White Paper
HiSilicon Optoelectronics 400G All-Scenario Optical Module

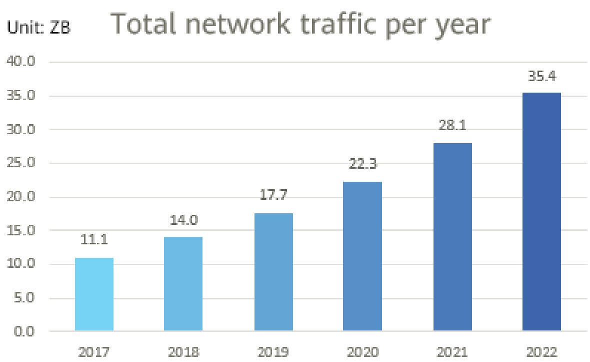
HISILICON
OPTOELECTRONICS

CONTENTS

1. Arrival of the 400G Era

The emergence of new services — 4K VR, Internet of Things (IoT), and cloud computing — bring greater bandwidth, concurrency ratio, and real-time requirements on networks. According to third-party research, the average annual growth rate of network traffic remains at a high level of 26%.

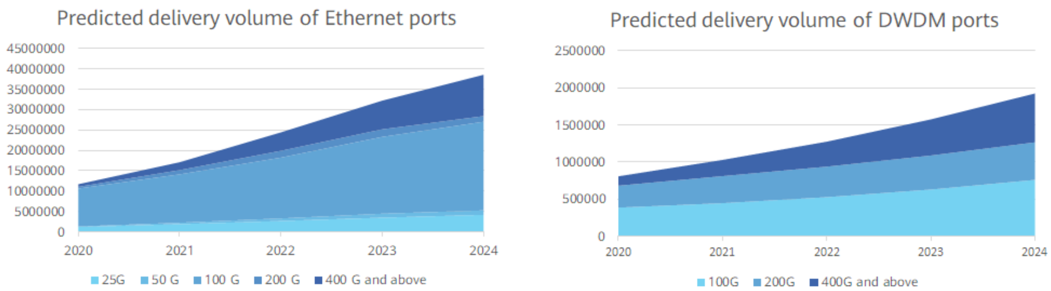
Figure 1-1 Rapid growth of network traffic



The emergence of 100GE technology in 2013 also represents a technical turning point in the industry, with 100GE ports unable to meet the increasing traffic requirements posed by traffic floods. If multiple 100G links are bundled, optical fiber resources lag behind the increase of bandwidth resources, and load imbalance may occur. Therefore, high-performance ports with higher bandwidth capabilities are required. Accordingly, 100G ports for long-haul transmission need to be upgraded, as coherent transmission technologies with higher rates are used in an increasing number of networks.

According to LightCounting's market forecast report in October 2019, the growth rate of 400G optical interconnect ports on the Ethernet and WDM/OTN side is much higher than that of other ports.

Figure 1-2 Delivery volume prediction for optical ports with different rates



400G is the next-generation mainstream port technology, with the ability to significantly improve network bandwidth and link utilization, helping operators and over-the-top (OTT) customers effectively cope with the explosive growth of data traffic.

2. 400G Optical Interconnection Application Scenarios

Communications network standards are evolving to support 400G and three international standards organizations — IEEE, ITU, and OIF — have already released 400G standards. IEEE 802.3bs — the

400GE standard baseline — was completed at the beginning of 2015, with the final version completed in December 2017. Meanwhile, ITU-T SG15 focuses on the definition of standards related to optical transport networks (OTNs) and to this day, ITU-T has completed the definition of beyond 100G OTN standardization.

Optical Internetworking Forum (OIF) has also been publishing white papers on 400G interconnect from the client side to the line side since 2013.

With the maturity of industry standards and network requirements, 400GE has led the development of the ICT industry, gaining increasing attention and application prospects particularly across three scenarios: data center (DC) networking, the metro integrated bearer network, and the long-distance and large-capacity transport network.

3. 400G Optical Module Solution for DC Networking

3.1 Background: Rapid Growth of East-West Traffic

By 2021, about 70% of DC east-west traffic will stay within the DC, with an expected growth rate much higher than that of south-north traffic and of traffic between DCs.

The penetration of cloud computing leads to traditional DCs being replaced by cloud DCs, significantly increasing requirements for high-speed optical modules.

- Traditional DCs use 10G low-speed optical modules, while cloud DCs mainly use 100G high-speed optical modules.
- Traditional DCs mainly transmit north-south traffic, while cloud DCs mainly transmit east-west traffic, driving a large number of east-west connections and significantly increasing the usage of optical modules on a single server. Services that rely primarily on east-west traffic — such as machine learning and artificial intelligence — therefore require more computing and storage capabilities.

