Photonic Integrated Circuits for Microwave Photonics

Larry A. Coldren
Electrical & Computer Engineering and Materials Departments
University of California, Santa Barbara, CA 93106, USA

(Plenary Talk)
coldren@ece.ucsb.edu

***Abstract*—InP-based Photonic Integrated Circuits (PICs) have found applications in the telecommunication and sensing arena because they have offered improvements in cost and function as well as size, weight and power. For microwave photonics applications, it has been found that some analog functions such as optical-phase locked loops (OPLLs) can be greatly improved and enabled with PIC technology. Primary reasons are significantly reduced path lengths that enable much higher loop bandwidths and very stable optical paths enabling low noise coherent summing of optical signals.**

In this paper significant advances in PIC technology will be summarized. Integrated PIC coherent receivers and phase-locked transmitter arrays using OPLLs will be reviewed. Progammable PIC microwave photonic filters will also be briefly discussed.

I. INTRODUCTION

Photonic integration provides a reduction in system footprint, inter-element coupling losses, packaging cost, and usually power dissipation, as a single cooler can be used for multiple functions. Although yield issues must be addressed, overall reliability appears to improve, once such issues have been.

In the past decade the complexity of photonic integrated circuits (PICs) has steadily increased. At the turn of the century an integrated widely-tunable laser transmitter chip as illustrated in Fig. 1 represented a fairly advanced PIC [1]. As can be seen, it contained a widely tunable sampled-grating distributed-Bragg-reflector (SGDBR) laser, a semiconductor-optical-amplifier (SOA), and an electro-absorption modulator (EAM) all along a common waveguide.

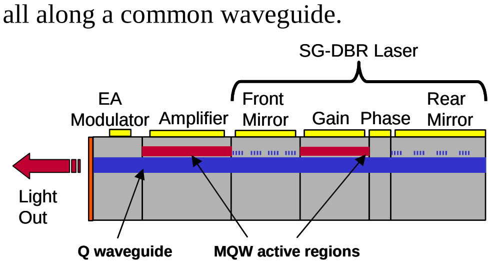

Fig. 1. SGDBR/SOA/EAM widely-tunable transmitter.

This work was partially supported by DARPA through the Phorfront, DoDN, PhASER, and other seed projects.

By the end of the current decade, PICs such as that shown in Fig. 2 have been demonstrated. This chip contains over 200 functional elements. This is an 8x8 optical router chip that uses 8 wavelength converters, which each contain an SGDBR followed by an SOA, and an optically-controlled modulator [2]. The wavelength converters then feed an arrayed waveguide grating router (AWGR), which is a dispersive element that directs different wavelengths to different outputs, thus providing the desired space switching.

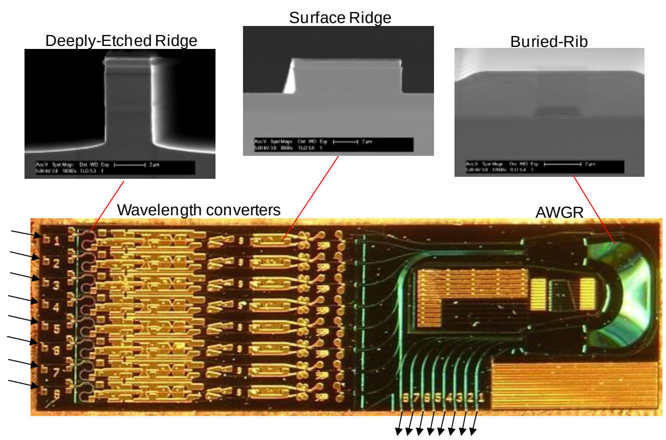

Fig. 2. Monolithic Tunable Optical Router (MOTOR) photo together with SEM cross sections of waveguides at various locations.

The MOTOR chip shown in Fig. 2 operates at 40Gb/s with RZ data, and although all of its inner workings are analog, it really is only intended to function with digital data. It has a fairly limited dynamic range ~10 dB for inputs in the -10 dBm range, a signal insertion loss ~10 dB, but it can switch digital data error-free with these limitations.

Other PICs of similar complexity to that of Fig. 2 are being manufactured and are carrying live telecom traffic. The most significant player in the commercial arena is Infinera. They are selling commercial systems that contain transmitter and receiver PICs together with all of the drive, receive, and control electronics [3]. Their PICs generally consist of a number of parallel transmit or receive channels together with an AWG multiplexer or de-multiplexer for the transmitter or receiver, respectively [4]. 100 Gb/s systems containing 10 parallel transmit or receive channels of 10Gb/s each have been in the market for several years.

