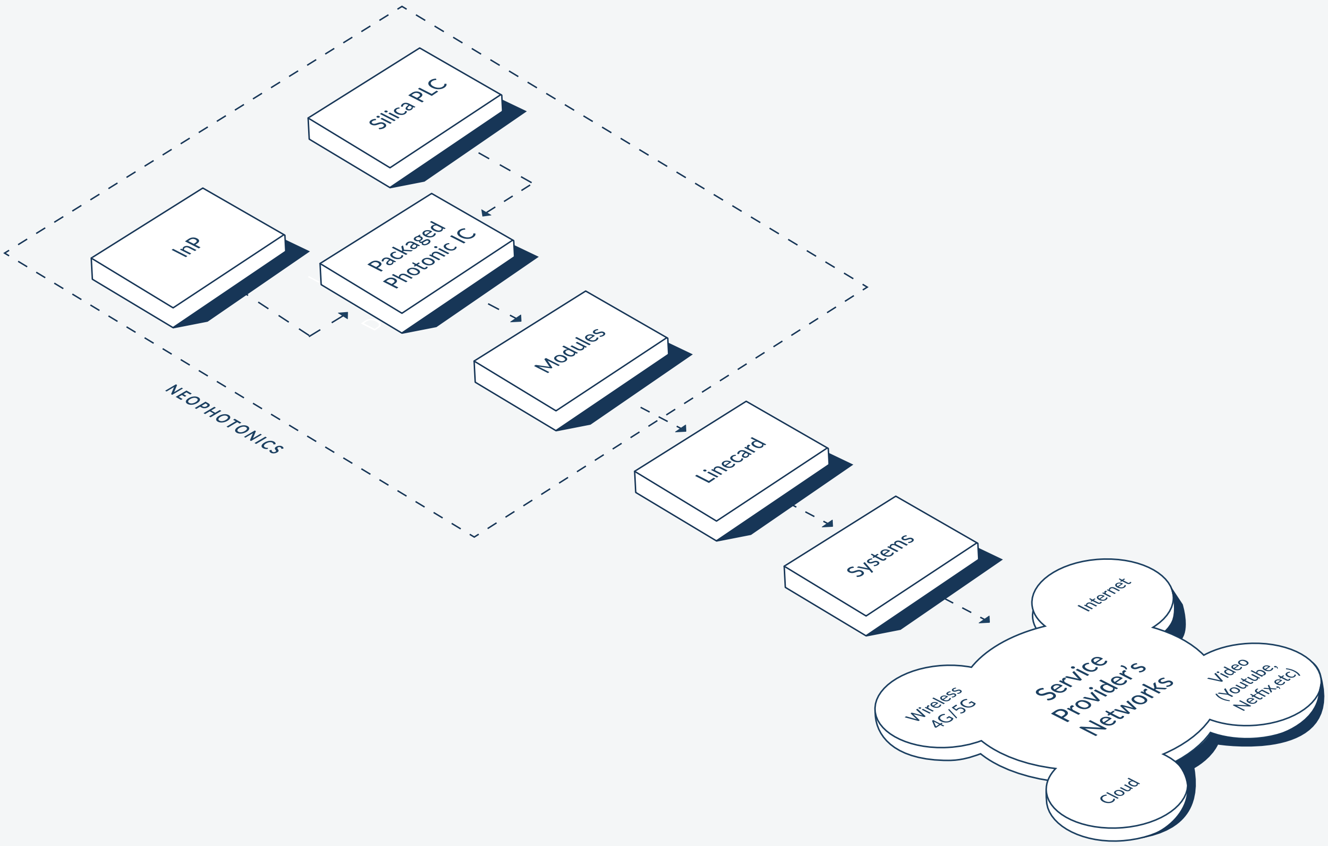
Photonic IC Enabled Coherent Optical Systems

White Paper

NeoPhotonics

Photonic ICs and modules set the foundation for telecom infrastructure



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1. Introduction

Global internet protocol (IP) traffic will grow 3-fold from 2015 to 2020[1]. To transport the explosive Internet traffic, a corresponding bandwidth growth in long-haul and metro optical fiber networks will have to happen at the same time. Consequently, optical fibers in service providers' networks have been quickly exhausted. In order to slow down the consumption rate of precious optical fiber trunk lines, service providers are in urgent need of more bandwidth-efficient transmission systems. To that end, newly developed 100 Gb/s coherent systems (more description of coherent systems is given in Sec.2) have become a timely savior because they can provide ten times more transport capacity than today's 10Gb/s systems, while providing a much higher spectral efficiency and simpler transmission infrastructure.

Further motivation for service providers to use 100 Gb/s coherent systems is because not only are 100 Gb/s Ethernet (100GE) and OTN (Optical Transport Network) interfaces well defined in existing standards (IEEE802.3ba[2] and ITU-T[3], respectively), but the modulation and detection technologies are also defined in OIF (Optical Inter-networking Forum) implementation agreements[4]. As a result of the well-defined standards, 100 Gb/s technology adoption is being driven by products in all network layers, from transport systems to edge routers and datacenter switches. Therefore, we expect to witness a sea change in optical transport networks that will become "coherent-centric" in the next few years.

NeoPhotonics is a fast-growing optical components and sub-system company, and is a leading supplier of 100 Gb/s coherent optical components. Knowing that photonic ICs (Integrated Circuits), or PICs, set the foundation for worldwide telecom infrastructure (as is illustrated in the first diagram of this White Paper), NeoPhotonics started with silica PLC (Planar Lightwave Circuit) components, and acquired complementary indium-phosphide and gallium-arsenide platforms. Furthermore, envisioning that coherent systems are becoming the most important elements for telecom transmission infrastructure in the next decade, NeoPhotonics has focused its research and development activities on developing all the enabling PICs, modules, and analog electronic ICs.

