Scaling capacity and functionality in large-scale photonic integrated circuits

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While large scale integrated circuits have revolutionised the electronics industry, the optical components industry has been surprisingly slow to recognise the benefits that photonic integration can bring. The concept of photonic integration has been proposed for over 35 years [1-5], but commercial, large-scale photonic integrated circuits (LS-PICs) were not realized until 2004, with the introduction of 10-channel 100 Gb/s transmitters and receivers [6].

LS-PICs are a key enabling technology to meet the growing bandwidth demand at reduced cost, power consumption and equipment footprint. At the same time the optical systems based on PICs deliver huge increase in reliability – mainly thanks to dramatic reductions in the number of fibre couplings. **Figure 1**, for example, shows the reliability results for a commercially available PIC-based digital reconfigurable optical add-drop multiplexer (ROADM). The yellow bars illustrate the cumulative deployed field hours (in millions), while the blue line shows the Failure in Time value (FIT, number of failures in 10^9 hours). As of the end of 2007, the total PIC pairs (transmitter and receiver, Tx and Rx) that have been deployed in the field have accumulated over 40 million hours of actual operation with zero failures, resulting in a FIT value of about 20 at a 60% confidence level.

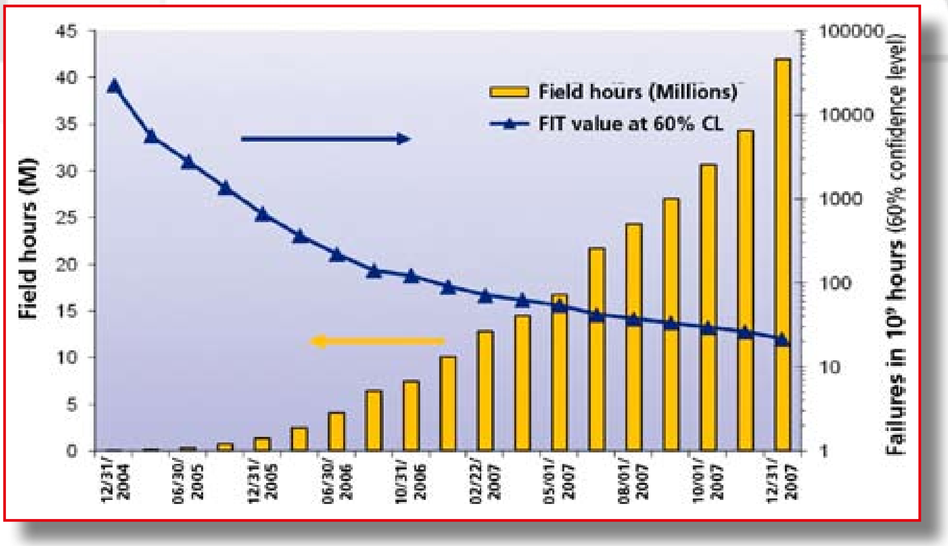

Figure 1: Reliability data for a PIC-based ROADM system

Thus InP-based PICs demonstrate high reliability in real-world network applications. These results provide quantitative reinforcement of the well-established paradigm in electronic silicon ICs that higher level of device integration improves reliability.

1 Previous PIC developments

Figure 2 shows an LS-PIC development timeline, beginning in 2004 with the demonstration and commercial introduction of a transmitter LS-PIC (Tx LS-PIC) with integrated laser, modulator, variable optical attenuator and multiplexer, and a receiver PIC (Rx PIC) with integrated high-speed photodiodes and demultiplexer [6]. This chip integrates 10 DWDM channels (dense wavelength division multiplexing), each transmitting at 10 Gb/s for a total chip capacity of 100 Gb/s.

Since then, a number of technology demonstrations have been successfully completed to investigate how PIC technology can be scaled in the dimensions of per-chip capacity and functionality. Still referring to the timeline in figure 2:

