

The Advantages of Indium Phosphide Photonic Integration in High-performance Coherent Optics

A wide range of cloud and video applications, together with the increased access speeds enabled by 5G, DAA, and next-generation PON, are driving the need for ever more optical bandwidth. To deliver this bandwidth, optical vendors are developing a broad range of coherent optical transceivers addressing different segments of the market, each with its own set of design considerations. This white paper focuses on the high-performance segment, with ever-higher baud rates, higher-order modulation, and advanced capabilities such as Nyquist subcarriers and probabilistic constellation shaping that deliver more capacity per wavelength and increased spectral efficiency while maximizing reach.

In order to identify the optimal material choices for the photonic elements of the transceiver, this paper first examines the inner workings of a high-performance transceiver to identify the optical functions that are needed and the benefits of integrating these functions into photonic integrated circuits (PICs). It then looks at the material options for each function, comparing indium phosphide (InP) and silicon photonics (SiPh) and identifying the functions that can only be delivered with InP, the functions that can be delivered with InP or silicon photonics but for which InP has an advantage, and the functions for which neither photonic integration platform has an advantage. Based on this analysis, the case is made for InP as the superior photonic integration material for the high-performance segment, while recognizing that silicon photonics can still be an attractive option for applications with more modest data rate requirements.

HIGH-PERFORMANCE COHERENT OPTICAL FUNCTIONS

A modern high-performance coherent transceiver consists of digital electronics, analog electronics, and a large number of photonic functions. Silicon-based digital electronics include the digital signal processor (DSP), digital-to-analog converter (DAC), and analog-to-digital converter (ADC) on a single ASIC for transmit and receive. Analog electronics, typically made from silicon germanium, gallium arsenide (GaAs), or InP, include the driver, which converts lower voltages from the DSP/DAC to the higher voltage required by the modulator, and transimpedance amplifiers (TIAs), which convert current from the photodetectors to the voltages required by the ADC/DSP on the receive side.