2. How a 100Gb/s coherent system works

2a. Coherent Detection

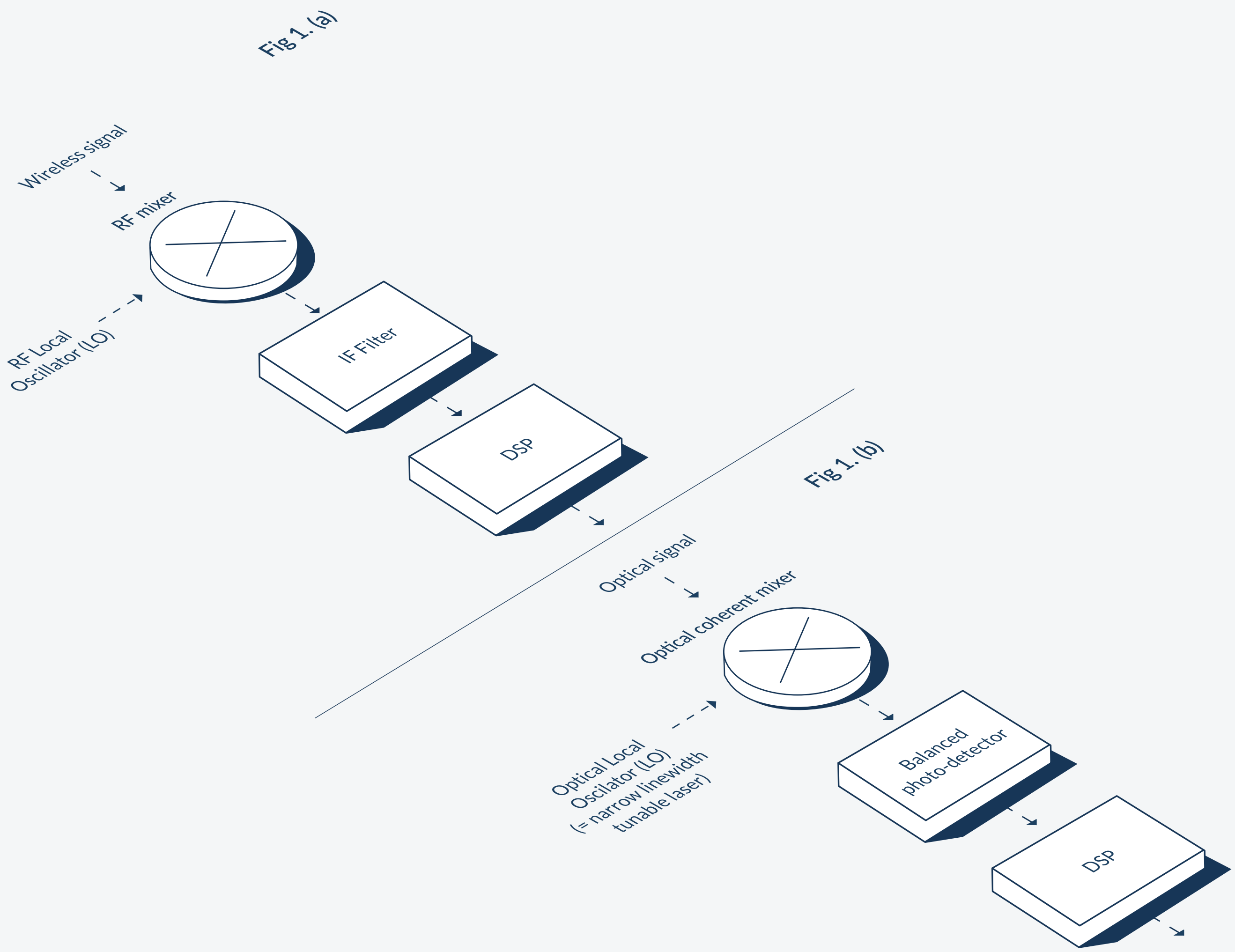
The key feature of a "coherent" system is characterized by its capability to do "coherent detection," which means that a receiver can track the phase of a transmitter (and hence have "phase coherence") so as to extract any phase and frequency information carried by a transmitted signal.

Coherent detection is well known in wireless communication systems. In those wireless systems, a radio frequency (RF) local oscillator (LO) is tuned to "heterodyne" ("heterodyne" is a signal processing technique which combine a high-frequency signal @ f_1 with another @ f_2 to produce a lower frequency signal @ f_1 - f_2) with a received signal through an RF mixer, as shown in Fig.1(a), so that both the amplitude and phase information contained in an RF carrier can be recovered in the following digital signal processor (DSP).

For an optical coherent system, shown in Fig. 1(b), a narrow linewidth tunable laser, serving as an LO, tunes its frequency to "intradyne" with a received signal frequency through an optical coherent mixer, and thereby recovers both the amplitude and phase information contained in a particular optical carrier. Here, "intradyne" means that the frequency difference between an LO and a received optical carrier is close to, but does not have to be zero.

This implies that the frequency and phase of an LO do not have to be actively controlled to an extreme accuracy, therefore avoiding the use of a complicated optical phase locked loop.

Fig.1



A simple illustration of how coherent detection works for (a) wireless systems and (b) optical coherent systems.

The contrast to coherent detection is direct detection, typically used by 10Gb/s or lower-speed. In a direct detection receiver, its photo-detector only responds to changes in the received signal optical power, and cannot extract any phase or frequency information from the optical carrier.

Coherent detection therefore offers several key advantages compared to direct detection:

(1) Greatly improved receiver sensitivity.

(2) Can extract amplitude, frequency, and phase information from an optical carrier, and consequently achieve much higher capacity in the same spectral bandwidth.

(3) Its DSP can compensate very large chromatic and polarization mode dispersion caused by optical fibers, and eliminate the need of optical dispersion compensators and the associated optical amplifiers. This saves not only significant capex, but also simplifies optical network design tremendously because the complicated dispersion map associated with 10G and 40G direct detection systems is no longer needed.

(4) When using balanced detectors with a high common mode noise rejection ratio (CMRR), not only can signal-to-noise ratio (SNR) be improved further, but also agile wavelength selection can be achieved by LO tuning without the use of an optical filter or demultiplexer.

It should also be noted that laser phase noise of an LO is an important impairment in coherent systems as it impacts the "phase coherence." The "linewidth" parameter of a laser diode is directly related to its phase noise.

