From Tunable Lasers to Photonic Integration

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Abstract: This paper will review some of the author's efforts in the development of commercially-viable widely-tunable lasers and photonic integrated circuits (PICs). Recent work on integrated transmitters and receivers as well as optical phase-locked loops using such PICs will be emphasized.

Introduction

Early efforts at Bell Labs to create multiple-section tunable single-frequency lasers using etched slots indicated the ability to tune over wide ranges using the vernier effect[1-3]. However, all-active devices were limited due to carrier clamping, and thus, it later became obvious that active-passive structures, such as those pursued in Prof. Suematsu's group at TIT[4,5], were more desirable. This line of thinking led to the invention of the multi-element mirror concept[6] and associated widely-tunable lasers[7], which have become very important commercially[8]. The research also became the basis for a large activity on photonic integrated circuits (PICs), since the robust combination of different active and passive regions, DBR reflectors, and waveguide junctions were developed from this tunable laser work. Examples in recent years include: 1) widely-tunable transmitters, incorporating a sampled-grating DBR (SGDBR) laser, either electro-absorption (EA) or Mach-Zehnder (MZ) modulators, semiconductor-optical-amplifiers (SOAs), and monitoring photodiodes PDs)[9-10], 2) widely-tunable transceivers (or wavelength converters), incorporating an SOA-PD receiver stage and an SGDBR-SOA-EA (or MZ) transmitter stage [11-12], and 3) an "all-optical" monolithic tunable optical router (MOTOR) PIC that operated as an 8 x 8 space switch using wavelength converters as the switching fabric[13].

Most recently, coherent transmitters[14] and receivers[15] with Hz-level tracking accuracy, either to a reference or the incoming carrier, respectively, have been demonstrated using optical phase-locked loops (OPLLs). These utilize PICs that again incorporate widely-tunable SGDBRs, but now with optical hybrids and balanced detector pairs. These are closely co-packaged with custom electronic ICs that provide feedback to the tuning section for the phase and frequency locking. Very stable operation has been demonstrated for the first time in an OPLL with a large tuning range as well as rapid tuning and locking capability.

The Widely-Tunable Sampled-Grating DBR (SGDBR) Laser

In 1988 the first patent was filed on the multi-section tunable laser with differing multi-element mirrors, and it issued in January of 1990. Although initially constructed with etched-grooves, the preferred embodiment quickly became the Sampled-Grating Distributed-Bragg-Reflector (SGDBR) laser. Considerable research on other widely-tunable lasers was also carried out in the 1990s at UCSB [16,17], but none appeared to be as simple to create or as high in performance as the SGDBR. Full C-band tuning with reasonable output powers was demonstrated. The monolithic integration of the SGDBR with SOAs, EAMs, MZMs, and PDs was also demonstrated. In 1998 Agility Communications was formed to commercialize widely-tunable lasers, transmitters, and transponders, all using the SGDBR at their core as the laser engine. After some measure of success, the company was acquired by JDSU in 2005, and today the SGDBR in various integrated forms in various modules is a key product for JDSU [8].

Photonic Integrated Circuits (PICs)

As already indicated, the SGDBR became the basis of a large amount of PIC research at UCSB in the 1990s, and this continues to the time of this writing. Some of the most recent work has involved the integration of widely-tunable transmitters and receivers for coherent communication and sensing applications. These include both PICs and electronic ICs (EICs) closely co-packaged on the same carrier to create OPLLs as indicated in Fig. 1. The loop bandwidth has been measured to be about 1.1 GHz—a record level. The novel IC design provides both frequency and phase locking for wide capture and stable phase locking, even while sweeping an offset source in heterodyne operation. As shown by the illustrated data, the normally relatively wide linewidth of the SGDBR (> 1MHz) will duplicate the reference to which it locks, it can be continuously swept, while phase locked, over about a mode spacing by an rf source, and good eyes and BER can be demodulated from phase-modulated data. It is important to note that the optical carrier can be recovered, and phase locking can occur, well past the dispersion limit of the data (~10x) after the signal is propagated through a length of fiber.

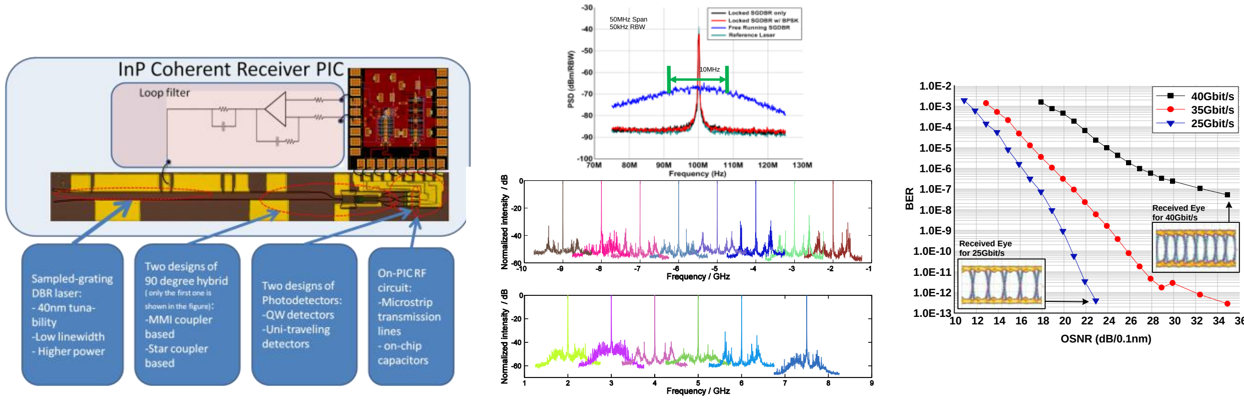

Fig. 1. (left) Schematic of OPLL with photos of PIC and EIC; (center-top) demonstration of linewidth reduction when locked to a narrow linewidth reference; (center-bottom) demonstration of continuous tuning while phase locked; (right) BPSK-BER data up to 40 Gb/s—limited by detector bandwidth [14,15].

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Larry A. Coldren is the Fred Kavli Professor of Optoelectronics and Sensors at UC-Santa Barbara, CA. He received his Ph.D. in EE from Stanford and spent 13 years in research at Bell Labs before joining UCSB in 1984, where he holds appointments in ECE and Materials. He co-founded Optical Concepts, acquired as Gore Photonics, to develop novel VCSEL technology; and later Agility Communications, acquired by JDSU, to develop widely-tunable integrated transmitters.

At Bell Labs Coldren worked on SAW filters and tunable coupled-cavity lasers using novel RIE technology. At UCSB he continued work on multiple-section lasers, in 1988 inventing the widely-tunable multi-element mirror concept, now used in numerous commercial products. He has also made seminal contributions to efficient VCSEL designs. His group continues efforts on high-performance InP-based photonic integrated circuits (PICs) and high-speed, high-efficiency VCSELs.

He has authored or co-authored over a thousand journal and conference papers, a number of book chapters, a textbook, and has been issued 65 patents. An original member of ISI's highly-cited researchers database, he now has over seventeen thousand citations with an H-index of over sixty. He is a Fellow of the IEEE, OSA, and IEE, a recipient of the 2004 John Tyndall and 2009 Aron Kressel Awards, and a member of the National Academy of Engineering.