- March 2005: the number of channels on the PIC could be scaled to 40 DWDM channels at 10 Gb/s [7].
- March 2006: the individual channel data rate was scaled from 10 Gb/s to 40 Gb/s, for a total on-chip capacity of 1.6 Tb/s [8].
- March 2007: Semiconductor optical amplifier (SOA) functionality was integrated on the Rx PIC. Note that, while SOAs actually predate EDFAs, the former is not generally used as a multi-channel DWDM amplifier because in such applications there is significant intra-channel and inter-channel interference. However, when enough channels are passed through a single SOA there is a statistical averaging effect that effectively eliminates this interference. The effect was reported in [9], but conventional DWDM systems (i.e. those not based on PICs) cannot guarantee that enough DWDM channels will be passing through the SOA because channels are added individually [10]. In an integrated system, enough channels (ten channels in the commercial implementation) are always operating through the SOA to ensure the statistical averaging takes place.
- February 2008: one amplifier (SOA) per channel integrated on the Tx PIC. In addition to enabling higher emission power and longer reach DWDM links, individual SOAs for each channel can

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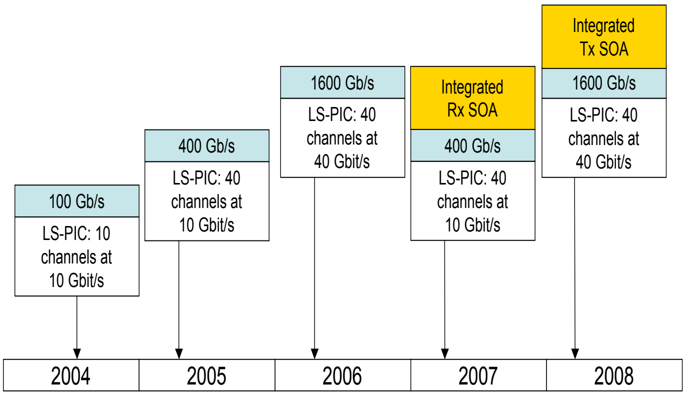

Figure 2: Timeline of Infinera PIC developments

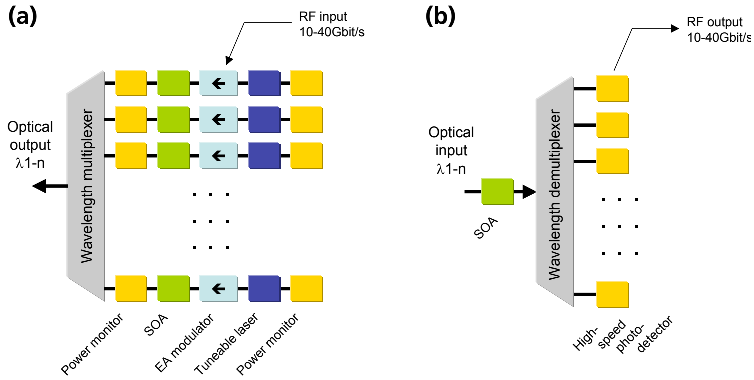

Figure 3: (a) Schematic for TxLS-PIC (sender) with SOAs (b) Schematic for RxLS-PIC (receiver) with SOA

also be used for power flattening and skewing while eliminating the need for the variable optical attenuators of earlier PIC designs [6,7,8].

2 Device architecture

The schematic of a Tx LS-PIC device with per-channel monolithically integrated SOAs is shown in **figure 3a**. Each channel of this device has a laser and an electro absorption (EA) modulator for encoding data onto the laser output. Data rates from 10 Gb/s to 40 Gb/s can be supported by chips with different modulator designs. The encoded optical signals are amplified by the individual SOAs. Each channel also has a power monitoring photodiode as in the previous version of the Tx LS-PIC [6]. The amplified optical signals from all the channels are multiplexed into a single output waveguide for coupling to an external fibre.

In **figure 3b** the equivalent schematic for the Rx LS-PIC device features a single wide bandwidth SOA at the input. The input channels, up to a maximum of 40, are then demultiplexed using an arrayed waveguide grating (AWG) router. The demultiplexed channels are then terminated in an array of high speed, waveguide photodetectors. The SOA and AWG were designed to be polarization independent.

3 Results

The results to be presented in the following will concentrate on the Rx LS-PIC design in figure 3b. This is because the Rx LS-PIC is a much more challenging approach because the SOA is used in multi-channel mode, and because the entire PIC is engineered to be polarization-independent.

3.1 Amplified spontaneous emission

The amplified spontaneous emission (ASE) spectrum of the SOA shown in **figure 4** was measured at 250 mA bias. The –3 dB width of the ASE spectrum is 53 nm.