Currently, cloud computing DCs have fully adopted the 25G/100G optical interconnect solution. In the second half of 2018 however, large OTT customers in North America (such as company G) led the switch to the 50G/400G optical interconnect solution. Meanwhile, company A plans to begin deployment of the 400G solution in 2020. China's OTT customers have also started 400G research as seen in the first half of 2019, when company T initiated the first 400G test in China involving multiple 400G optical module vendors.

Table 3-1 Comparison between different types of DCs

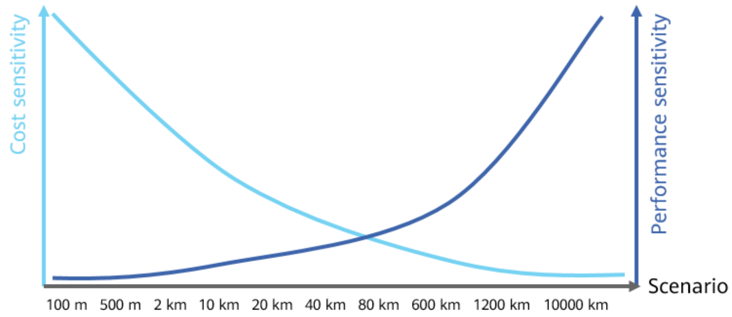
Customer Type Item	Traditional enterprise DC	Cloud DCs in China	Cloud DCs in North America
Scale	Small	Medium/Large	Large
Networking architecture	Traditional three-layer network architecture	Spine/Leaf architecture	Spine/Leaf architecture
Traffic & direction	Small Mainly north-south traffic	Medium/Large Mainly east-west traffic	Large Mainly east-west traffic
Optical module quantity per server	Small	Medium/Large	Large

Customer Type **Item**	**Traditional enterprise DC**	**Cloud DCs in China**	**Cloud DCs in North America**
Optical module rate	1G/10G	25G/100G	25G/100G→50G/400G

3.2 Trend: Lower Cost Per Bit & Power Consumption

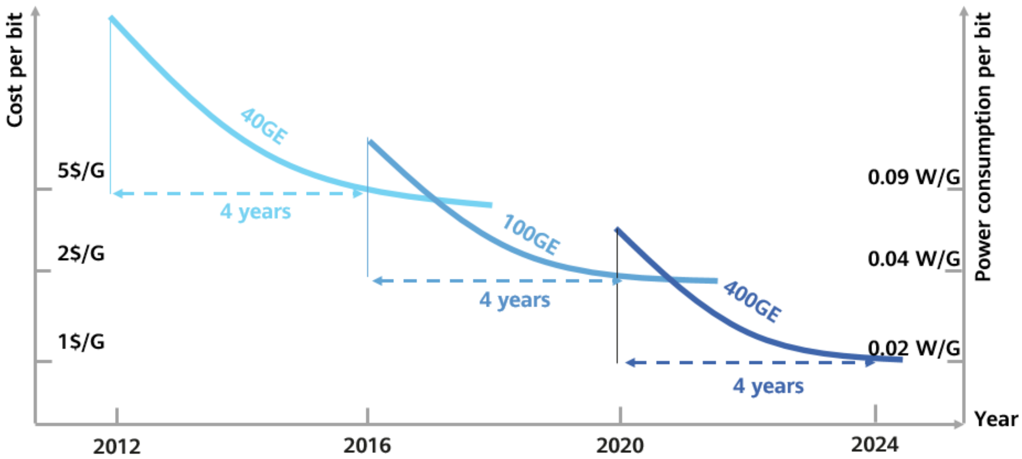
Generally, user experience varies with application scenarios. In long-haul WDM scenarios, users are more sensitive to performance, with an expectation of longer transmission distance and higher spectral efficiency. In contrast, users in short-distance DC scenarios are more sensitive to costs, taking distance, volume, and power consumption into account.

Figure 3-1 Architecture of the metro integrated bearer network



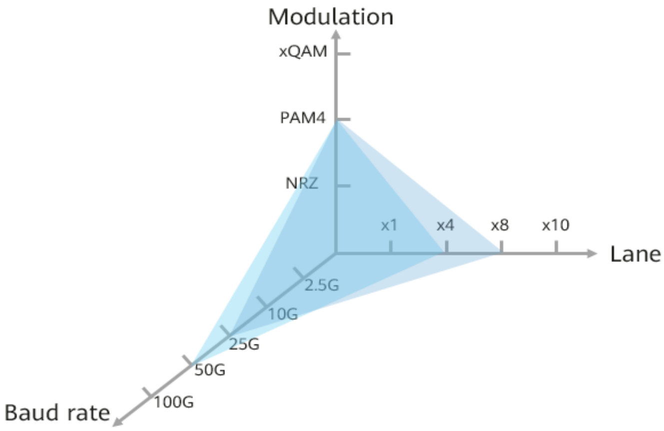
Founder of Intel, Gordon Moore, proposed the Moore's Law, predicting that the number of transistors on a microchip doubles every 24 months, significantly profiting the semiconductor industry over the last half century. There is also an optical Moore's Law that applies to the opto-electronics field, which states that short-distance optical modules evolve to the next generation every four years, halving per bit costs and power consumption.

