Photonic Integrated Circuits as Key Enablers for Coherent Sensor and Communication Systems

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***Abstract*— InP-based Photonic ICs (PICs), together with closely integrated Electronic ICs, have recently been shown to enable robust, compact coherent optical communication and sensor systems that have not been possible in the past. Experimental results will illustrate these functionalities.**

I. INTRODUCTION

SOME years ago, coherent communication was intensively investigated as a means of increasing receiver sensitivity and repeater spacing in fiber telecommunication systems [1]. When wavelength division multiplexing (WDM) systems became more practical and inexpensive with the advent of the erbium-doped fiber amplifier (EDFA) these relatively costly and temperamental coherent communication approaches were put on the shelf for such fiber optic systems [2,3]. Nevertheless, they have continued to be explored in free-space communications as well as sensing applications where the cost and the difficulties are worth the benefits [4]. In recent years coherent techniques have also reemerged in the telecommunications sector, mainly driven by spectral efficiency, as we again are running out of fiber bandwidth, now driven totally by data, mostly from social networking, HD video, and other exponentially growing data demands on the network [5,6].

Recently, we have been exploring more integrated approaches, where only a single photonic integrated circuit (PIC) may contain all of the transmitter or receiver optics (except for coupling) and the feedback to lock the local oscillator or transmitter to some reference may be done with a single electronic IC, or perhaps with no electronic IC (EIC) at all [7-9]. These approaches have the potential to vastly simplify coherent transmitters and receivers and make them much more robust. Environmental controls are relaxed, locking and capture ranges increased, and overall stability is significantly improved in a much smaller, lighter, less costly, and lower power package.

Figure 1 describes a heterodyne experiment in which two SGDBR lasers are offset-locked together [7]. 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.

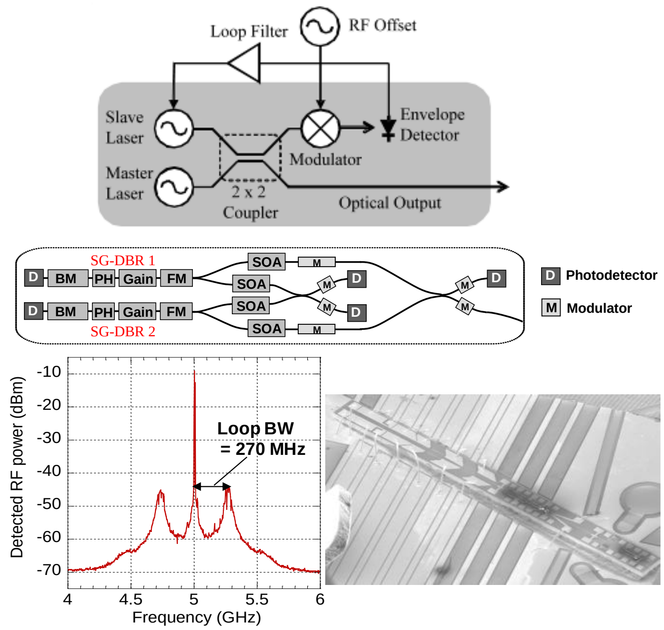

Fig. 1. Circuit schematic; PIC schematic; heterodyne result; and SEM of InP-based PIC

Fundamental offset locking as high at 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 amplifier, 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.

II. RECENT WORK

Figure 2 shows a block diagram of a phase-locked coherent receiver, which contains photos of the PIC and EIC. The PIC contains a widely-tunable SGDBR LO laser (40 nm range) and a 90 degree hybrid along with monitoring detectors and adjustment amplifiers [8-10]. The EIC is a Costa's loop design for frequency and phase locking. At this writing simple phase locking with a 1 GHz capture range was demonstrated using the loop filter alone. Lower noise than that in Fig. 1 was observed, but detailed data is still being acquired. The linewidth of the

SGDBR laser was significantly narrowed by locking it to a narrow linewith reference laser.

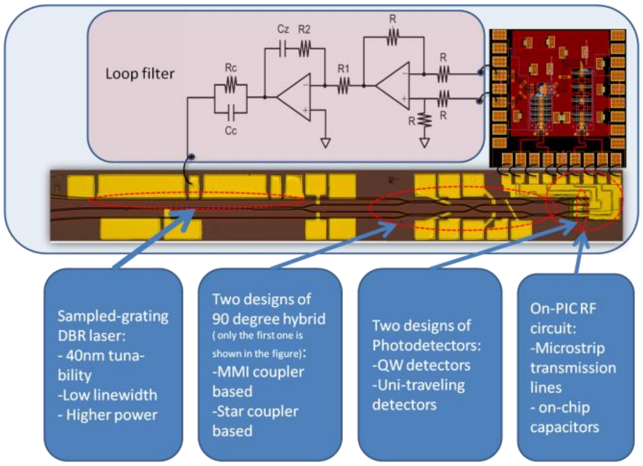

Fig. 2. Block diagram of phase-locked receiver with inserted photos of PIC and EIC. Widely-tunable SGDBR on-chip laser as well as external LO laser inputs possible; integrated optical hybrid and balanced I & Q detector pairs on-chip.

Figure 3 compares receiver output when the LO SGDBR laser is unlocked relative to a narrow linewidth input cw signal vs. the case of phase locking with a 100 MHz offset. A vast reduction in phase noise as well as a 'clean' 100 MHz optical interference waveform is observed.