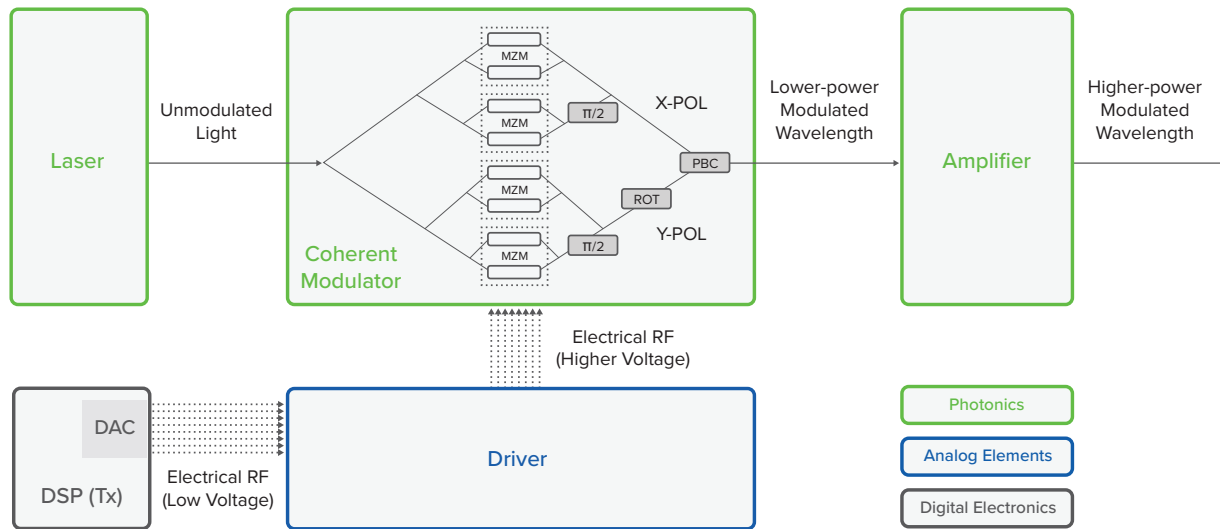


Figure 1: High-performance coherent transceiver – transmit

Then you have the photonics. As shown in Figure 1, the transmit side for each wavelength includes a laser and a coherent modulator. The coherent modulator itself comprises four nested Mach-Zehnder modulators (MZMs), together with splitters, combiners, phase shifters, a polarization rotator, and a polarization beam combiner. As shown in Figure 2, on the receive side for each wavelength, you also have a laser, though in many devices the same laser is used for transmit and receive; polarization beam splitter; two 90° hybrids; and eight photodetectors.

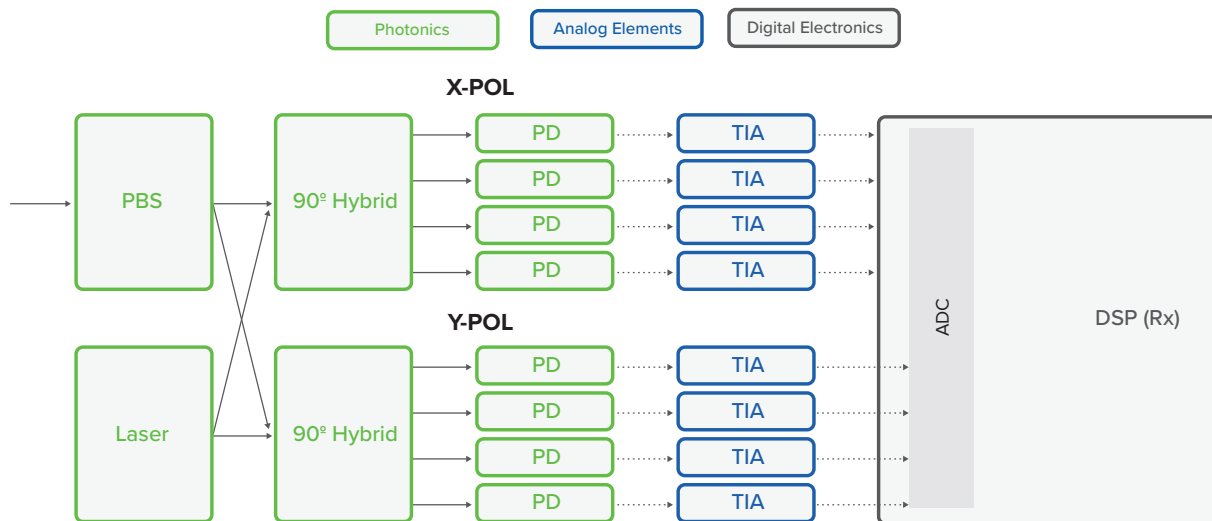


Figure 2: High-performance coherent transceiver – receive

THE NEED FOR PHOTONIC INTEGRATION

The photonic complexity of high-performance optical transceivers with large numbers of functions on both the transmit and receive sides is driving optical vendors to embrace photonic integration.