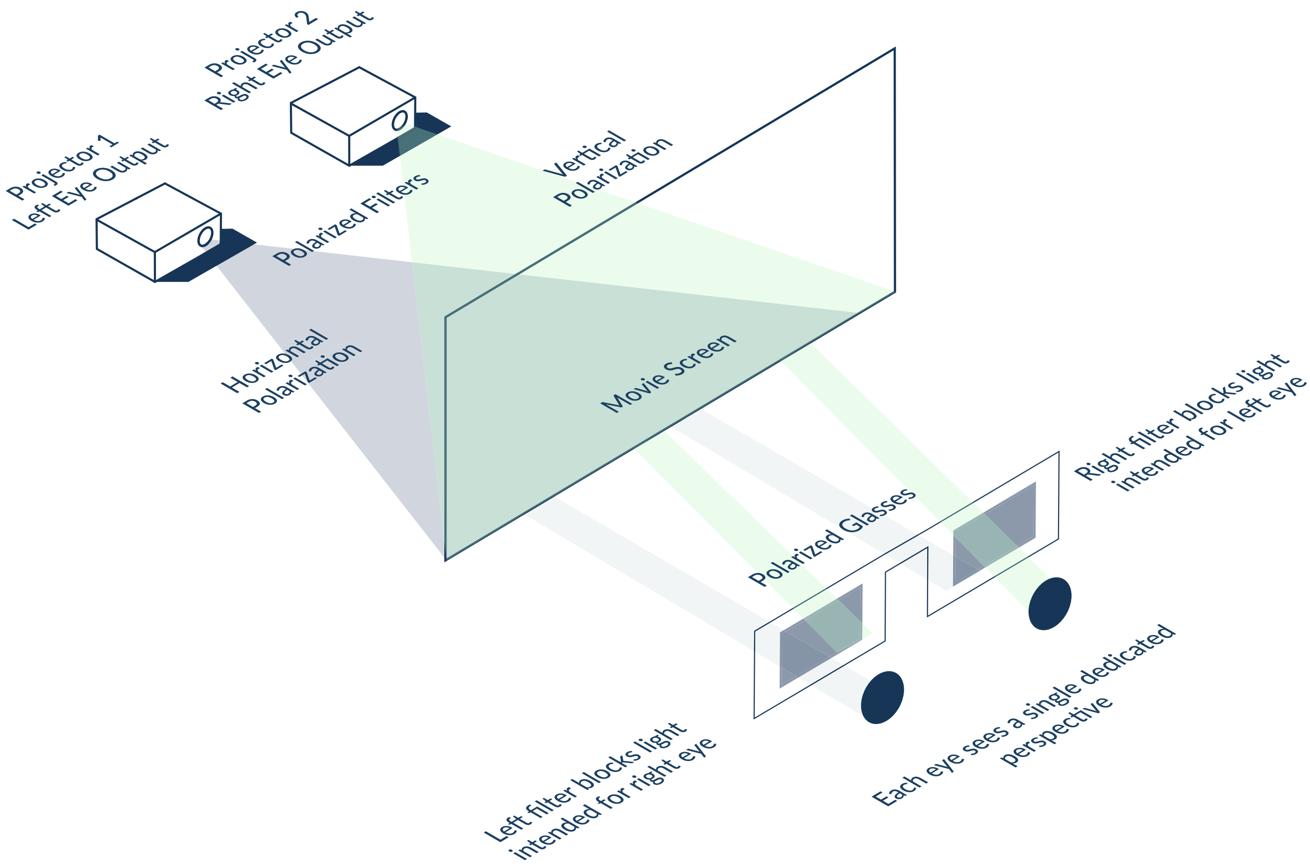
2b. Modulation Scheme

A modulation methodology allows information to be carried by an optical or radio-frequency wave. A few modulation schemes have been used for 100 Gb/s coherent systems, including DP-BPSK (mainly used for undersea cable systems), DP-QPSK (mainly used for long-haul terrestrial systems), and DP-16QAM (mainly used for metro/regional terrestrial systems). Here "DP" stands for "dual-polarization," "BPSK" stands for "binary phase shift keying," "QPSK" stands for "quadrature phase shift keying," and "16QAM" stands for "16 quadrature-amplitude-modulation." The details of each term will be explained as follows.

First of all, we notice that dual polarizations are used in all modulation schemes above. A simple analogy can be used to explain why dual polarizations are used to carry twice as much information. As shown in Fig. 2, a 3D movie theater uses two projectors to generate two orthogonal polarizations on a silver screen, and the reflected light which combines the two polarizations is received by a viewer who is wearing polarized glasses. Each polarization is received by only one eye, and consequently enables the perception of depth. A 100Gb/s coherent transmission system follows the same principle that its optical transmitter generates two orthogonal polarizations, each carrying a stream of 50Gb/s of data, and its integrated coherent receiver (ICR) and an optical local oscillator (LO) function as the polarized glasses, while a high-speed digital signal processor (DSP) functions as human eyes and brain.

Next, let us see how BPSK and QPSK work. BPSK can be understood by comparing it to BASK (Binary Amplitude Shift Keying), which is commonly used in today's conventional 10 Gb/s optical systems. BASK modulates data via "light-off," representing a symbol "0," and "light-on," representing a symbol "1," which result in merely 1 bit per symbol. In contrast, BPSK uses phases 0 and π to transport the same amount of information as BASK. QPSK uses four phases, e.g., 0, $\pi/2$, π, and $3\pi/2$ to transport twice as much information as BASK or BPSK, and achieves 2 bits per symbol. As a result, QPSK in combination with dual polarizations (i.e., DP-QPSK) can achieve $2\times2=4$ bits per symbol. This implies that a 100Gb/s DP-QPSK coherent optical link only requires 25G symbols/s or 25G baud, which in turn reduces the bandwidth requirement of all electrical circuits, printed circuit boards, and optical components by four times. Similarly, the optical spectrum that must be allocated to a DP-QPSK 100 Gb/s signal can be nominally four times less than if one were to use an "on-off" 100Gb/s optical signal. In summary, in comparison to

Fig.2



A 3D theater viewing, analogous to a dual-polarization coherent transmission system, is using dual-polarization projectors at the transmitter, and a polarized glasses at the receiver (http://www.cinema3dglass.com).

10Gb/s BASK modulation which has a spectral efficiency of 1 bit/s/symbol, 100Gb/s DP-QPSK offers four times improvement (4 bits/s/symbol).

