Integrated Photonics

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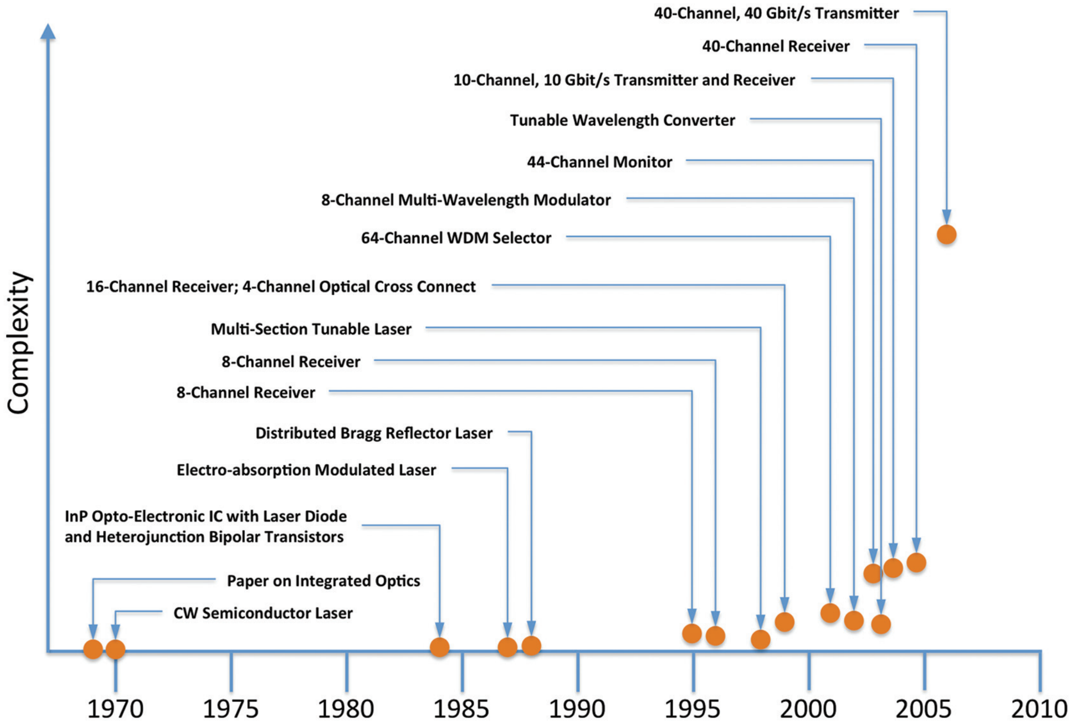
An essay on the history of integrated photonics invariably starts with the seminal paper by Miller [1]. In 1969 the idea was way ahead of its time, and many of the components needed to make such an integrated circuit a reality had yet to be invented. Hayashi and Panish's demonstration of the continuous wave (CW) room temperature operation of a semiconductor laser, a critical device for the photonic integrated circuit (PIC), was still a year away [2]. Optical transport, where PICs find their applications, got its somewhat fortuitous start in 1970 as well with the report of a low-loss optical fiber by the group at Corning [3].

There is always some personal bias in presenting the historical evolution of any technology. Figure 1 graphically shows one such historical progression of PIC complexity, as measured in the number of integrated components on a single InP substrate, with time. The details of the devices and references presented in Fig. 1 are in [4]. InP and its alloys are the material of choice in fabricating light emitters for optical transport applications. This is due to the low-loss window at 1550 nm and the low-dispersion point at 1300 nm in the standard silica optical fiber.

For the first decade or so after the demonstration of the CW laser in the GaAs system, InP lasers started to mature. In the mid-1980s there was active work in the area of opto-electronic integrated circuits (OEICs), where the integration of electronic devices such as HBT (heterojunction bipolar transistor) and FET (field effect transistor) with laser diodes and photodetectors was pursued. In the late 1980s three-section tunable DBR (distributed Bragg reflector) lasers were introduced. This was also when electro-absorption modulators (EAMs) integrated with distributed feedback (DFB) lasers were demonstrated. The trend continued with more complicated (four and five section) tunable laser sources that were also integrated with an EAM or a semiconductor optical amplifier (SOA). The next step was the demonstration of the arrayed waveguide grating (AWG) or PHASAR (phased array) router integrated with photodetectors for multi-channel receivers or with gain regions and EAM for multi-frequency lasers and multi-channel modulated sources. One of the most complex PICs reported in the last century was a four-channel optical cross-connect integrating 2 AWGs with 16 MZI (Mach–Zehnder interferometer) switches. At this stage the most sophisticated laboratory devices still had component counts below 20 while those in the field had component counts of about 4.

The trend in low-level photonic integration continued into the 2000s with one of the larger chips reported being a 32-channel WDM channel selector. In 2003, ThreeFive Photonics reported a 40-channel WDM monitor chip, integrating 9 AWGs with 40 detectors. MetroPhotonics reported a 44-channel power monitor based with an echelle grating demultiplexer. The commercial development of both chips was subsequently discontinued. The first successful attempt at a commercial large-scale photonic integrated chip (LS-PIC) was made in 2004 when Infinera introduced a 10-channel transmitter, with each channel operating at 10 Gbit/s. This device with an integration count in excess of 50 individual components was the first LS-PIC device deployed in the field to carry live network traffic. This was quickly followed in 2006 by a 40-channel monolithic InP transmitter, each channel operating at 40 Gbit/s, with a total component count larger than 240, and aggregate data rate of 1.6 Tbit/s. The complementary 40-channel receiver PIC also had an integrated, polarization independent, multi-channel SOA at the input.