Figure 3-2 Optical Moore's Law in DC Networking (DCN)



There are three methods by which an optical module can achieve a higher rate to meet the requirement described by the optical Moore's Law: increasing the rate of optical components (higher baud rate), using more lanes, or reducing the transmission cost per bit through high-order modulation.

Figure 3-3 Technology directions for increasing the rate of DCN optical modules



- **Using High-Order Modulation, PAM4**

  4-level pulse amplitude modulation (PAM4) technology is more efficient and can effectively improve bandwidth utilization. PAM is the most popular signal transmission technology after non-return-to-zero (NRZ) encoding.

  An NRZ signal uses high and low signal levels to represent 1 and 0 in digital logical signals and one bit of logical information can be transmitted in each clock cycle. In contrast, a PAM4 signal uses four signal levels for transmission and two bits of logical information — 00, 01, 10, and 11 — can be transmitted in each clock cycle. Therefore, under the same baud rate, the bit rate of a PAM4 signal is twice that of an NRZ signal, making it optimal for 400G modules to improve transmission efficiency and reduce transmission costs.

- **Using More Lanes**

  According to historical data, solutions with more than eight lanes (such as x10 and x16) resulted in lower yield rates and lower reliability whereas multi-lane (x4 or x8) architectures are more cost-effective and improve power consumption.

  The 100G (4 x 25G) CWDM4 and 100G SR4 modules have become the mainstream solutions for the previous-generation of DC optical interconnect.

- **Using Optoelectronic Chips with Higher Baud Rates**

  Based on the 25 Gbaud/s optical chip industry chain, including the direct modulation laser (DML) and vertical cavity surface emitting laser (VCSEL), DC 100G optical modules adopt NRZ signals and the x4 architecture to achieve business success. Various 25 Gbaud/s optical chips — including DML, electro-absorption modulator integrated laser (EML), and VSCEL — are evolving to support a higher baud rate of 56 Gbaud/s. Currently, a 56 Gbaud/s EML industry chain is available, while 56 Gbaud/s DML and VCSEL chips are still being researched.

Table 3-2 DC requirements on optoelectronic chips

Scenario	100G Solution	400G Solution
TOR to Leaf (100 m)	100G SR4 4CH:25Gbaud VCSEL+NRZ	400G SR8 8CH:25Gbaud VCSEL+PAM4
Leaf to Spine (500 m)	100G PSM4/CWDM4	400G DR4

Scenario	100G Solution	400G Solution
	4CH:25Gbaud SiP/DML+NRZ	4CH:56Gbaud EML/SiP +PAM4
Leaf to Spine (2 km)	100G CWDM4 4CH:25Gbaud DML+NRZ	400G FR4/DR4+ 4CH:56Gbaud EML/SiP+ PAM4

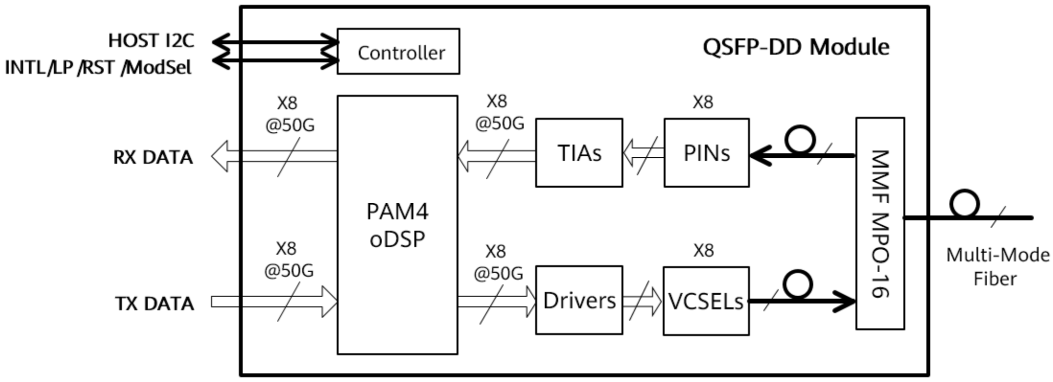
3.3 Solution: 400G Optical Modules for DCN

To meet the high-speed optical interconnect requirements of DCs from 70/100 m to 2 km, HiSilicon Optoelectronics provides three types of 400G optical modules: 400GE-SR8, 400GE-DR4/DR4+, and 400GE-FR4. The following describes the design architecture and key technologies of each optical module.