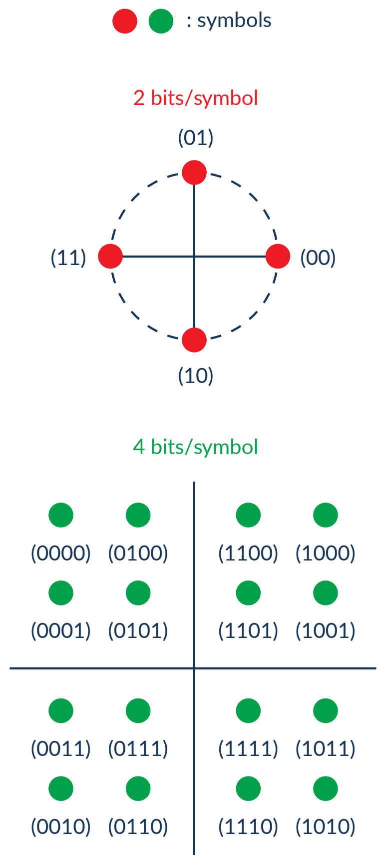
A DP-16QAM signal contains not only dual polarizations, but also both amplitude and phase modulation from symbol to symbol, and therefore further improves the spectral efficiency of DP-QPSK by two times, i.e., it has a spectral efficiency of 8 bits/s/symbol. A simple illustration is shown in Fig.3, where we can see that to change from one symbol to another in a QPSK constellation diagram requires only phase variation, while to change one symbol to another in a DP-16QAM constellation diagram requires both phase and amplitude variation. We also notice that each symbol (running at 25G symbols/s) in a QPSK constellation diagram is composed of 2 bits, therefore we obtain 2 bits/symbol × 25G symbols/s= 50 Gb/s in a single polarization and 100 Gb/s with two polarizations. Similarly, each symbol in a 16QAM constellation (also running at 25G baud) is composed of 4 bits, therefore we obtain 4 bits/symbol × 25G symbols/s= 100 Gb/s in a single polarization, and 200Gb/s in two polarizations.

2c. Building Blocks

Having reviewed the coherent modulation and detection schemes, we can now take a look at the basic building blocks of the current coherent transmitters and receivers, as shown in Fig.4. The key components at the transmitter side are: an integrated tunable laser assembly (ITLA), a lithium-niobate, silicon, or indium-phosphide I/Q (In- and Quadrature-phase) modulator, and four driver amplifiers. The key components at the receiver side are: an integrated coherent receiver (ICR), an ITLA serving as an LO, and a DSP chip. The DSP is used to separate the two polarizations, compensate various transmission impairments, and recover carrier frequency and phase.

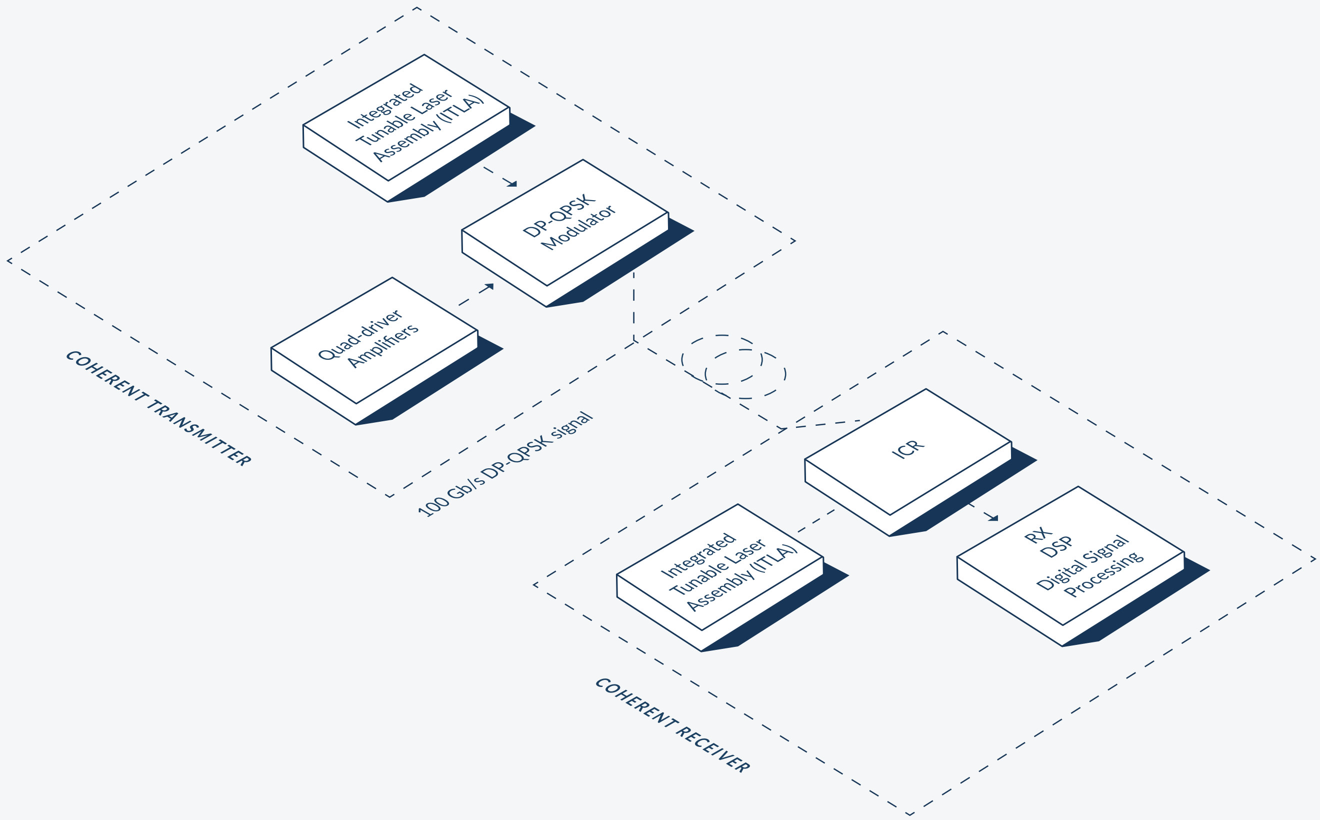
Gen2 coherent transmitters and receivers, to be described in Sec.5, require another level of photonic and electronic integration to get to smaller size and lower power consumption to fit inside pluggable coherent transceivers.

Fig.3



The constellation diagrams of a QPSK and 16QAM signals, respectively. For QPSK, we have 4 symbols with 2 bits/symbol, while for 16QAM, we have 16 symbols with 4 bits /symbol. Each symbol is assumed to be running at ≥ 25Gbymbols/s.

Fig.4



The basic building blocks of coherent transmitter and receiver.