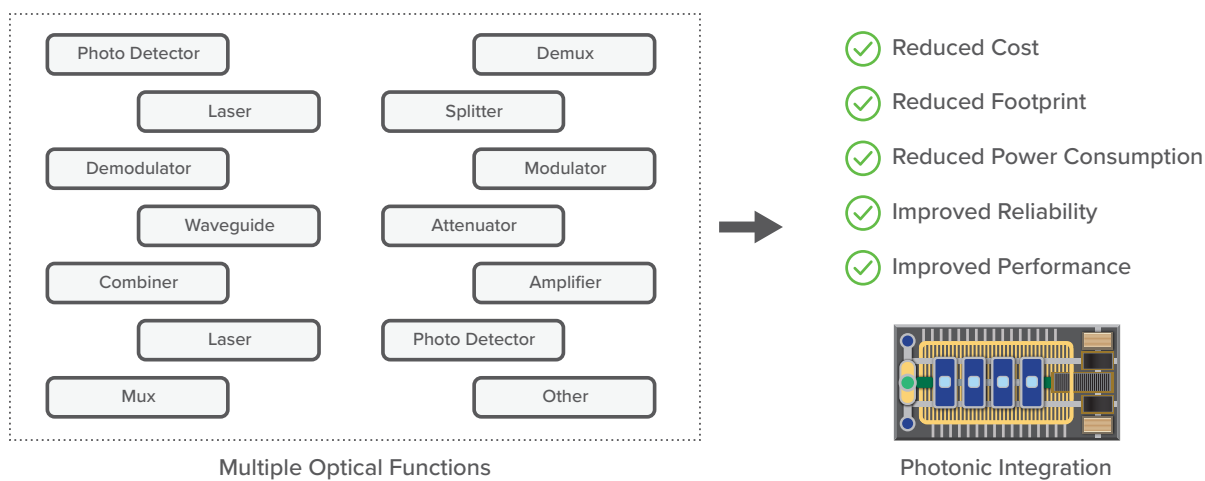


Figure 3: The benefits of photonic integration

Photonic integration enables multiple optical functions to be delivered on a single chip, a photonic integrated circuit. As is the case with conventional electronics, manufacturing one high-function chip is far more cost-effective than manufacturing individual optical components and then integrating and packaging them. Photonic integration also has a dramatic impact on footprint, enabling the miniaturization of optical devices, such as the evolution from coherent transponders to digital coherent pluggables. Power consumption is also reduced, while performance can be improved due to minimized coupling losses when connecting optical functions with waveguides inside the PIC, as opposed to coupling optics between discrete components. Equipment failures are also reduced as these coupling optics are eliminated as a source of failure.

The value of photonic integration increases with the number of functions that are integrated on a single PIC. More complex transceivers, such as high-performance coherent, benefit to a greater extent than simpler direct-detect transceivers with just a laser, driver, and modulator on the transmit side and a photodetector and TIA on the receive side. The value of photonic integration also increases when transmit and receive functions are integrated on a single PIC and/or when multiple wavelengths are integrated on a single PIC, as shown in Figure 4.



Figure 4: Dimensions of increased photonic integration value

MATERIAL OPTIONS FOR OPTICAL FUNCTIONS: INDIUM PHOSPHIDE OR SILICON PHOTONICS

There are two primary materials that can be used to provide various functions in a photonic integrated coherent transceiver: indium phosphide and silicon. While indium phosphide has to date been the primary technology for DWDM photonic integration, after a long incubation period, silicon photonics has emerged as a potential alternative. As detailed in Table 1 below, while several functions of a transceiver can be built with either silicon or indium phosphide, there are some for which indium phosphide has a performance advantage, and several functions that can only be built with indium phosphide.

	Indium Phosphide	Silicon Photonics
Laser	✓✓✓ (Only Option)	x (External InP Laser)
Amplifier	✓✓✓ (Only Option)	x (EDFA with III-V Pump Laser)
Modulator – > 90 Gbaud	✓✓✓ (Demonstrated)	x (Not Demonstrated)
Modulator – ≤/ < 70 Gbaud	✓✓ (Best Performance)	✓
Photodetector	✓	✓ (With Germanium)
Passive Functions	✓	✓

Table 1: Materials for high-performance coherent transceiver optical functions

LASERS AND AMPLIFIERS

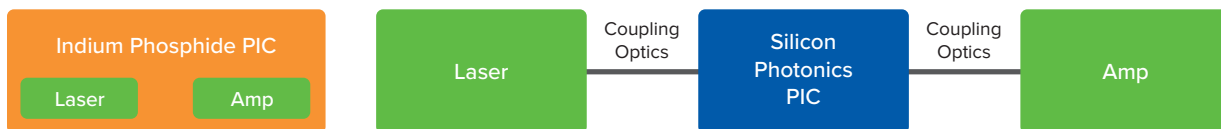


Figure 5: Indium phosphide PICs can integrate lasers and amplifiers, unlike silicon photonics