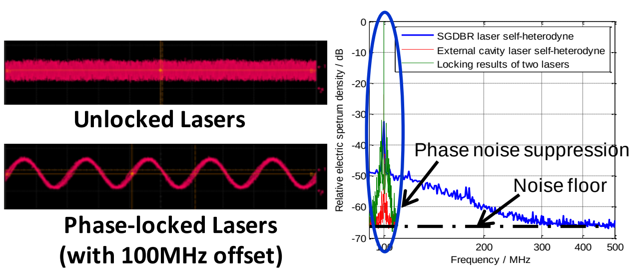

Fig. 3. Optical phase locked loop results.

Finally in Fig. 4 we illustrate the concept of a widely-tunable digitally-synthesized sweeping transmitter which might be relevant to a LIDAR system or some other sensor or communication system [9]. By using a single narrow-linewidth optical reference and two rf sources (one tunable) together with what could be one PIC (now two), we have proposed and partially demonstrated that we can digitally synthesize linear sweeps (or any other frequency pattern) up to 40 nm (5 THz) in width. A gain-flattened mode-locked ring laser is used to generate a comb spectrum up to this width. Currently 2 THz has been demonstrated as shown [11]. If one of the lines is locked to a stable reference, all of the lines are coherently referenced to it. The SGDBR can be tuned between lines using a millimeter wave source in the feedback electronics as shown. Then, in the next clock cycle the laser can jump to lock to the next mode-locked line and so forth.

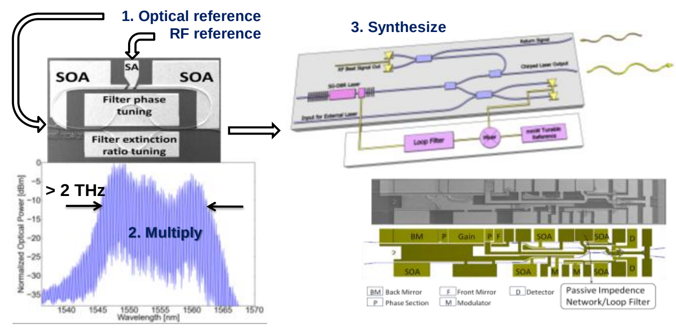

Fig. 4. Schematic of a digitally-synthesized optical transmitter capable of outputs over a 5 THz range with Hz level relative frequency accuracy.

REFERENCES

[1] Y. Yamamoto and T. Kimura, "Coherent optical fiber transmission systems," *IEEE J. Quantum Electron*, vol. 17, no. 6, pp. 919-925, Jun. 1981.

[2] R.J. Mears, L. Reekie, I.M. Jauncey and D. N. Payne, "Low-noise Erbium-doped fibre amplifier at 1.54pm," *Electron. Lett.*, vol. 23, no. 19, pp.1026–1028, Sept. 1987.

[3] N. S. Bergano and C. R. Davidson, "Wavelength division multiplexing in long-haul transmission systems", *J. Lightwave Technol.*, vol.14, no. 6, pp. 1299-1308, Jun. 1996.

[4] A. J. Rogers, "Polarization-optical time domain reflectometry: a technique for the measurement of field distributions," *Appl. Opt.*, vol. 20, pp. 1060-1074, 1981.

[5] R. Tkach, "Optical Network Capacity: From Glut to Scarcity," *OIDA Annual Meeting*, Santa Clara, CA, Dec. 1-2, 2009.

[6] M. Nakazawa, K. Kikuchi, T. Miyazaki (eds.), *High Spectral Density Optical Communication Technolgies, Optical and Fiber Communications Reports 6*, Springer-Verlag Berlin Heidelberg, vol. 6, pp 103-127, 2010.

[7] S. Ristic, A. Bhardwaj, M.J. Rodwell, L.A. Coldren, and L.A. Johansson, "An optical phase-locked loop photonic integrated circuit*," J. Lightwave Techol.*, vol. 28, no. 4, pp. 526-538, Feb. 15, 2010.

[8] M. Lu, A. Bhardwaj, A. Sivananthan, L. Johansson, H. Park, E. Block, M. Rodwell, L. Coldren, "A widely-tunable integrated coherent optical receiver using a phase-locked loop," *IEEE Photonics Conf (IPC'11)*, Arlington, Oct. 2011.

[9] P. Binetti, M. Lu, E. Norberg, R. Guzzon, J. Parker , A. Sivananthan, A. Bhardwaj, L. Johansson, M. Rodwell, L. Coldren, "Photonic integrated circuits for coherent optical links, in press, *J. Quantum Electron.* , special issue on integrated optoelectronics, 2011.

[10] L.A. Coldren et al, "High Performance InP-Based Photonic ICs—A Tutorial," *IEEE J. Lightwave Tech*., vol. 29, no. 4, pp. 554–570, Feb. 2011.

[11] J.S. Parker, A. Bhardwaj, P.R.A. Binetti, Y.-J. Hung, C. Lin, L.A. Coldren, "Integrated 30GHz passive ring mode-locked laser with gain flattening filter," in *Proc. IEEE International Semiconductor Laser Conf.*, Kyoto, Japan, Sept. 26-30, 2010, Paper PD1; also to be published *IEEE J. Quantum Electron.*