Widely-Tunable Transmitters and Photonic Integrated Circuits

Larry A. Coldren, James W. Raring, Jonathon S. Barton, Matt Sysak, and Leif Johansson
Electrical &Computer Engineering and Materials Departments, University of California Santa Barbara, CA 93106
and
Agility Communications, Inc., 475 Pine Ave, Santa Barbara, CA 93117
Ph: (805) 893-4486; Fax: (805) 893-4500; email: lcoldren@agility.com

INVITED PAPER

Abstract: Widely-tunable lasers and single-chip transmitters, in which such lasers are integrated with modulators and semiconductor-optical-amplifiers, have recently become the core of practical modules that are gaining wide-spread use in new wavelengh-division-multiplexed systems. More advanced photonic ICs have been demonstrated for use in advanced communication and sensor systems.

1. Introduction

Despite a significant downturn in the market for telecommunication products, certain new enabling components are enjoying rapid market growth as their capabilities to reduce operational costs gain acceptance. One such example is the widely-tunable laser and derivative products that provide a 'one-size-fits all' solution in dense wavelength division multiplexed (DWDM) communication systems. In the future, such devices may also find use in reconfigurable optical add-drop multiplexers (ROADMs), photonic switch architectures, and other elements in dynamically reconfigured networks.

In this paper, we shall summarize recent advances with InP-based single-chip photonic integration techniques that are gaining wide acceptance for such applications[1,2]. Such photonic integration has long been sought after as the next big step toward low-cost, low-size, and low-power dissipation chips with increased capability. Although efforts in this area have been ongoing for decades, only within the past several years have practical photonic integrated circuits (PICs) emerged.

Key to the active PICs to be discussed here are having seamless transitions in absorption edge, so that the various amplifying, modulating, splitting, and passive interconnecting waveguides can be integrated together without loss or reflections. As illustrated in Fig. 1 various approaches have been developed. The first, butt-joint regrowth, requires an extra regrowth, but the waveguide properties can be chosen nearly arbitrarily. The other three require no regrowths, but are somewhat restricted due to the inherent relationships between the sections. Nevertheless, such approaches are being widely used because of the relative simplicity of the fabrication process and the fact that relatively good properties for the various elements of many PICs can be obtained.

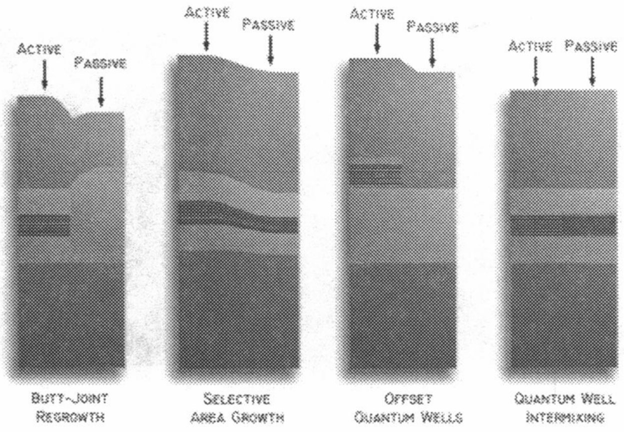


Figure 1. Schematics of active-to-passive waveguide integration techniques.

In principle, there is no limit to the scale of the PICs that can be created, once waveguides of about three or four different different bandgaps can be integrated with high yield. The PICs to be discussed also achieve a high level of

0-7803-9040-7/05/$20.00 ©2005 IEEE

functionality by using only photonic components with no electronics or the interconnections to such electronics required. For example, optical amplifiers (SOAs) are used for power gain and pre-amplification of weak signals, in many cases obviating the need for any electronic components in the entire sub-system.