3. Advantages of 100G coherent systems over conventional 10G/40G systems

As mentioned in Sec.1, 100G has been standardized at all layers which has resulted in concentrated efforts on the development of optical and electronic components, thus enabling a high-momentum ecosystem. In contrast, 40G is and will remain a fragmented market because there are still four modulation formats competing against each other for long-haul DWDM transport systems, including coherent, DQPSK, DPSK, and ODB (optical dual binary). As a result, the possible range of cost reduction for 100G DP-QPSK transponders has been much steeper than that of 40G transponders.

When comparing 10G to 100G for long-haul transmission systems, due to the fact that 100G offers at least a ten-fold capacity increase, and saves significant system cost by eliminating numerous optical dispersion compensators (by using the powerful DSP in a 100G coherent receiver) and the associated optical amplifiers (which were needed to compensate for the loss of those dispersion compensators), 10G transponders simply cannot compete in this market.

This is especially true when we consider the fact that a 100G transponder module already offers a lower price than ten tunable 10G transponders in XFP or SFP+ form factors.

4. Future Trends of Coherent Systems and Components

There are three future trends of coherent systems, i.e., higher baud rate (evolving from today's 32Gbaud to tomorrow's 45, 56, and 64Gbaud), higher constellations (evolving from today's DP-QPSK, DP-16QAM, to tomorrow's DP-32QAM and DP-64QAM), and smaller form factors (evolving from today's line-cards and CFP modules to tomorrow's CFP2, CFP4, or even QSFP modules). These three trends are illustrated in Fig. 5. Also shown in the figure are the associated component trends (in green arrows) which are needed to enable each of the coherent system trends: For higher baud rates, higher bandwidth transmitters and receivers are needed (evolving from today's ~20GHz components to tomorrow's ~30 or 40GHz components); for higher constellations, the transmitting laser and local oscillator laser both need to have a narrow-linewidth (e.g., < 100KHz); for higher port density and lower power consumption, the components needed to enable small form factors are micro- or nano-tunable lasers, modulators and receivers.

4.a Emerging 400G coherent systems and the required optoelectronic components

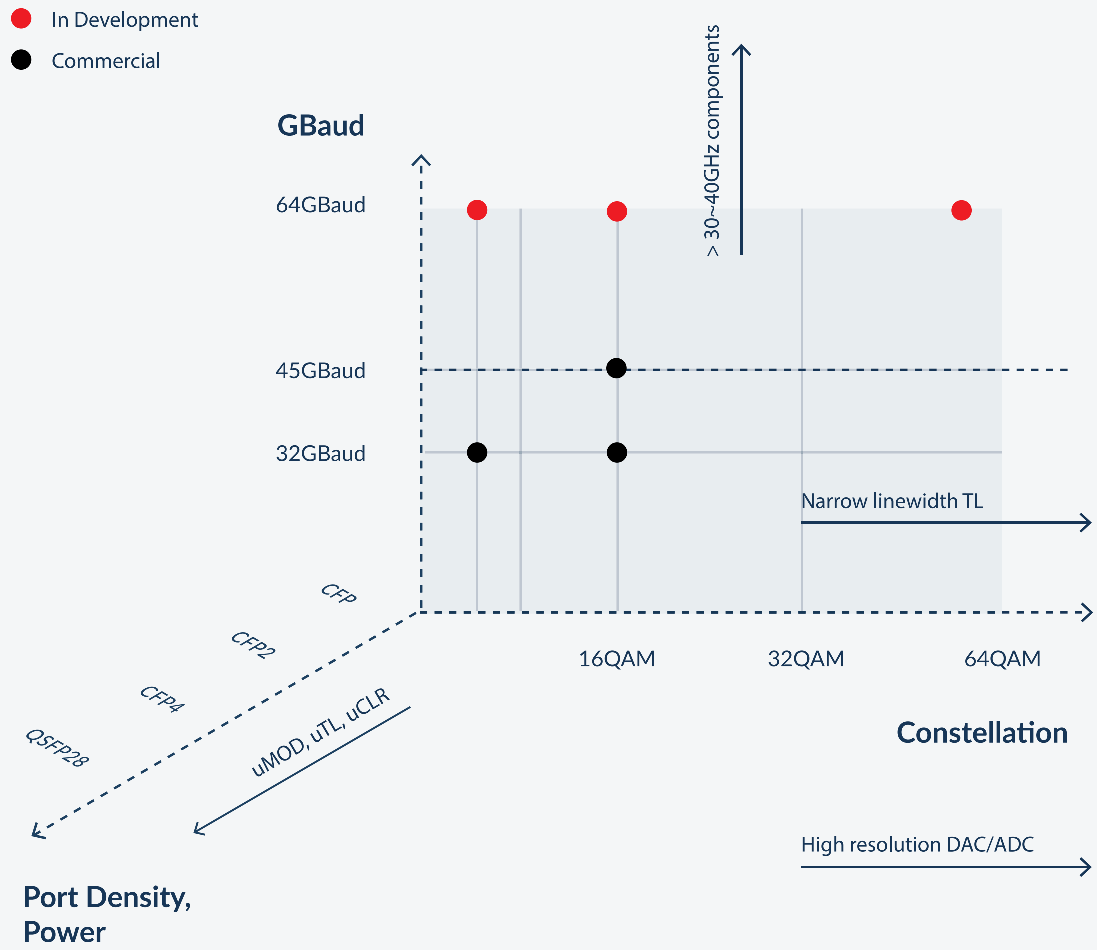
Quite a number of 400G coherent systems products have been deployed. Here we discuss the pros and cons of different 400G modulation techniques.

Starting 2015: 2×200Gb/s using 32Gbaud/DP-16QAM (Fig.6(a))

As mentioned in Sec.2b, a wavelength could double its capacity from 100Gb/s to 200Gb/s by replacing DP-QPSK with DP-16QAM modulation, while the baud rate is maintained at 32Gbaud. The same hardware in Fig.4 can be used, except that four limiting driver amplifiers need to be replaced by four linear driver amplifiers. As a result, the same 100G optical components can continue to be used while the capacity is doubled, thereby achieving essentially 50% cost reduction. By using two such wavelengths, we can obtain 2×200Gb/s or 400Gb/s capacity.

A transmitter DSP/DAC must be used, not only for pulse-shaping, but also for assembling bits into symbols. The total occupied spectrum of 2×200Gb/s DP-16QAM is ~75 GHz. The penalty of 2×200Gb/s, however, is that its transmission distance of 400~600km is much shorter than the 2,500~3,000km of a 100Gb/s DP-QPSK signal. This is due to the fact that the 16QAM symbol constellations are much closer than those of QPSK (see Fig. 3), and therefore cause 7~8 dB OSNR penalty.