Due to the physical properties of silicon, it is not capable of providing optical gain for either the laser or amplification functions. As such, only transceivers designed with indium phosphide can be built as fully integrated PICs with integrated semiconductor optical amplifiers (SOAs), while silicon-based transceivers would require a separate, unintegrated InP-based laser and erbium-doped fiber amplifier (EDFA).

In addition to the obvious cost and footprint benefits of a fully integrated InP-based PIC, the use of waveguides rather than coupling optics provides superior performance and power consumption relative to SiPh-based transceivers by avoiding coupling losses. Plus, while an EDFA can provide lower noise than an SOA, an integrated SOA with lower coupling losses delivers overall better performance. In addition, the cost advantage of integrated lasers and amplifiers with the InP PIC implementation increases as the number of channels supported per component increases. Finally, integrated lasers also enable testing of the PICs earlier in the manufacturing process, resulting in a reduced need to discard failed units late in the manufacturing process, after more cost has been incurred.

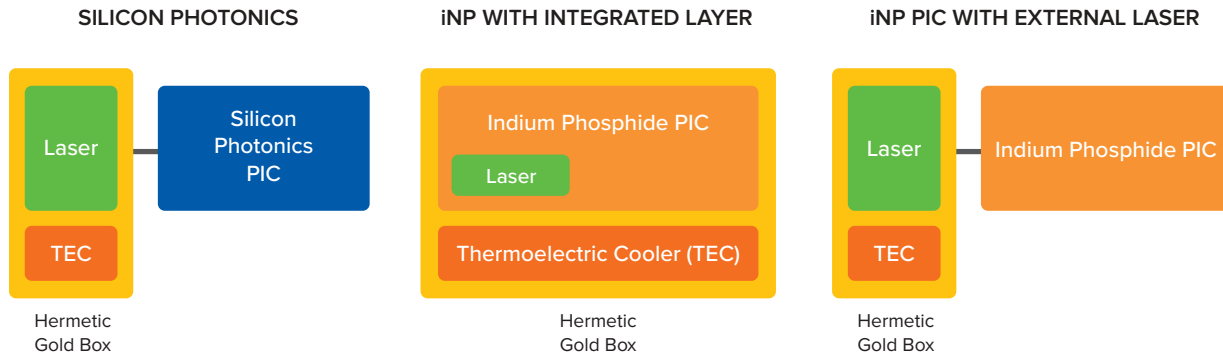


Figure 6: Lasers drive the need for TEC/gold box irrespective of the material used

But are there any advantages to not integrating the laser? One potential benefit from external lasers is that the PIC, whether indium phosphide or silicon photonics, no longer requires tight temperature control and hermetic packaging. As a result, for some applications, the DSP can be placed closer to the PIC, thus reducing radio frequency (RF) distortion in the electronic signal path between the two and improving performance. However, in the high-performance embedded transceiver segment that is the topic of this white paper, the heat generated by a high-function DSP and the need for analog electronics between the DSP and PIC prevent the DSP from being much closer than is the case in a fully integrated PIC with integrated lasers. Moreover, the high modulation voltage required for high-bandwidth SiPh MZM cannot be supplied directly by a DSP CMOS chip, and there would remain a need for the driver analog electronics as the RF bandwidth is extended.