2. Recent Technology Advances: Quantum-well intermixing

Figure 2 illustrates how quantum-well intermixing (QWI) works and details the process of the novel approach used at UCSB for InGaAsP/InP[1]. In this case, low-energy P^+ ions are implanted near the surface of a sacrificial InP layer to create vacancies, and in a subsequent rapid-thermal-annealing (RTA) step, these are then diffused through this layer and then across the multiple-quantum-well (MQW) active region to intermix this MQW region and increase its effective bandgap energy. Multiple bandgaps are formed by performing multiple short RTAs with intermediate selective etching steps to remove the implanted sacrificial InP, and thus vacancy source, in regions where the bandgap is to be frozen. Finally, all of the sacrificial InP is removed, other processing such as grating formation is performed if desired, and then the top waveguide cladding layers are regrown. Thus, only a single regrowth step, as required for grating reflector formation, is typically carried out.

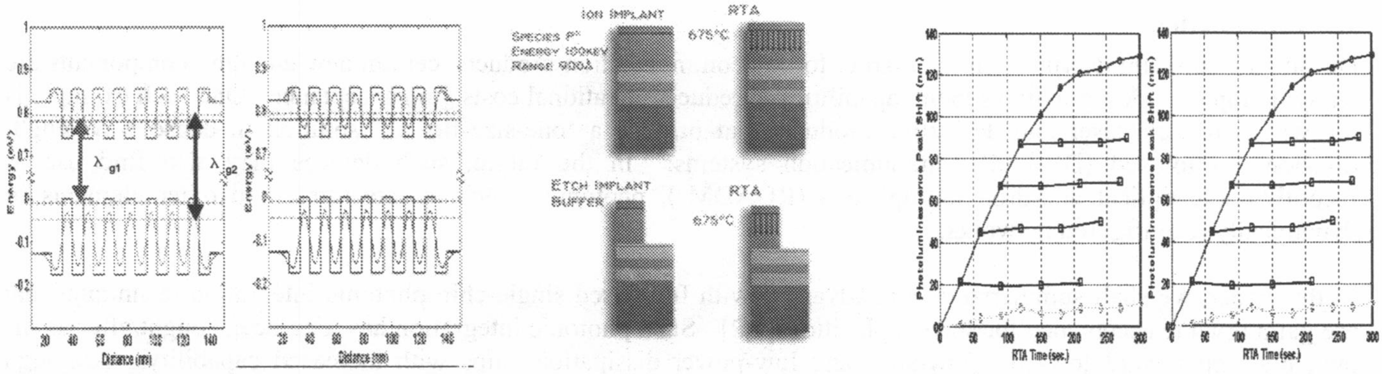


Figure 2. Schematic of QWI in InGaAsP/InP; procedure for multiple bandgaps from one implant; experimental bandgaps vs RTA time after sequential etch steps to remove vacancy source[1].

3. Example Device Advances: Photonic ICs

Figure 3 illustrates a widely-tunable transmitter in the 1550nm wavelength band formed with the QWI process. It includes a widely-tunable laser, a back-side absorber/detector, an electro-absorption-modulator (EAM), and a curved-waveguide output coupler, all monolithically integrated on the same chip with the process described above[3,4]. As shown by the results in Fig. 4 high output power, full C-band tunability, and negative chirp capability is demonstrated with three different QWI bandgaps formed from the single MQW growth.