Fig.5



Three future trends for coherent systems and the associated components.

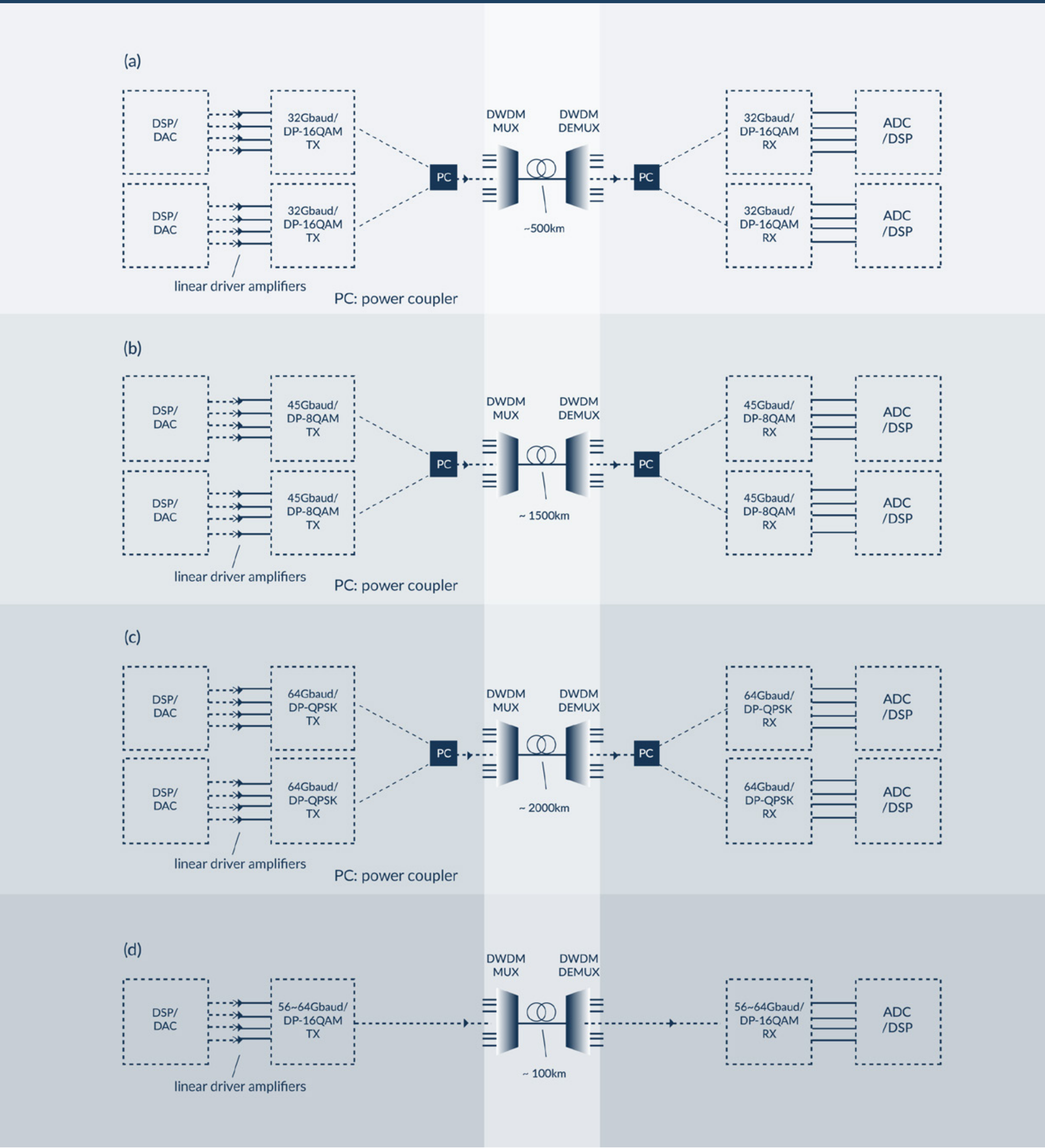


Fig.6 Four potential configurations of 400G optical transponder. PC: power coupler; DSP: digital signal processing; DAC: digital-to-analog converter; ADC: analog-to-digital converter. The transmission distances are first-order estimate and depend on inter-office distances, fiber types, and optical amplifier types.

Starting 2016: 2×200Gb/s using 45Gbaud/DP-8QAM (Fig.6(b))

By upgrading the speed of DACs, drivers, modulators, ICRs, and ADCs, one can use two wavelengths to achieve 2x200Gb/s capacity via 45Gbaud/DP-8QAM modulation. The reason to change from 32Gbaud/DP-16QAM to 45Gbaud/DP-8QAM is that the latter can achieve a longer transmission distance (~1,500km) due to the lower constellations.

Starting 2017: 2×200Gb/s using 64Gbaud/DP-QPSK (Fig.6(c))

Similar to 45Gbaud/DP-8QAM, this method uses an even higher baud rate while lowering the constellations further to QPSK. It can also achieve a much longer transmission distance than 32Gbaud/DP-16QAM. However, the speed of all components (DACs, drivers, modulators, ICRs, and ADCs) needs to be upgraded.

Starting 2017/2018: 1×400Gb/s using 56~64G baud/DP-16QAM (Fig.6(d))

Data center interconnection is one of the fastest growing areas among all optical fiber networks. The typical interconnection distance is shorter than 80km. As a result, the coherent system design is very different from that of a long-haul system. For this application, one can try to maximize the baud rate and constellations such that the OSNR can still remain beyond 30~32dB, which is a lot looser requirement than that for typical metro-core or long-haul systems. However, higher constellations requires high resolution DACs and ADCs (i.e., high effective number of bits or ENOBs) to maintain a sufficient signal-to-noise ratio, which will not be available until late 2016/early 2017. Therefore, in the short term, to develop a single-carrier 400Gb/s, most companies will use a high baud rate rather than a high constellation. For example, a single wavelength of 56~64Gbaud/DP-16QAM can offer a total capacity of 448~512Gb/s.