3.3.1 400GE-SR8

The 400GE-SR8 optical module complies with IEEE 802.3cm (draft) and meets the requirements of 70 m OM3 and 100 m OM4/OM5 transmission links. Figure 3-4 shows its working principles. The module uses a standard 16-core multi-mode MPO connector and consists of Tx and Rx optical components, VCSEL drivers, trans-impedance amplifiers (TIAs), a PAM4 service chip (oDSP), and a controller. The x8 optical and electrical components at Rx and Tx ends are placed in the QSFP-DD package through a compact engineering design.

Figure 3-4 Functional block diagram of 400GE-SR8



400GE-SR8 has eight lanes, each carrying 53.125 Gbps signals while using PAM4 modulation. The oDSP inside the module implements clock recovery, signal shaping, and signal adjustment.

To make 400GE-SR8 a high-performance, low-cost, and deliverable multi-mode short-distance optical module for the DC application scenario, the following key technologies are used:

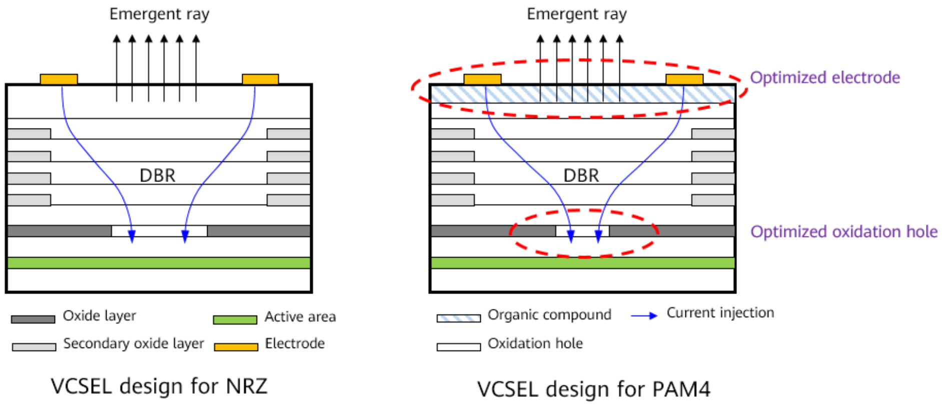
- **High-Performance VCSEL**

  Entering the 400GE era, optical module modulation technology is upgraded from 25.78125 Gbaud NRZ signals to 26.5625 Gbaud PAM4 signals. To ensure the transmission performance of PAM4 signals, high-bandwidth VCSEL is used, with a typical bandwidth of 19 GHz. The following figures shows two kinds of VCSEL structures. Compared with the 25 Gbaud NRZ component, this laser ensures the performance of 400GE service transmission and achieves higher bandwidth (typical bandwidth: 13 – 15 GHz) by:

  a. increasing the photon density by reducing the oxidation aperture;

  b. optimizing the metal electrode design to reduce parasitic parameters.

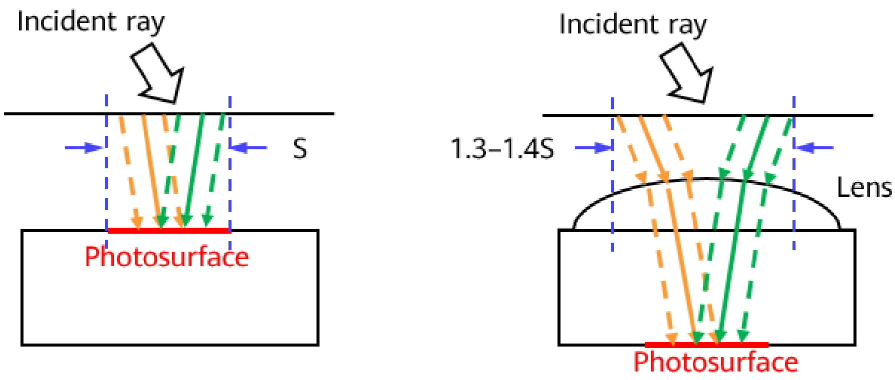
Figure 3-5 VCSEL structure diagram



- **Multi-Mode Lens Photonic Detector (PD)**

  400GE-SR8 uses the HiSilicon-developed high-performance multi-mode PD, with a typical bandwidth of 20 GHz and a built-in lens for the chip. As shown in Figure 3-6, compared with the traditional PD, the lens PD converges light and has a stronger optical receiving capability, increasing the coupling tolerance by 30% to 40%. This improves Rx performance and reduces the requirement on production process precision.