II. Optical-Phase-Locked-Loops

A. *Coherent Receiver*

The first example microwave PIC to be discussed is a coherent receiver for phase-modulated signals. The receiver circuit is outlined in Fig. 3 [5]. Microwave photonic links using intensity modulation tend to limited in dynamic range by the transmitter [6]. For direct modulation of a laser the modulation speed must be kept significantly lower than the relaxation resonance frequency of the laser, or nonlinearities result for any modest modulation depth as the carrier density becomes unclamped. For higher frequencies external modulation must be used. Unfortunately, there are no intensity modulators that inherently have a linear relationship between drive voltage and the optical output.

If phase modulation is used, then linear modulators do exist with the basic linear electro-optic effect. Also, an effectively much deeper modulation can be imparted to the optical signal because one is not limited to simple on/off, which might be viewed as a 180˚ modulation, but one in principle could modulate to many times this level to enhance the potential signal/noise. However, now the problem of linearity in the link has been switched to the receiver, and this is the problem we address with the circuit of Fig. 3.

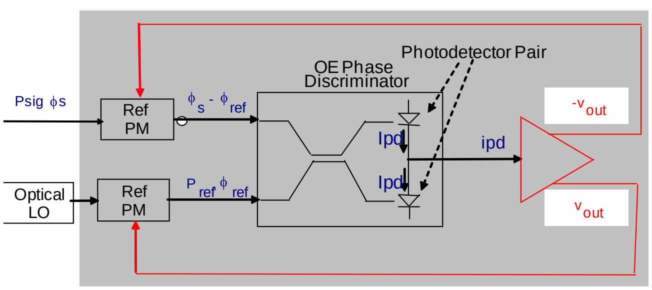

Fig. 3. Coherent receiver for phase-modulated input. Feedback from balanced photodetector is directed to tracking modulator pair.

In Fig. 3 the negative feedback signal to the tracking modulator pair reduces the level of the interference signal on the detectors so that the output is reduced to the linear range. The differential pair also suppresses even order distortions that may exist in the semiconductor modulators as well as amplitude modulation. This approach also enables the use of >> π-modulation depth since the signals leaving the differential tracking modulators are made to be almost in-phase even if hugely out of phase because of a large phase modulation prior to them.

One major issue with this approach is that the tracking phase modulators must nearly instantly track the phase deviation detected in the diode pair. Thus, the delay must be very small. In fact, for the circuit to work in the GHz range, it has been found that delays > 10ps are unacceptable. This not only calls for monolithic integration of both the electronics and photonics, it also demands the elimination of any unwanted signal paths between the two. Figure 4 illustrates the flip-chip bonding configuration that has been implemented to eliminate all additional delays in the practical implementation of the circuit of Fig. 3. The coupler has also been implemented as a beam-splitter to further eliminate propagation delay in a directional coupler embodiment, which was first explored.

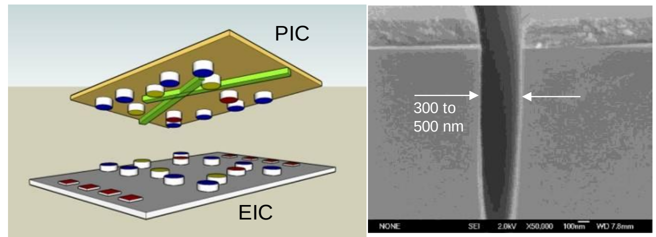

Fig. 4. Schematic of flip-chipping of electronic and photonic ICs together with SEM of etched slot beam splitter.

Initial results using this configuration will be reported in other papers [7,8], but to summarize briefly, a link gain of – 2 dB and a spur-free dynamic range (SFDR) of 122dB·Hz$^{2/3}$ was demonstrated with a transmitter V_π = 4.4 V and only 2.8 mA on each photodetector. Also, a peak-to-peak phase modulation depth of 1.62 π was used for these results, demonstrating the ability to employ a significant modulation depth.

B. *Phase-locked tunable lasers*

Loop delay is also important for phase locking lasers together. Figure 5 shows a chart of initial laser linewidth vs. loop delay for various levels of phase error. Explicitly shown are lines that represent the phase error allowed for different types of digital multilevel phase and amplitude coding. The corresponding SNRs in the signal bandwidth are 9.5dB (PSK), 12.5dB (QPSK), 20dB (16 QAM), and 26.2dB (64 QAM).