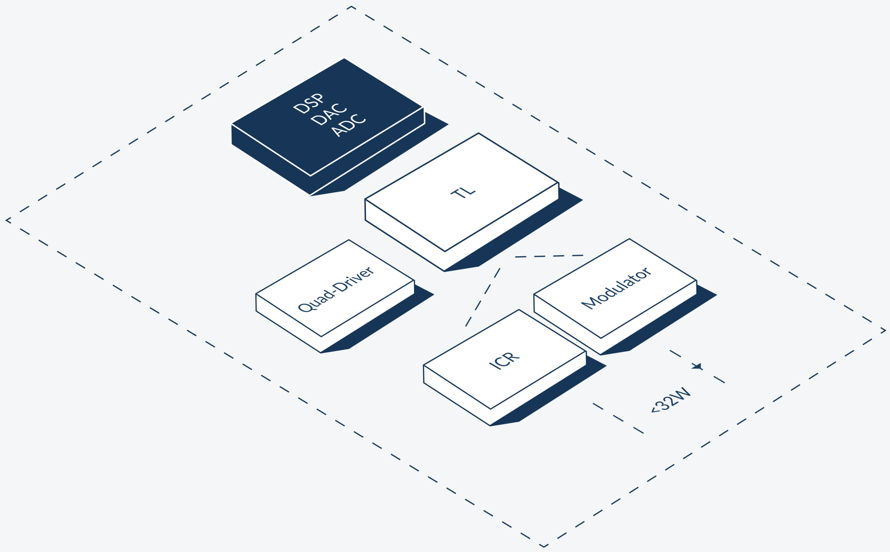
In a single-wavelength 400Gb/s coherent transceiver module, since only one tunable laser (serving both as TX and LO), one I/Q modulator, and one coherent receiver are used, the cost per bit can be significantly lower than a conventional 100Gb/s coherent transceiver today.

4.b Pluggable coherent modules and the required optoelectronic components

Pluggable coherent optical transceiver modules are needed mainly because of the highly desirable features such as "pay-as-you-grow" and easy replacement, which a multiple-port line-card cannot offer. It is essentially following the same deployment history of 10G pluggable transceivers.

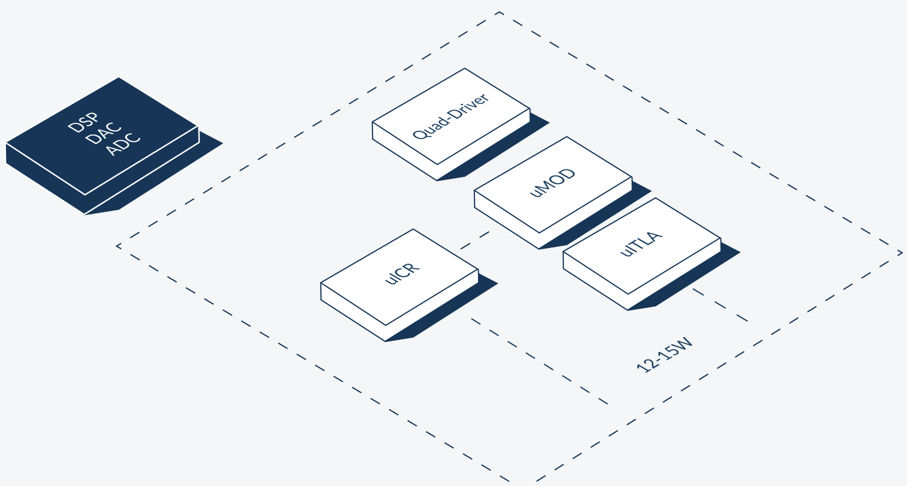
There are two main categories of pluggable coherent transceivers: analog coherent optics (ACO) and digital coherent optics (DCO). ACO implies that the DSP ASIC is outside the transceiver module, while DCO implies that DSP ASIC is inside the transceiver module. ACO and DCO can fit inside a form factor of CFP, CFP2, CFP4, or even QSFP. Fig. 7 (next page) illustrates the electronic and optical components inside a CFP-DCO, a CFP2-ACO, and a CFP2-DCO. The key electronic components are DSP ASIC (which includes digital-to-analog converter (DAC) and analog-to-digital converter (ADC)) and four driver amplifiers. The key optical components are micro-integrated tunable laser assembly (µITLA), micro-modulator (µMOD), and micro-integrated coherent receiver (µICR).

Fig 7 Illustration of CPF-DCO, CFP2-ACO, and CFP2-DCO



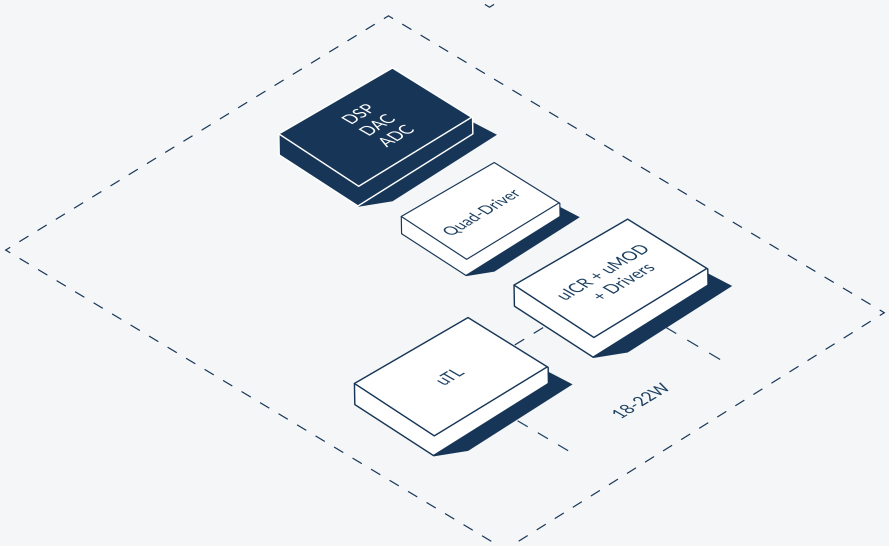
CFP-DCO (long-haul)

(+) Plug into any client-side line-card with CFP slots
(--) Poor port density



CFP2-ACO (metro)

(+) Good port density
(--) Analog RF interface



CFP2-DCO (metro)

(+) Good port density
(+) Plug into any client-side line-card with CFP2 slots
(--) Mechanically (thermal & size) challenging

	Market Availability	Application Area
CFP-DCO	2014/2015~	Switch/Router
CFP2-ACO	2015/2016~	DWDM/switch
CFP2-DCO	2017~	Switch/Router
CFP4-ACO	2017/2018~	DWDM
QSFP-ACO	2019~	DWDM/switch

Table 1. Market availability and application areas

Regarding the optical components, we believe that the best approach to keep the pluggable transceiver cost low is to leverage the existing high-volume of µITLA and µICR which have been used for line-card applications. Alternatively, when either one of the two devices is combined with a low-volume µMOD in a new gold-box, the total cost of the transceiver module will be increased significantly due to the low yield and low volume of the new gold-box. Table 1 above summarizes the application areas and estimated timeframe for each type of pluggable coherent transceiver. Note that CFP4 may be completely skipped, depending on how soon QSFP-like high port-density modules will be available.