Figure 3-6 Multi-mode PD structures

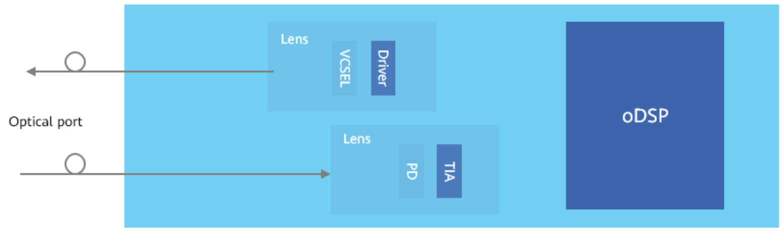


Traditional surface PD Lens PD

- **Chip-On-Board (COB) Package**

  The optical chips of 400GE-SR8 — including the Tx chip (VCSEL), the Rx chip (PD), and electrical chips (Driver and TIA) — adopt the COB package and hybrid integration design. The chips are mounted to the PCBA board through surface-mount and bonding techniques. Compared with other packages, the COB package can implement a more compact assembly design for optical modules and supports automatic production and processing, resulting in lower costs and better performance.

Figure 3-7 COB package of optical modules



In addition, HiSilicon Optoelectronics offers joint optimization for optical and electrical systems in terms of structure and technique. In doing so, the size of the multi-lane lens is reduced by 40%, and the Rx and Tx lenses are deployed on a single side of the PCB. Compared with the standard QSFP-DD Type 2 optical module, the length of this optical module is shortened by 9 mm, saving more space for fiber cabling in the cabinet and stopping the fiber reaching the cabinet door.

- **Other**

  400GE-SR8 also uses the low-noise and high-performance TIA chip developed by HiSilicon Optoelectronics, as well as the high-bandwidth driver and 7 nm PAM4 oDSP chip, lowering costs and improving performance.

3.3.2 400GE-DR4/DR4+ and 400GE-FR4

The optical modules 400GE-DR4/DR4+ and 400GE-FR4 comply with IEEE 802.3bs and 802.3cu (draft) respectively. They also adopt the platform-based hardware design solution to meet the requirements of 500 m and 2 km transmission links, respectively. The modules' working principles are shown in Figure 3-8 and Figure 3-9. 400GE-DR4/DR4+ uses a standard 12-core MPO connector while 400GE-FR4 uses a standard dual-LC connector. The optical modules consist of Tx and Rx optical components, EML drivers, TIAs, a PAM4 service chip (oDSP), and a controller. HiSilicon owns all intellectual property rights (IPR) in terms of module design, which features a full series of key bottom-layer components, resulting in an end-to-end vertical integrated solution covering optical chips (EML and PD) and electrical chips (Driver, TIA, and oDSP).

Figure 3-8 Functional block diagram of 400GE-DR4/DR4+

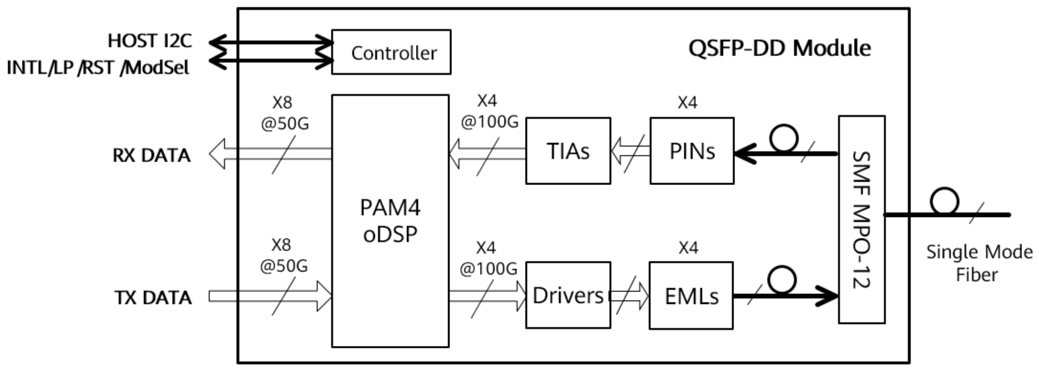
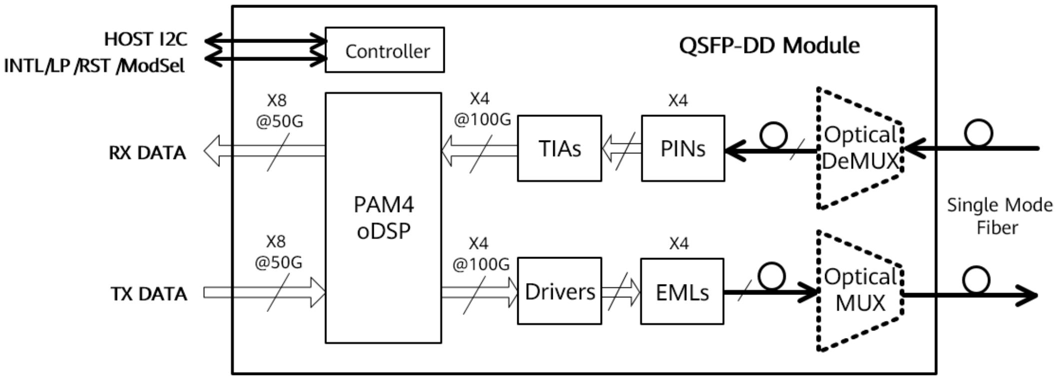