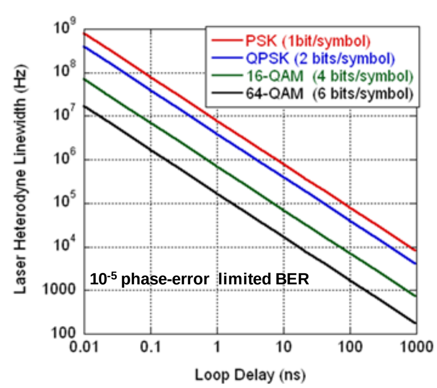

Fig. 5. Laser linewidth vs. OPLL loop delay to enable 10^{-5} error rate for given modulation format.

Widely tunable lasers as the SGDBR shown in Fig. 1 tend to have inherent linewidths in the 1- 3 MHz range. Fig. 5 would indicate a need for OPLL loop delay < 100ps for a correctable error rate of 10^{-5} in a 64-QAM digital system. But this would actually be a fairly distorted signal from a microwave photonics perspective. Instead of an equivalent spectral efficiency of 6 bits/symbol, we would like to see the line for 10 or 12 bits/symbol, which would again require a loop delay < 10ps in the OPLL if we started with the rather noisy SGDBR. So, again very tight integration is called for.

Phase locking of semiconductor lasers is desired in order to make inexpensive arrays of coherent sources for such applications as phased-array LIDAR and other optical-coherence-tomography (OCT) and imaging applications. It is also desired to have temperature insensitive synthesized sources that are locked to an offset from some stable reference to allow much more efficient use of the spectrum as in the rf domain. As a result, some initial experiments have been done to demonstrate integrated OPLLs formed from a pair of widely-tunable SGDBRs together with most of the required optical elements.

Figure 6 describes a heterodyne experiment in which two SGDBR lasers are offset-locked together [9]. The circuit schematic shows that an integrated modulator is used to generate sidebands on the mixed signal, so that the OPLL can lock on one of these. In this case a 5GHz fundamental offset locking is illustrated. With deep phase modulation of the on-chip modulator it is possible to generate a number of side bands and such modulators can be made with bandwidths up to ~ 100GHz, so it is anticipated that such offset locking might be possible up to the THz range without having to generate rf higher than 100 GHz.

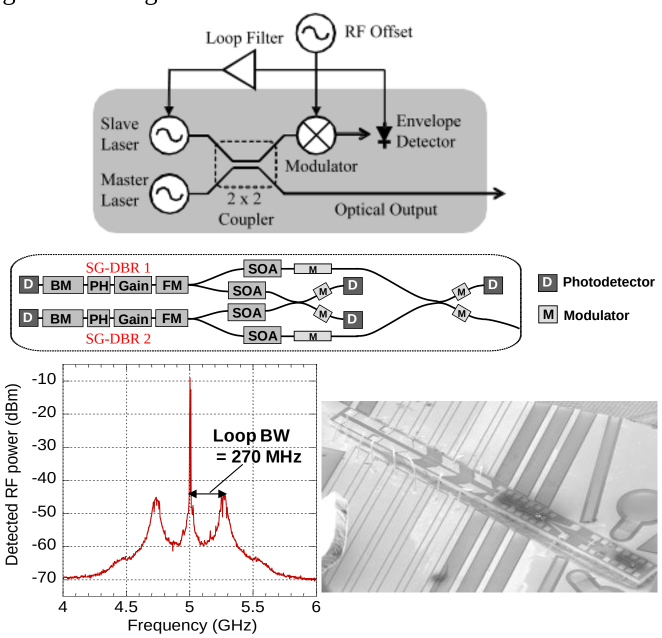

Fig. 6. Circuit schematic; PIC schematic; heterodyne result; and SEM of InP-based PIC.

Fundamental offset locking as high as 20 GHz was demonstrated with the current set up. Although a balanced detector pair was available on the chip, the electronics used only had a single-input TIA, so only a single detector was used, and this resulted in more AM and noise in the feedback loop than necessary. Nevertheless, a respectable phase error variance ~ 0.03 rad^2 was measured over the 2 GHz measurement window.

C. Future OPLL Directions

Figure 7 illustrates a cartoon of a futuristic LIDAR system-on-a-chip that will be one of the long-term research directions of a newly formed “Photonic Integration for Coherent Optics” (PICO) Center that involves five US universities [10]. As illustrated with OPLLs it is anticipated that both chirping of the beam in frequency as well as sweeping it in angle will be possible by rapid control of the offset locking as outlined in Fig. 6. This will involve significant developments in the control/feedback electronics as well as in the PICs themselves. As also noted, it is anticipated that much of this work may migrate to the hybrid-Si integration platform.