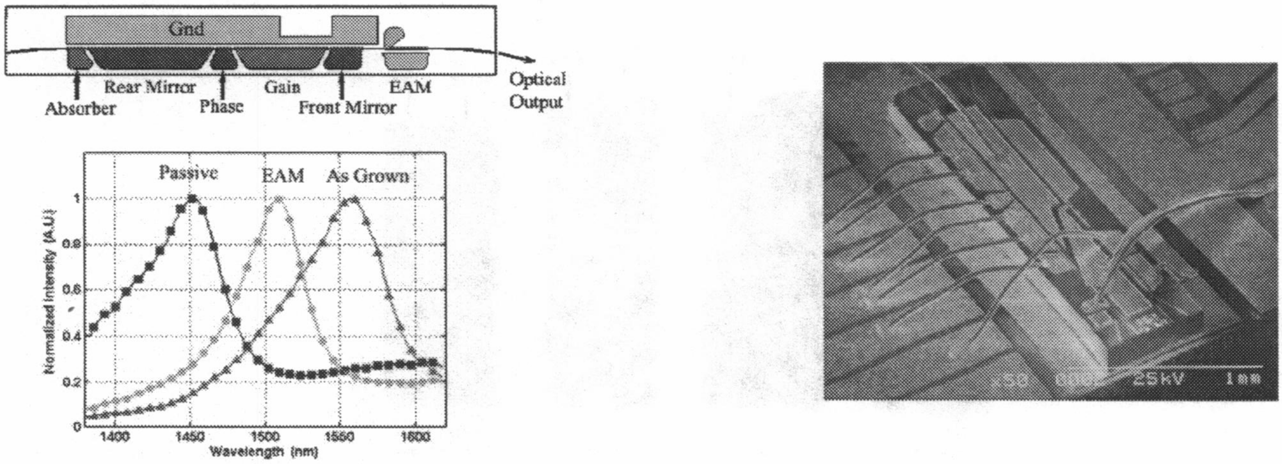
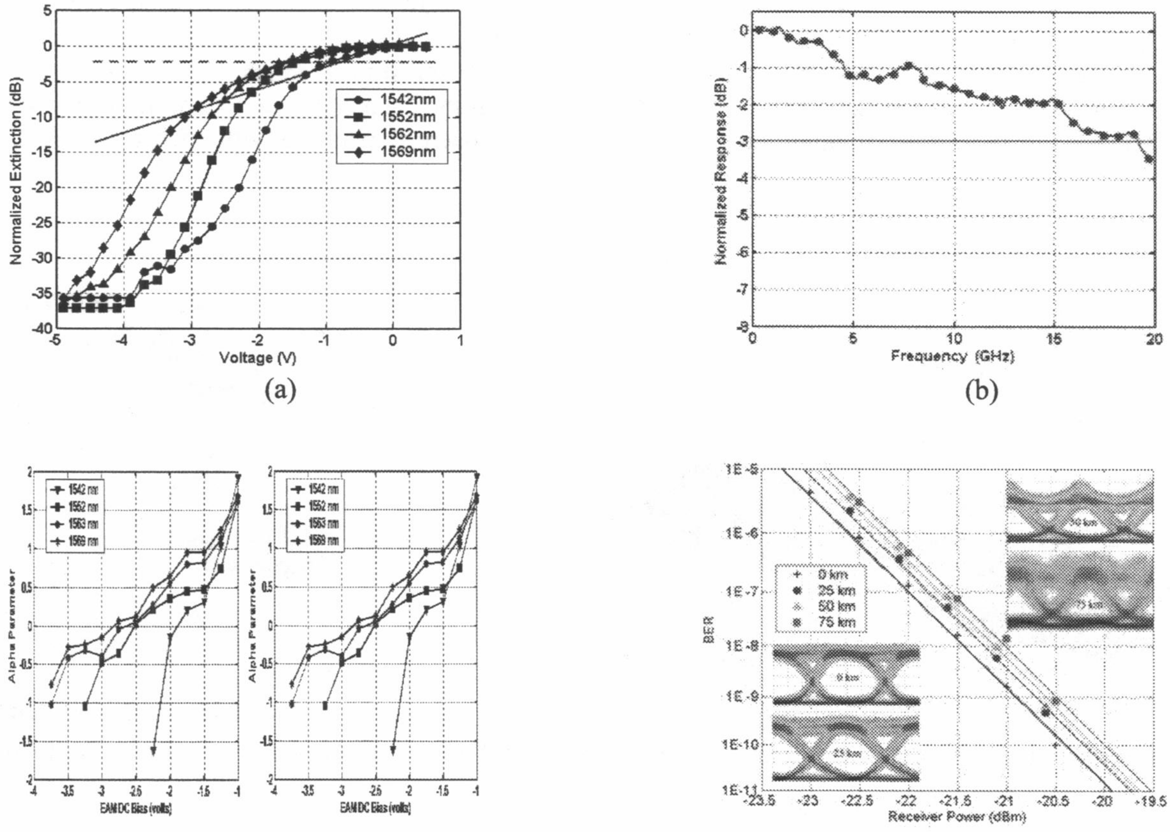


Figure 3. Schematic, SEM and photoluminescence spectra of an integrated SGDBR-EAM transmitter that uses a three-bandgap QWI process. Full C-band tunability with negative chirp demonstrated [3,4].