3.2 Gain

Figure 5 shows the gain distribution for the SOA and AWG combined. The median gain[1] is 22.7 dB. The total variability in gain (95% to 5%) over 300 channels is about 2.5dB. The maximum polarization dependent gain (PDG) over the same number of devices is less than 0.8 dB (95% point of the distribution). SOA length is 900 µm in this case, although we investigated SOA's of various lengths. The typical bias is about 250 mA. The electrical bandwidth of the integrated high speed photodetector (PD) is greater than 10 GHz at a bias of -1 V and 20 GHz at a bias of -5 V [11]. The performance of this PIC exceeds that of an 8 channel device described in [12] where the gain of the SOA was just sufficient to overcome the chip losses and the PD's had a bandwidth of 3.5 GHz.

3.3 Noise

Figure 6 shows the Noise Figure (NF) as a function of SOA bias, where NF reaches a minimum value of 4 dB (excluding fibre coupling). This is comparable to the performance of an Erbium-doped fibre amplifier (EDFA).

3.4 Gain saturation

Figure 7 shows the gain saturation behaviour of the SOA as a function of output power. The 3 dB saturation output power (P_{sat}) is 16 dBm. This P_{sat}, obtained here at a lower pump current, is comparable to the best values published for a standalone polarization independent SOA [13].

[1] Median refers to the middle value in a distribution. It's different from "average" or "mean" because it refers to a discrete measured value.

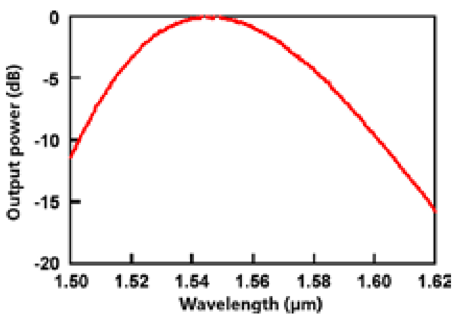

Figure 4: ASE spectrum of the SOA at 250 mA

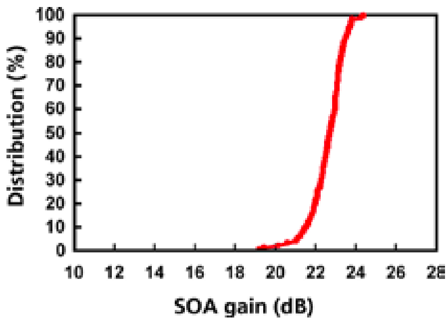

Figure 5: SOA Gain distribution for 300 channels

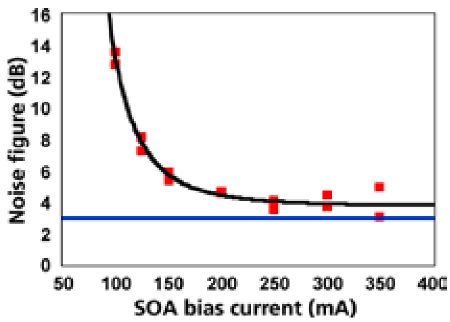

Figure 6: SOA Noise Figure as a function of bias. The blue line indicates a typical EDFA noise level

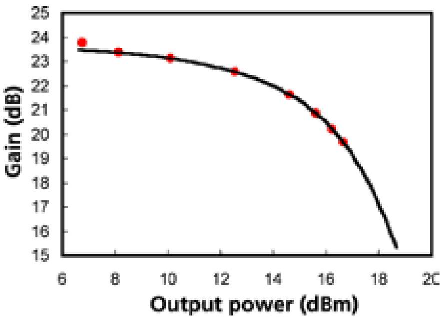

Figure 7: Gain saturation of the SOA

3.5 Tx PIC Performance

In contrast to the single SOA used on the Rx PIC, the Tx PIC employs a dedicated, integrated SOA device for each channel. This ensures the maximum gain for this channel before launching into the fibre. Briefly, the results show that the Tx PIC SOA is operating as a practical optical amplifier with outstanding gain characteristics and low noise. The Tx LS-PIC performance includes SOA gain of 13 dB with a saturated output power of 15 dBm.

4 Conclusion

Systems based on PIC technology have already demonstrated an ability to change the economics and service response time for optical transmission networks, while increasing system reliability. The results described above of the PIC developments over the past five years also prove the inherent scalability of photonic integration in terms of channel count, channel speed and now additional functionality in the form of on-chip wideband amplification.

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