Figure 3-9 Functional block diagram of 400GE-FR4



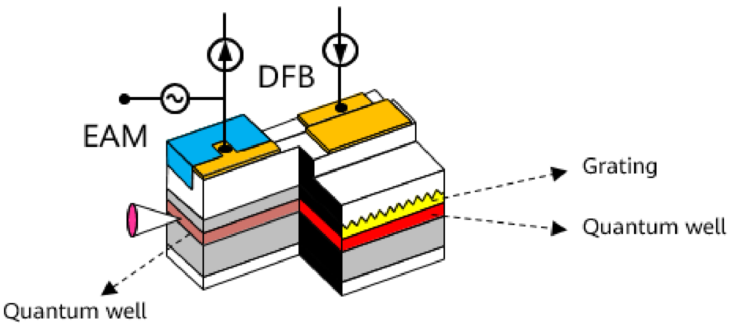
The two optical modules have four optical lanes and eight electrical lanes, respectively. Each optical lane carries 106.25 Gbps signals and each electrical lane carries 53.125 Gbps signals, while both optical and electrical signals use the PAM4. Rate conversion is implemented by the oDSP inside the module, which is also responsible for clock recovery, signal amplification, and signal conditioning. In addition, 400GE-DR4/DR4+ is designed to emit parallel light, and optical signals of the four lanes have the same wavelength. In comparison, optical signals of the four lanes have different wavelengths for 400GE-FR4; therefore, an optical multiplexer is used to multiplex optical carrier signals onto a single optical fiber, which is output by an optical port. Compared with 100GE-CWDM4 and 100GE-PSM4, 400GE-DR4/DR4+ and 400GE-FR4 increases the transmission rates of optical and electrical signals and the number of electrical signal lanes.

To make 400GE-DR4/DR4+ and 400GE-FR4 high-performance, low-cost, and deliverable multi-mode short-distance optical modules for the DC application scenario, the following key technologies are used:

- **High-Performance EML**

  The optical modules use the high-performance EML laser developed by HiSilicon. As shown in the following figure, the EAM quantum well, DFB quantum well, and grating design are optimized to achieve high bandwidth applications with no cooling requirements. The typical bandwidth is greater than 40 GHz, and the transmitter dispersion eye closure quaternary (TDECQ) performance is optimized to be greater than 0.5 dB. This reduces the requirements on the optical power of the Tx optical modulation amplitude (OMA), reducing system power consumption and improving long-term reliability.

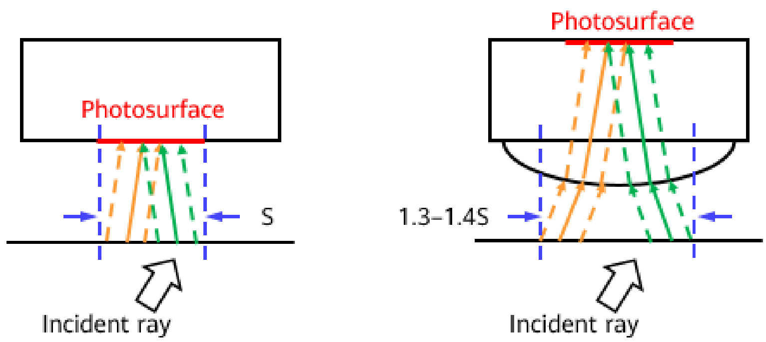
Figure 3-10 EML architecture diagram



- **Single-Mode Lens PD**

  400GE-DR4 & FR4 use a high-performance single-mode PD independently developed by HiSilicon. This lens PD is mounted using the flip chip technique to match the silicon optical demultiplexer — also independently developed by HiSilicon — for special performance optimization. As shown in Figure 3-11, compared with the traditional PD, the single-mode lens PD receives upwards incident rays and converges them. It has a strong light receiving capability and increases the coupling tolerance by 30% to 40%. Moreover, the flip chip mounting technology of the lens PD shortens the wire bonding length from the PD to the TIA. The preceding characteristics improve Rx performance of modules and reduce the requirement on production process precision, effectively ensuring performance and cost competitiveness.