Additionally, if the laser is not integrated, then only the separate InP laser requires a thermoelectric cooler (TEC) and hermetic gold box, which could reduce power requirements. However, in the high-performance segment, the cost of the TEC and gold box are minimal compared to the overall cost of the transceiver, and the power consumption of the TEC is minimal compared to overall system power consumption, hence any such savings from a separate laser are negligible. Also, the TEC requirement is proportional to the number of lasers, so the main reason InP PICs have a higher TEC requirement is that they typically have independent lasers for transmit and receive. This provides performance advantages and the ability to transmit and receive on different frequencies, for example, in single fiber applications, when compared to SiPh-based transceivers, which typically share a single laser for transmit and receive. Furthermore, InP laser technology has improved to allow operation at higher temperatures, thus reducing the need for thermoelectric cooling and the power it consumes.

MODULATORS

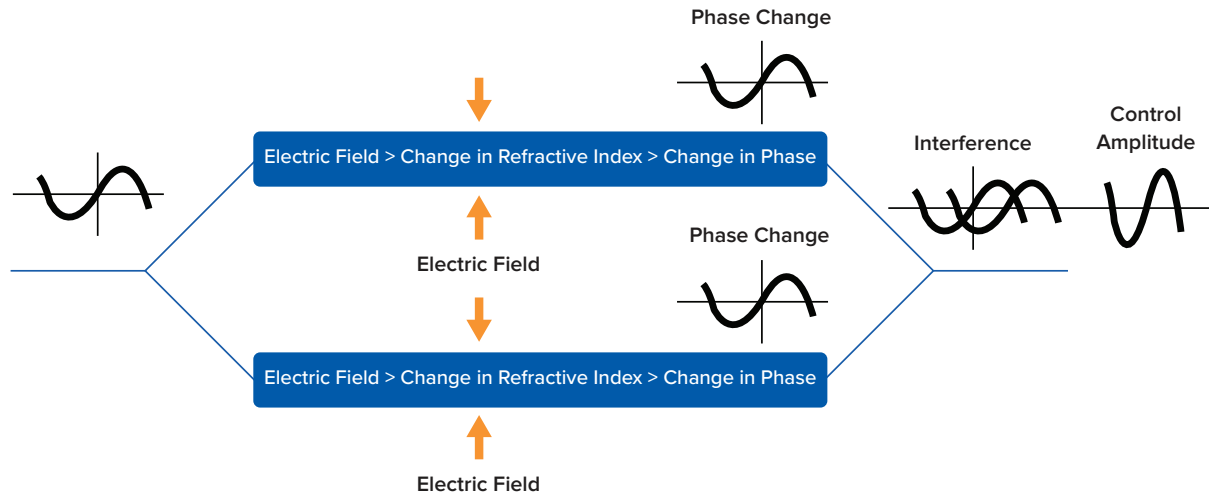


Figure 7: Mach-Zehnder modulator

Now let's take a look at the modulator, which can be built with either InP or SiPh. The modulator provides a critical function on the transmit side of the transceiver. It takes light of the required frequency from the laser, and by changing the phase and amplitude, adds the data that is being transmitted. It does this by using an electric field to change the refractive index of the material the light is passing through. Coherent modulators use a nested Mach-Zehnder modulator design. Each Mach-Zehnder interferometer or modulator splits the light into two arms, changes the phase in one arm or more typically both arms, as shown in Figure 7, and then combines these two arms, letting them interfere to control the amplitude. A pair of phase-shifted Mach-Zehnder modulators can control amplitude and phase, with four in total required for the two polarizations used in polarization-multiplexed coherent transmission, as shown previously in Figure 1.

Indium phosphide and silicon modulators use different physical effects to change the refractive index. Indium phosphide primarily uses the electro-optic effect, while silicon modulators use the plasma dispersion effect. The electro-optic effect is fundamentally more efficient, producing a phase change up to 10 times higher for a given unit length and voltage, resulting in more compact and power-efficient modulators with lower loss, better linearity, larger modulation voltage for higher transmitter signal to noise, and therefore better reach. Indium phosphide modulators can also have much higher electrical/ RF bandwidth (>50 GHz) at a given voltage or modulator loss limit, enabling ultra-high baud rates (>90 Gbaud) that have yet to be demonstrated with silicon-based modulators. Hence, while SiPh-based modulators will perform adequately for lower-performance transceivers, InP performs significantly better for higher-performance applications, and is currently the only demonstrated option for ultra-high baud rates.