2004, the year when the first commercial large-scale photonic integrated circuit was deployed, proved to be a watershed year for silicon photonics as well when Intel demonstrated

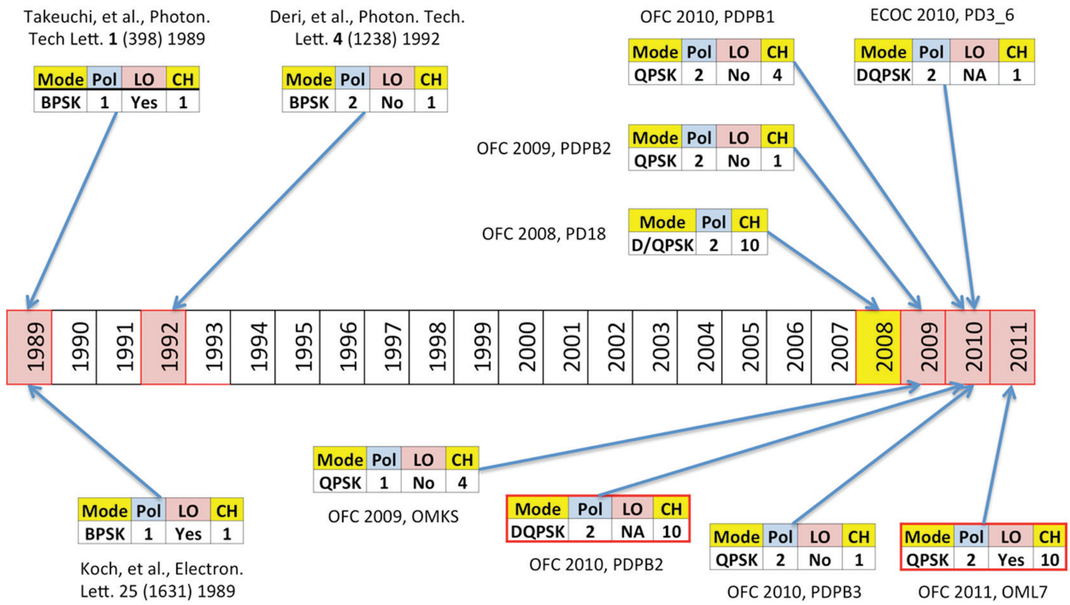


▲ **Fig. 1.** Historical trend and timeline for monolithic, photonic integration on InP (without including vertical cavity InP devices). The vertical scale is linear, and the red filled circles start at 1 and go to 240. The trend shows an exponential growth in PIC complexity in recent years. Unlike silicon ICs where the transistor count is a universal metric, there is no unique benchmark for complexity in photonic integration. For this exercise, we have counted a functional unit (which may be a combination of other optical elements) as a device. For example, an MZI is counted as 1 and not as 3. Likewise an AWG is counted as 1 irrespective of the fraction of the PIC real estate it occupies.

the first gigabit per second optical silicon (Si)-on-insulator (SOI) modulator [5]. Si as a platform for optical integration dates back to the 1980s [6,7]. In [6] can be found an excellent review of the early years of Si photonics. Unlike InP, Si has a centro-symmetric crystalline structure and does not exhibit the linear electro-optic effect that is commonly used for modulating light in InP. Most Si modulators are based on the carrier plasma effect, change of refractive index with carrier accumulation, or depletion. Although this is a weak material effect, the capacitor structure, which allows for a large effective charge transfer, improves the efficiency considerably [6]. Although there are reports of integrated Ge lasers on Si substrates [8], for the most part the light sources for Si photonics are made of InP and are integrated using hybrid techniques [9].

In Fig. 1 we saw the progression of PIC complexity thru the 2005 timeframe. Although some of the PICs, such as the switches and CW sources, were modulation format agnostic, for the most part these operated using OOK (on–off keying). Figure 2 shows the progression of PICs used for advanced modulation formats such as QPSK (quadrature phase shift keying) used in optical coherent communication. The details of the devices and references presented in Fig. 2 can be found in [10].

Coherent optical communication development started in the mid-1980s. After a gap of more than ten years, in the mid-2000s the field went through a revival with the availability of high-speed Si ASICs and advanced digital signal processing algorithms that eliminated the need for ultra-stable optical sources and analog phase/frequency/polarization tracking of the optical carrier at the receiver. Early coherent receiver PICs were all single channel. They were designed for binary phase shift keying (BPSK) modulation format. BPSK is similar to QPSK except that there are no data in the quadrature



▲ **Fig. 2.** A timeline for the development of coherent PICs. There is a gap between the early 1990s, when EDFAs were first introduced, and late 2000s when coherent communication systems saw deployment. Key: Mode = BPSK, QPSK; Pol = number of polarizations detected; LO = whether a LO was integrated into the PIC; CH = number of channels integrated onto a PIC. Most of these PIC's are receivers, with exception in 2008 when a 10 channel transmitter PIC was reported which included an I /Q modulator integrated with an optical source, for each channel, on the same substrate.

component of the signal. A simple, single-stage MZ modulator (MZM) may be used to generate a BPSK signal. BPSK signals have lower spectral efficiency but better noise margin for longer transmission distances. There were early attempts to integrate a LO (local oscillator) on the receiver PIC as well. A multi-channel PIC with I/Q MZM integrated with an optical source was reported in 2008. There have been a number of variants on the DQPSK and QPSK (with external LO) receiver PICs reported since then. The DQPSK PICs also have the polarization components integrated onto the same substrate. The first multichannel, dual polarization, QPSK receiver PIC with an integrated LO per wavelength was reported in 2011. Unlike the first phase of the history of integrated photonics discussed in Fig. 1, the evolution of coherent PICs shown in Fig. 2 has devices on both the InP and Si platforms.

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