5. Why NeoPhotonics?

NeoPhotonics has been a market share leader in both the ICR and narrow linewidth tunable lasers and has been a leader in developing next generation component technologies. These 100G and beyond products utilize NeoPhotonics Advanced Hybrid Photonic Integration technology, which consists of photonic integrated circuits (PICs) that comprise both arrayed and individual photonic functional elements using optimized materials systems and processes from NeoPhotonics in-house Silicon, Indium Phosphide and Gallium Arsenide wafer fabrication facilities. These individual PICs from different materials are then combined using hybrid integration technology to make complete products, such as Integrated Coherent Receiver (ICR) for 100G coherent transport applications. The complete suite of coherent-related photonic and electronic components offered by NeoPhotonics is summarized in Table 2 (next page).

6. Summary

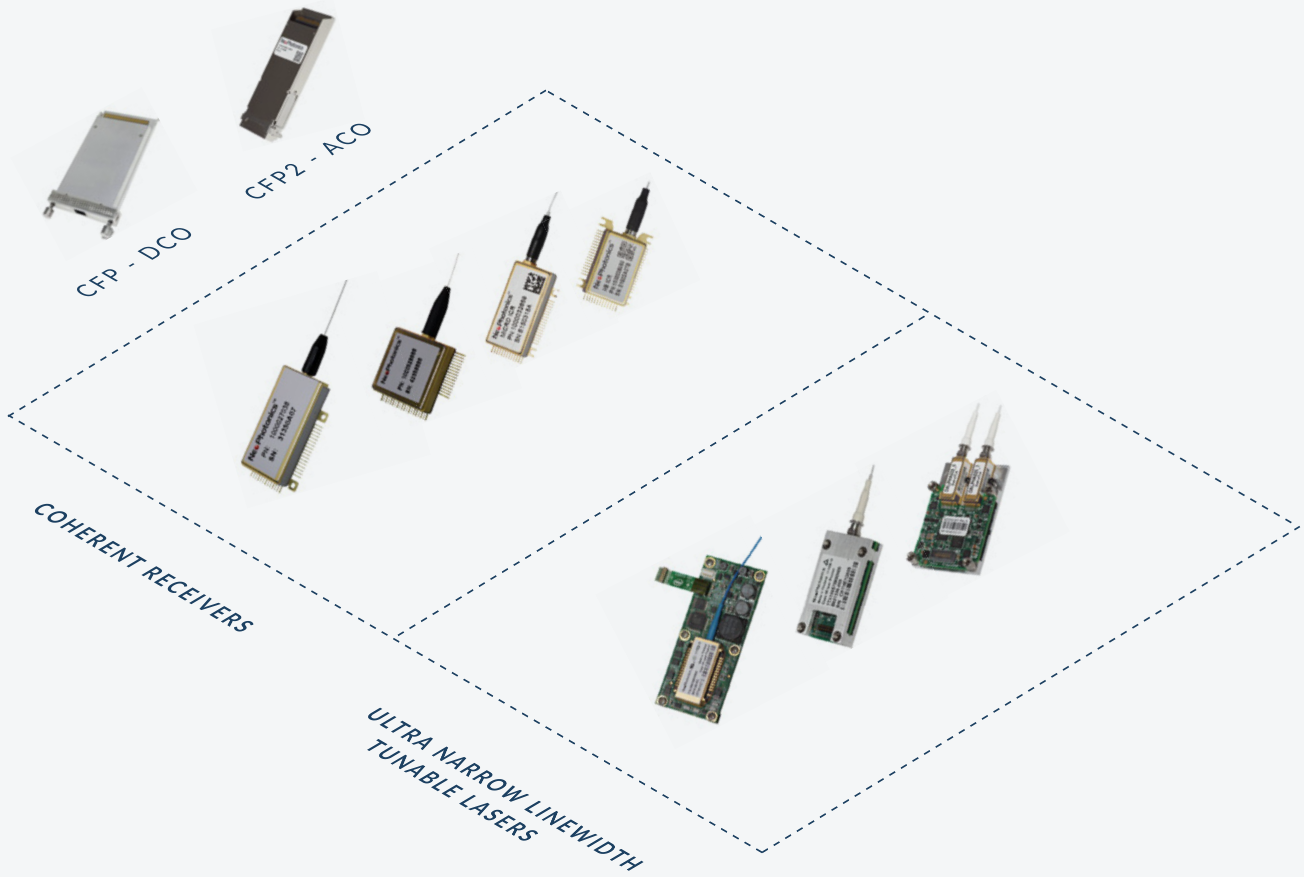
Although its fundamental concept is derived from wireless communications systems, coherent detection has started another paradigm shift in optical fiber communications. Its impact has become as large as that which commercial laser diodes and erbium-doped fiber amplifiers brought to the industry. Consequently, long-haul and metro optical networks are bound to become coherent-centric in the next decade. Infonetics projects that the number of 100G ports deployed will grow with a 5 year CAGR of 47%, reaching more than 700,000 in 2019[6].

In addition, by the time pluggable coherent transponders such as CFP2 are available, metro and Ethernet-over-DWDM markets will both be rapidly expanding, and the potential volume could be 2~3 times higher - based on the experience the industry had in 10Gb/s market. NeoPhotonics has already been the market share leader today in ICR and narrow linewidth tunable lasers for the current coherent components, and its leading PIC technology will continue to enable the next-generation coherent components and transceiver modules.

Table 2

Extending Our PIC-Based Coherent Product Portfolio into More Powerful and Compact form factors

Our PIC based Coherent Solutions enable 400G transport for Long Haul, Metro and Inter-Datacenter Networks



NeoPhotonics next-generation of coherent products

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