PHOTODETECTORS

Indium phosphide can be used for the photodetectors that detect light and convert it to an electrical current. While silicon itself cannot detect light at the wavelengths for DWDM (1525-1565 nm and 1570-1610 nm), the recent addition of germanium into silicon photonics platforms has now enabled the integration of photodetectors. Both InP and SiPh can therefore provide this function, with no widely accepted advantage on either side.

PASSIVE FUNCTIONS

Passive functions, including splitters, combiners, phase shifters, polarization combiners/splitters/rotators, 90° hybrids, waveguides, and muxes and demuxes can all be implemented with both indium phosphide and silicon, with no clear overall advantages provided by either platform.

THE CASE FOR INDIUM PHOSPHIDE IN HIGH-PERFORMANCE COHERENT

Based on this analysis, indium phosphide has a number of compelling advantages over silicon photonics for high-performance coherent transceivers. It is the only demonstrated option for ultra-high baud rate (90+ Gbaud) modulators and provides better modulator performance for high baud rate (>70 Gbaud) applications. Furthermore, indium phosphide enables far greater photonic integration, with the ability to integrate lasers and SOAs, enabling all the optical transmit and receive functions in a single PIC. As an example, Infinera's sixth-generation Infinite Capacity Engine (ICE6) optical engine integrates all the transmit and receive photonic functions for two ultra-high-baud-rate wavelengths onto a single PIC. This reduces cost, footprint, and power consumption while maximizing performance and availability by eliminating the need for coupling optics.

WHY PEOPLE USE SILICON PHOTONICS FOR HIGH-PERFORMANCE COHERENT

Despite the cost and performance advantages of a fully integrated InP-based PIC, a number of optical equipment and component vendors are investing in silicon photonics for high-performance coherent transceivers. The main reason for this is that it takes time, expertise, and a large up-front investment to establish an indium phosphide manufacturing facility that can deliver commercial volumes of high-performance coherent InP-based PICs. For vendors that do not have experience with InP-based PICs and do not own or have access to an indium phosphide fab, the ability to leverage an ecosystem of CMOS foundries leveraging legacy (65-130 nm process node) equipment provides the option to bring photonic integrated circuits to market more quickly and with a lower upfront CapEx investment.

There has been much discussion about the potential per-unit manufacturing cost advantage for SiPh-based solutions at extremely high volumes, with studies on both sides of the debate. However, the total market volume levels of high-performance coherent solutions do not even approach the necessary volume levels, making the entire argument moot for this segment. One further consideration for high-performance SiPh PICs is that they require very close interworking between the transceiver manufacturer and the CMOS foundry engineers, increasing the complexity of the effort.

SUMMARY

Optical vendors are investing in the high-performance segment of the coherent transceiver market to deliver increased capacity per wavelength, spectral efficiency, and reach for high-end data center interconnect, metro/regional, long-haul, and subsea applications. In order to benefit from photonic integration, these vendors have two choices: indium phosphide and silicon photonics. By enabling greater integration, superior performance, smaller form factors, and lower power consumption, fully integrated InP provides the optimal photonic platform for high-performance coherent transceivers. However, silicon photonics can still be an attractive option for vendors that do not have the necessary expertise to build a fully integrated InP-based PIC and/or are unwilling or unable to make the substantial investment required to build their own indium phosphide manufacturing facility. However, one critical factor, irrespective of material chosen, is that designing and then manufacturing ultra-high-performance coherent PICs requires frequent redesigns in the development process, which is much easier with an in-house indium phosphide fab that provides faster learning cycles when compared to using a third-party CMOS foundry.