Figure 3-11 Single-mode PD structures

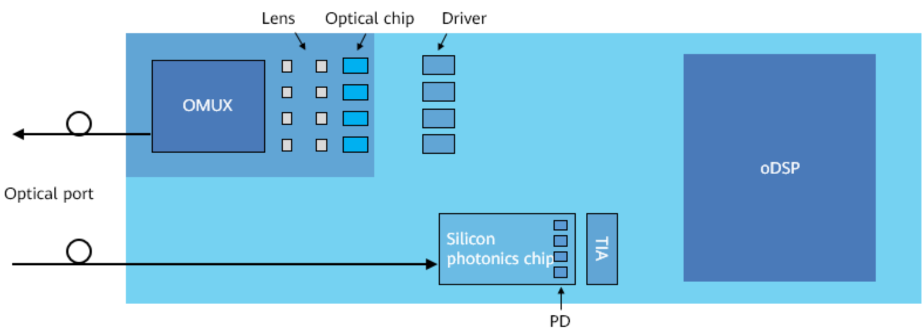


Traditional PD Lens PD

- **COB Package**

The optical chips (EML and PD) and electrical chips (Driver and TIA) of 400GE-DR4/DR4+ & FR4 adopt the COB package and hybrid integration design, and are mounted to the PCBA board using surface-mount and bonding techniques. The 400GE-FR4 module is used as an example to describe the system structure of the COB package at the Tx and Rx ends, which is similar to that of 400GE-DR4/DR4+.

Figure 3-12 COB package of optical modules



During COB packaging, the Tx adopts a non-airtight design. The substrate and airtight housing commonly used in conventional optical component packaging are removed, reducing material costs, simplifying the package process, and facilitating automatic production. Meanwhile, the Rx adopts the silicon photonics integrated optical components mentioned in the previous section, which is a less complex process and improves coupling efficiency. Therefore, the COB package improves the performance and lowers the cost of module solutions.

- **High-Performance oDSP**

A HiSilicon-developed 7 nm 106 Gbps PAM4 oDSP is used in the 400GE-DR4/DR4+ & FR4 optical modules. The oDSP has several features: adoption of an ultra-low core voltage, reducing power consumption; adoption of a high-bandwidth digital-to-analog converter, improving signal restoration quality; and support for diverse, powerful digital algorithm equalizers, as well as deployment of feed forward equalization (FFE) linear equalization and other non-linear compensation algorithms at the Tx and Rx to deal with various complex link impairments.

The oDSP provides rich and powerful features for easy O&M, including signal-to-noise ratio (SNR) monitoring, link transfer function inference, and online firmware upgrade, improving network O&M efficiency.

- **Other**

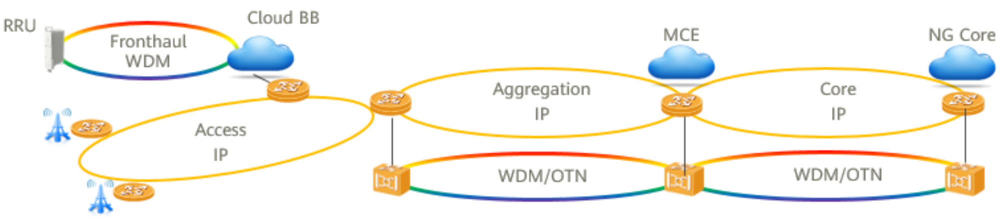
400GE-DR4/DR4+ & FR4 also adopt components independently developed by HiSilicon, such as the low noise, high-bandwidth linear TIA and high-bandwidth EML driver, meeting the cost and power consumption requirements of DCs.

4. 400G Optical Module Solution for Metro Integrated Bearer Networks

4.1 Background: New Services Drive Traffic Growth

With the rapid development of mobile broadband, new services — including 4K VR, IoT, ultra-HD video, VR, augmented reality (AR), and Internet of Vehicles (IoV) — pose the following new requirements on bearer networks: ultra-high bandwidth, multi-connection lanes, ultra-low latency, and high reliability. As 100GE ports of metro networks cannot support the aggregation and core layers that require ultra-broadband, the 400GE-based optical interconnect solution becomes a necessity.

Figure 4-1 Architecture of the mobile bearer network



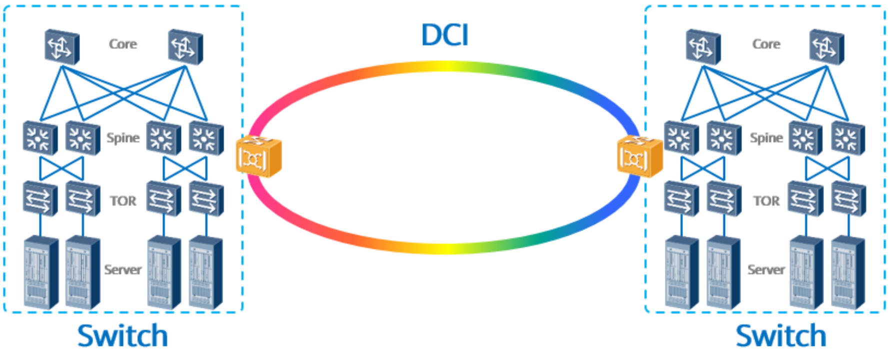
Take the mobile bearer network as an example. According to the bandwidth evaluation of the Next Generation Mobile Networks (NGMN) Alliance, access layer bandwidth will evolve to 50GE, while core layer bandwidth will evolve to 200GE/400GE during large-scale commercialization in metro networks.