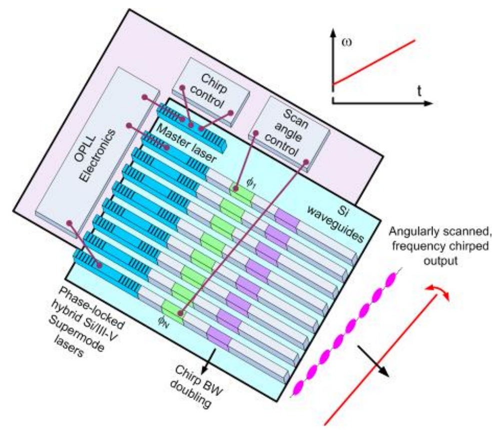

Fig. 7. Vision of future LIDAR system-on-a-chip [11].

III. PROGRAMMABLE MICROWAVE PHOTONIC FILTERS

Another area where photonic integration has potential to impact microwave photonics is in programmable optical filters. Particularly when the the rf information has already been modulated onto a lightwave carrier, it may be wise to perform some prefiltering in the optical domain prior to the receiver, where both the fractional bandwidths and the hardware are small.

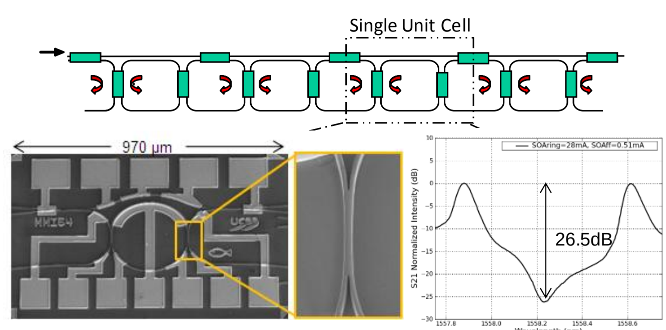

Fig. 8. Lattice filter schematic, SEM of unit cell/coupler, and combined pole/zero response [12].

Figure 8 shows some initial work in this area. The results are for a unit cell that could be an element of a more complex lattice filter [12]. As shown, the unit cell has two forward paths, and one contains a ring resonator. By selectively biasing the various SOAs and phase modulators placed in the arms of the unit cell, filters with a single pole, a single zero, or a combination of a pole and zero (as illustrated) can be programmed. All can be tuned in frequency by ~ 100 GHz. As also illustrated, novel tapered multimode interference couplers have been employed to save space in these designs.

More complex designs incorporating multiple unit cells as well as ones with different unit cell designs are being explored [13,14]. Figure 9 shows data taken from two integrated third order filters that are cascaded to give a very good extrapolated plot. 70 dB of rejection is predicted.

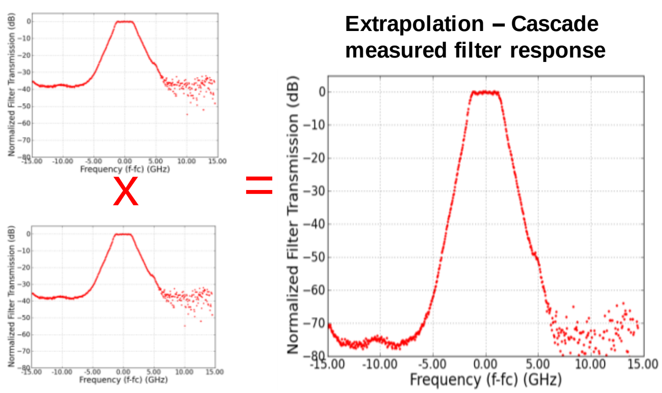

Fig. 9. Cascade of two 3-resonator filters simulated by multiplying transfer function data from the two monolithic filters.

Issues with such active filters are their noise and dynamic range properties. Some competitive designs have gone to great lengths to avoid the inclusion of SOAs because of concerns over their noise contributions and limited saturation levels. However, our simulations show, to the contrary, that some sort of amplification appears to be necessary in any realistic design because of the insertion loss that accumulates when many filter stages are cascaded.

Also, we have found that the net noise added by additional stages that contain SOAs after the first few is very small, even though the power level is just being maintained at the about same level through the cascade as at the input. This is because in a system with SOAs, the noise floor is no longer dominated by shot noise, but by added noise from the amplifiers. As a result, the effective noise figure of SOAs after a few stages in a cascade can be less than 0.5 dB, even though the measured NF for the stand-alone SOA might be ~ 4 dB.

