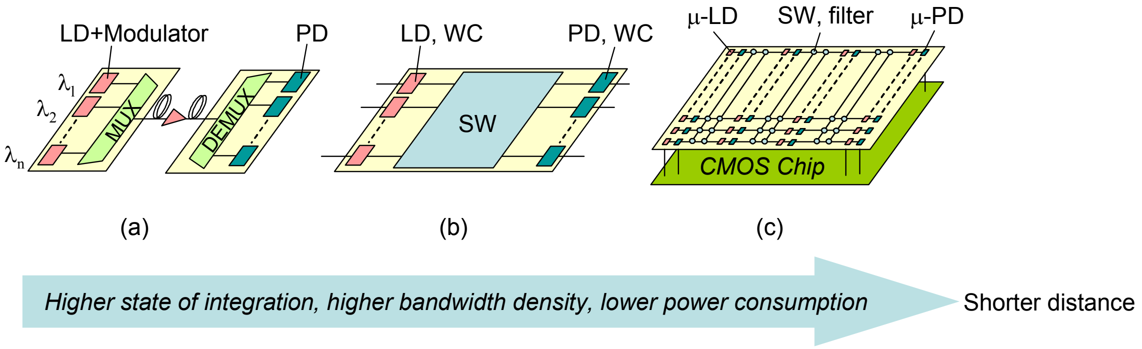
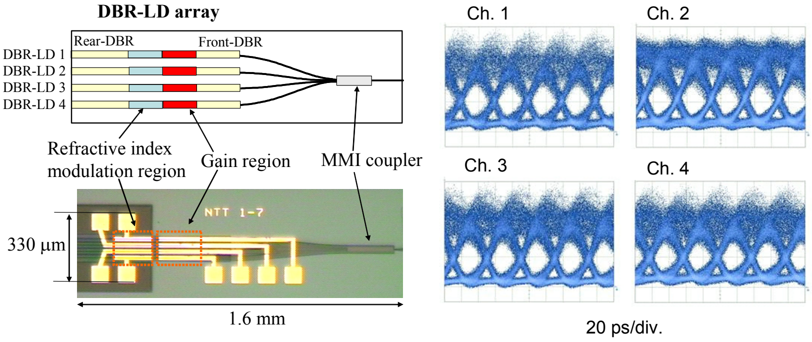


Fig. 1 PICs for (a) transmitter and receiver arrays, (b) optical switch, (c) photonic network chip on CMOS

2. Frequency modulated DBR laser array

To obtain a low cost transmitter array for 10 Gbit/s and 100-GbE applications, we have developed a novel transmitter consisting of a frequency modulated DBR laser and an optical filter [7, 8]. Reverse voltage modulation of the laser phase control region enables us to obtain fast refractive index modulation. Thus, a frequency modulated DBR laser array can be fabricated with only active and passive regions, without a traditional modulation region. In addition to photonic integration reducing size and power, the extremely simple device structure accentuates the promise of the device as a low-cost transmitter array.

Figure 2(a) shows the schematic diagram and a photograph of the fabricated, 4-channel frequency modulated DBR laser array. Each laser consists of a gain region, a refractive index modulation region, and front and rear DBRs. The output from each DBR laser is multiplexed by a multimode interference (MMI) coupler. Figure 2(b) shows the eye diagrams we obtained for the laser array. 25-Gbit/s NRZ signals with pseudo-random bit sequence (PRBS) of 2^{31}-1 were used. In these experiments, we employed an Mach-Zehnder interferometer filter (MZF) with a free spectral range (FSR) of 40 GHz to convert the frequency modulation signal to an amplitude modulation signal. The bias and modulation voltages were set at -1.0 V and 2.0 V_{pp}, respectively. The eye diagrams are clearly open and have an extinction ratio of about 10.0 dB. By using this device, we achieved an extended transmission reach of 180 km and 40 km for 10- and 25-Gbit/s NRZ signals, respectively. Furthermore, we confirmed that multiple channels can be simultaneously modulated without crosstalk between channels, demonstrating the device's suitably as a transmitter array.



(a) (b)

Fig. 2 (a) Schematic diagram and photograph of fabricated laser array. (b) Eye diagrams for 4-channel frequency modulated DBR laser array.

3. Wavelength routing switch

Wavelength routing optical switches consisting of tunable wavelength converters (TWCs) and an AWG filter have been developed [9, 10]. For our work, we employed a double-ring-resonator-coupled tunable laser (DRR-TL) and wavelength conversion based on a parallel amplifier structure (PAS) for the tunable wavelength converter [10]. The DRR-TL is easy to integrate with other components because it can be fabricated with the same fabrication process as the AWG filter.