(a) (b)

(c) (d)

Figure 4. Results of Fig. 3 device: (a) Static electro-absorption characteristics of EAM; (b) small signal bandwidth; (c) large-signal chirp parameter across tuning range; and (d) bit-error-rate vs. receiver power for transmission through various distances of standard fiber with eye-diagrams. [3,4]

Using the QWI process more narrowly tunable laser-EAM PICs have been investigated for optical interconnect applications, in which very high efficiency transmitters are desired[5]. For the expected higher data bandwidths anticipated within the next decade, the laser-modulator configuration will probably be required. Figure 5 illustrates preliminary results for a laser-EAM design formed with the same QWI technology platform as used in Figs. 3 & 4. In this case the EAM was better optimized for the wavelength being used, so very low voltage swing (0.6 V) for 10 dB extinction is possible. The high 3 dB bandwidth (~25GHz) obtained without any traveling-wave structures suggests that 40Gb/s operation should soon be possible with less than 10 mW of power dissipated in the EAM.

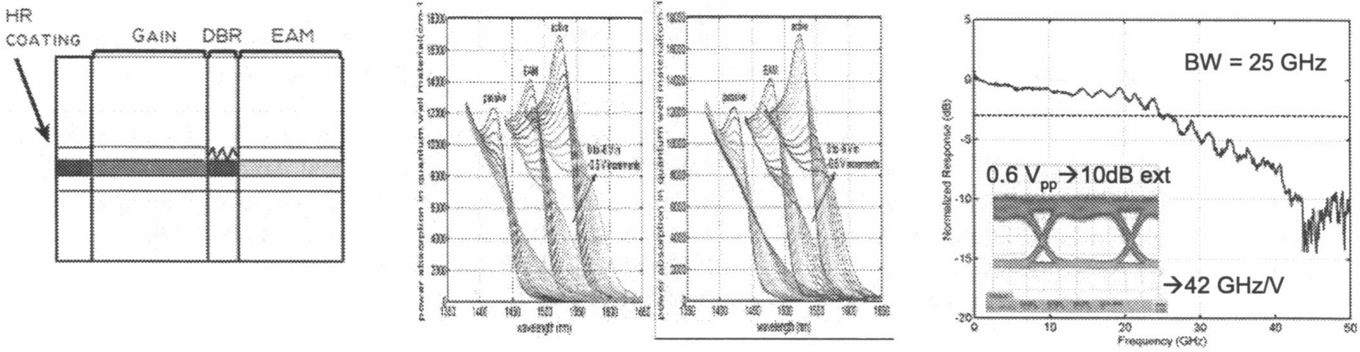
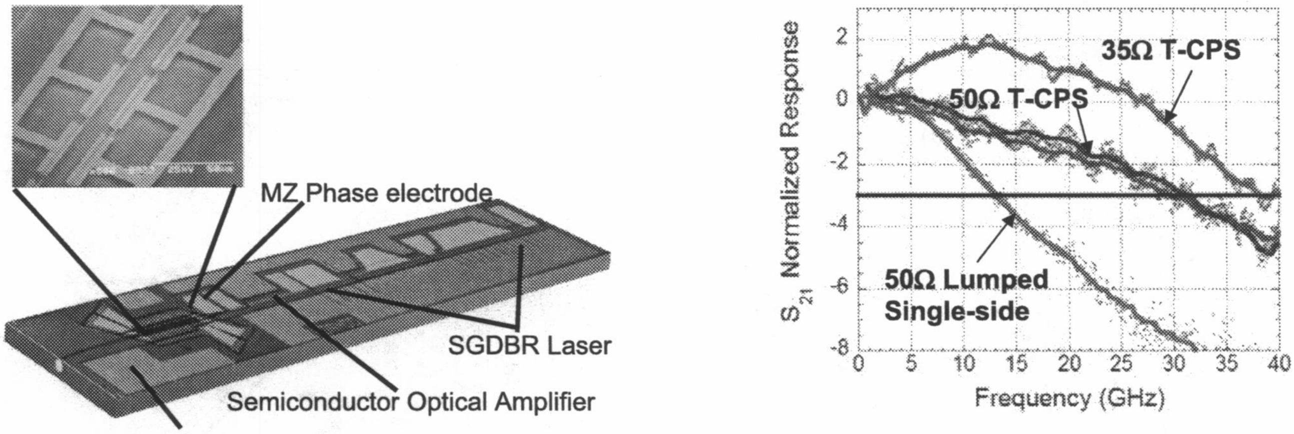