As a result, the noise figure for a filter cascade with no amplifiers quickly goes up, directly as the insertion loss, and values of 30 or 40 dB are easily reached in a typical 8-10 stage filter. On the other hand, the cascade with SOAs, which also may have zero insertion loss, has a noise figure that saturates after a few stages, depending upon the details of the design. Typical values are in the 10 dB range.

The SFDR concern can also be managed by using low-confinement-factor designs. For confinement factors ~2%, saturation powers ~20 dBm have been demonstrated [15], which is sufficient for the current filter goals. Still higher values are possible [16], but there is a tradeoff in power dissipation, because high-saturation power designs are also low-gain designs, so more input power is required for a given gain.

IV. Conclusions

Photonic ICs are becoming important elements for microwave photonics. Low size, weight and power is fairly obvious, but additional advantages of low noise, low cost as well as high stability for a number of applications is very appealing. The possibility of simple, widely-tunable semiconductor sources being able to take the place of some of the very expensive narrow-linewidth sources of today is especially interesting.

References

[1] L.A. Johansson, Y.A Akulova, G.A. Fish, and L.A. Coldren, "Widely tunable EAM-integrated SGDBR laser transmitter for analog applications," *IEEE Photon. Tech. Letts*., vol. 15 (9) , (Sept. 2003).

[2] S. C. Nicholes, M. L. Mašanović, B. Jevremović, E. Lively, L. A. Coldren, and D. J. Blumenthal, "An 8x8 InP Monolithic Tunable Optical Router (MOTOR) Packet Forwarding Chip," *IEEE J. Lightwave Tech.*,vol. 28, no. 4, pp. 641-650, (Feb. 2010).

[3] D. F. Welch *et al*., "The realization of large-scale photonic integrated circuits and the associated impact on fiber-optic communication systems," *J. Lightw. Technol.*, vol. 24, pp. 4674, (Dec. 2006).

[4] R. Nagarajan *et al*., "Large Scale Photonic Integrated Circuits," *IEEE J. Sel. Topics Quantum Electron.*, vol. 11, pp. 50-65, (Jan./Feb. 2005).

[5] H. F. Chou *et al.*, "High-linearity coherent receiver with feedback," *IEEE Photon. Technol. Lett.*, vol. 19, no. 12, pp. 940–942, (Jun. 2007).

[6] C. Cox, "Analog Optical Links: Theory and Practice", Cambridge University Press, Cambridge, 2004. .

[7] A. Ramaswamy, *et al.*, "Demonstration of a linear ultra-compact integrated coherent receiver," *Proc. MWP*, (Oct. 2010).

[8] U. Krishnamachari, et al, " An ultra-compact integrated coherent receiver for high-linearity RF-photonic links," *Proc. MWP* (Oct. 2010).

[9] S. Ristic, A. Bhardwaj, M. J. Rodwell, L. A. Coldren, and L. A. Johansson, "An optical phase-locked loop photonic integrated circuit,"*J. Lightwave Technol*, vol. 28, no. 4, pp. 526–538, (Feb. 2010).

[10] L. Coldren, J. Bowers, M. Rodwell, L. Johansson, A. Yariv, T. Koch, J. Campbell, R. Ram, "Photonic Integration for Coherent Optics (PICO)," part of DARPA CIPHER program (2010).

[11] Schematic supplied by A. Yariv as part of PICO project.

[12] E.J. Norberg, R.S. Guzzon, S. Nicholes, J.S. Parker, and L. A. Coldren, "Programmable photonic filters fabricated with deeply etched waveguides," *IPRM '09*, paper TuB2.1, Newport Beach (May, 2009)

[13] R. S. Guzzon, E.J. Norberg, J. S. Parker, L. A. Johansson, and L. A. Coldren,"Monolithically integrated programmable photonic microwave filter with tunable inter-ring coupling," *Proc. MWP*, (Oct., 2010).

[14] E. J. Norberg, R. S. Guzzon, J. S. Parker, L. A. Johansson, and L. A. Coldren,"A monolithic programmable optical filter for RF signal processing," *Proc. MWP*, (Oct. 2010).

[15] J. Raring *et al.*, "Demonstration of high saturation power/high gain SOAs using quantum well intermixing based integration platform," *Electron. Letters*, vol. 41, pp. 1345-1346, (2005).

[16] P.W. Juodawlkis, et al, "High-power 1.5 µm InGaAsP-InP slab-coupled optical waveguide amplifier," *IEEE Photon. Tech. Letts*., vol. 17, (Feb, 2005).