Figure 3(a) shows a photograph of the fabricated wavelength routing switch, consisting of an array of four TWCs and an 8x8 AWG filter. The device size is 5.1 mm x 2.1 mm. An enlarged view of the TWC is shown in Fig. 3(b). The TWC consists of the DRR-TL and the wavelength converter. Wavelength conversion is performed by modulating the CW light from the DRR-TL with cross-gain modulation caused by the input signal injected into the SOAs. The PAS enables the spatial separation of the converted signal and input signal to different output ports. Thus, the input signal is not routed through the AWG filter. Employing a high-mesa waveguide structure allows monolithic integration of the micro-ring resonator in the tunable laser, etched-gap mirror which defines the laser cavity, and compact AWG filter.

Figure 3(c) shows signal waveforms from three output ports of the wavelength routing switch when the input signal was fed into input port 3. High-speed and stable wavelength routing with a switching time of less than 5 ns was achieved.

4. Photonic crystal laser

To satisfy the requirements for constructing photonic network chip on CMOS, photonic crystals (PhCs) are the key technology, as InP-based PhCs provide a high-Q cavity with extremely small mode volume and is easy to integrate with other components such as photodetectors, switches, and filters [11, 12]. However, it is difficult to achieve

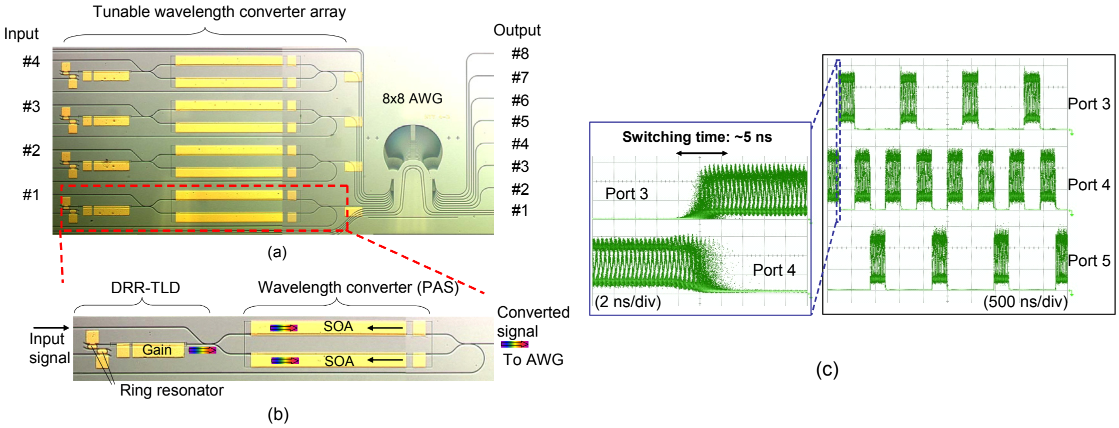
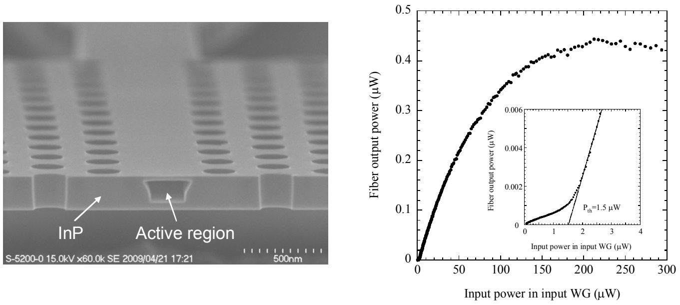


Fig. 3 Photograph of the fabricated wavelength routing switch. (a) Overall device. (b) Enlarged view of the TWC. (c) Waveforms for three output ports of the wavelength routing switch.



(a) (b)

Fig. 4 (a) Cross-sectional SEM image of BH-PhC laser. (b) Light-in versus light-out characteristics.

continuous wave (CW) operation of PhC lasers at room temperature because a PhC structure with an air-bridge structure exhibits extremely large thermal resistance. To overcome this problem, we employ an ultra compact buried heterostructure (BH) in which the active region is embedded within an InP layer, as shown in Fig. 4(a). The BH provides effective carrier confinement inside the 2D photonic crystal slab and good thermal conductivity. Figure 4(b) shows the light-in versus light-out (LL) characteristic of the fabricated device. The volume of the active region was 4.0 x 0.3 x 0.15 μm^3. To our knowledge, this is the smallest BH laser produced to date. A maximum fiber output power of 0.44 μW was obtained. The coupling loss from the PhC laser to single-mode fiber appears to be in the 10-dB range, so the output power of the BH-PhC laser is in the microwatt range. The inset shows the enlarged LL characteristic near the threshold input power. The device exhibits a clear kink at a threshold of 1.5 μW at room temperature (298 K), for CW operation. The threshold input power and maximum output power are the highest values ever reported for a PhC laser. These results indicate that the BH PhC laser will be a key device for constructing photonic networks on a chip.

5. Summary

We have successfully demonstrated monolithic integration of various photonic components, targeted for a variety of applications. The key to realizing these PICs is the use of a simple fabrication process while improving the device performance. Part of this work was supported by the National Institute of Information and Communications Technology (NICT).

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