Figure 5. Short-cavity laser-EAM formed with QWI technology at 1550nm and results. The center figure gives the photocurrent for the three sections, and the right side the bandwidth. Laser-L = 150 μm; EAM-L = 125 μm[5].

Figure 6 depicts an SGDBR integrated with a backside detector, an SOA post-amp, and a Mach-Zehnder modulator (MZM) [6,7]. In this case the electrodes of the MZM are formed with 'T-coplanar' series-connected traveling-wave transmission lines. Also, a separate phase section is included in the MZM to establish the zero-bias set point, and a curved output guide suppresses facet reflections. As can be seen the frequency can extend to nearly 40GHz with proper choice of load resistor. Digital data up to 40 Gb/s has been transmitted with such a device along short distances of fiber.



λ = 1555nm; L = 250μm

Figure 6. Integrated SGDBR-MZM schematic, inset SEM of T-CPS transmission line, and experimental small-signal modulation response[6,7].

References

1. E. Skogen, J. Raring, J. Barton, S. DenBaars, and L. Coldren, "Post-Growth Control of the Quantum-Well Band Edge for the Monolithic Integration of Widely-Tunable Lasers and Electroabsorption Modulators," *IEEE J. Sel. Topics in Quantum Electron.*, vol. 9, pp. 1183-1190, (September/October 2003).
2. T. Wipiejewski, Y.A. Akulova, G. Fish, C. Schow, P. Koh, A. Karim, S. Nakagawa, A. Dahl, P. Kozodoy, A. Matson, B. Short, C. Turner, S. Penniman, M. Larson, and L.A. Coldren, "Integration of Active Optical Components," *Proc. SPIE,* Vol. 4997A-02 , San Jose, CA (January 2003).
3. J. Raring, E. Skogen, L. Johansson, M. Sysak, J. Barton, Milan L. Masanovic, and L. Coldren , "Demonstration of Widely-Tunable Single-Chip 10 Gb/s Laser-Modulators Using Multiple-Bandgap InGaAsP Quantum-Well Intermixing" *Phot. Tech. Let.,* **16,** (7),pp. 1613-1615 (July 2004).
4. J. W. Raring, E. J. Skogen, L. A. Johansson, M. N. Sysak, L. A. Coldren, "Low dispersion penalty at 10 Gb/s, Over 75 km, using a quantum-well-intermixed electroabsorption-modulator/widely-tunable laser transmitter," *Proc. OFC 2004,* PDP13, Los Angeles, CA, (February 22-27, 2004).
5. Erik J. Skogen, Chad S. Wang, James W. Raring, Gordon B. Morrison, and Larry A. Coldren, "Small-Footprint, High-Efficiency, Integrated Transmitters for High-Speed Optical Interconnect Applications," *Proc. Integrated Photonics Research*, paper no. IThD2, San Francisco, CA (June 2004).
6. Jonathon S. Barton, Erik J. Skogen, Milan L. Masanovic, Steven P. DenBaars, and Larry A. Coldren, "A Widely-tunable high-speed transmitter using an integrated SGDBR Laser-Semiconductor Optical Amplifier and Mach-Zehnder Modulator," *Jour. Of Selected Topics in Quant. Elec.*, **9**, (5), pp. 1113-1117 (September/October 2003)
7. Jonathon S. Barton, Matt Dummer, Anna Tauke-Pedretti, Erik J. Skogen, James Raring, Matt Sysak, Milan Masanovich, Leif A. Johansson, Larry A. Coldren "InP-based Active Photonic Integrated Circuits" *Proc. LEOS annual meeting 2004*, paper no. TuA5, pp. 169-170, Puerto Rico (October 2004).