Network Layer	Metro Access Layer		Metro Aggregation Layer	Metro Core Layer
	fronthaul	midhaul	backhaul + DCI	backhaul + DCI
Distance	< 10/20 km	< 40 km	40–80 km	40–80 km
Optical module	10G/25G gray Nx25G WDM	25G/50G gray Nx25G/50Gb/s	100G/200G gray	200G/400G gray Nx100G/200G/400G

Network Layer	Metro Access Layer		Metro Aggregation Layer	Metro Core Layer
	colored	WDM colored	Nx100G WDM colored	WDM colored

Meanwhile, DCs are moving from the backbone layer to the edge of metro networks. As such, the rapid growth of DC traffic poses even higher DC bandwidth requirements, accelerating the bandwidth upgrade of DCI interfaces from 100G to 400G.

Figure 4-2 DCI networking diagram



4.2 Trend: Lower Transmission Cost Per Bit, Higher Reliability, and Longer Distance

Cell sites are expected to outnumber 4G sites by 1.5 to 2 times, with the number of optical modules used on metro networks expected to reach the tens of millions. The ratio of the optical module cost over the device cost is also constantly increasing, leading to operators prioritizing lower optical module costs in network construction investment. It is also an urgent need of carriers that 400GE optical modules require only half the power consumption and cost per bit of 100GE optical modules. In addition, carrier bearer networks have higher reliability and performance requirements than DCs.

Table 4-1 Lifecycle requirements on optical modules in different scenarios

Customer Key indicator	Operator	DC
Lifecycle	> 10 years	3–5 years

In contrast to DC networking with short transmission distances, the metro integrated bearer network with longer transmission distance has higher requirements of the optical module's transmission performance.

Table 4-2 Transmission distances in different scenarios

Scenario	Transmission Distance
DCN	100 m to 2 km
Metro Bearer Network	10–80 km
DCI	80–120 km

Technologies applied in DC networking scenarios are adopted in the metro integrated bearer network to achieve a higher transmission rate of 400G and reduce the transmission cost per bit.

- **Increasing the Baud Rate of Optical Components**

  Line capacity can be improved by increasing the rate of optical components, but this method is limited due to the performance bottleneck of the III-V semiconductor laser. As required by the metro network, 25 Gbps optical components (DML and EML) have been applied in batches; however, at the 56 Gbps level, only EMLs are available.

- **More Lances**

  Given that the bandwidth and performance improvement of optical components is limited, multiple lanes can be used in parallel to achieve 100G transmission, as seen in 4 x 25G NRZ technology. The mature industry chain of 25G components can be reused to offer large-capacity solutions in advance, meeting actual application requirements. In the 400G era, multi-lane solutions will be a necessity and with the consideration of costs and power consumption, the x4 or x8 multi-lane architecture is most appropriate.

- **Using Higher-Order Modulation**

  When the high-order modulation format is used, spectral efficiency can be improved without increasing the signal baud rate, thereby improving the total bearer rate. Currently, with a 25G transmitter and receiver, PAM4 is the mainstream modulation in the industry, as it helps implement a single-lane 50G transmission rate, reducing per-bit power consumption and costs.

  Given that the metro integrated bearer network has high reliability and performance requirements of optical modules, the industry has always placed high importance on such technologies.

- **Using More Reliable Components**

  In the metro integrated bearer network, optical modules are mainly applied in carrier-grade scenarios. They are required to have a 10-year lifecycle, work sufficiently at a temperature range of 0° C to 70° C, and adopt hermetic package to ensure their reliability. Lower costs have become increasingly important for DC modules, thereby driving the evolution of non-hermetic package technologies. However, such technologies are still facing the following challenges in carrier-grade scenarios:

  - **Laser diode (LD) reliability risk:** Non-hermetic package poses higher coating requirements of the LD end face.
  - **Thermo electric cooler (TEC) condensation and chemical corrosion risks:** LAN wavelength division multiplexing (LWDM) components use TECs for temperature control. As a result, the temperature of certain part (where the TEC is located) of an LWDM component is lower than the ambient temperature, posing condensation risks in a non-airtight environment. Long-term exposure to water vapor may cause electrochemical corrosion.
  - **Optical path pollution risk:** In the space between the LD chip and the optical port receptacle, non-hermetic package cannot avoid the following problems: the optical surface power may change due to condensation and pollution; and the glue inside the component may absorb water and cause the relative position of the optical path to change, which would also change the optical power output.

- **Using High-Performance LWDM Transmitter**

  The coarse wavelength division multiplexing (CWDM) wavelength spacing is 20 nm and TEC is not required for cooling, greatly reducing costs. A CWDM transmitter supports 2 km applications, and is the mainstream solution of DC scenarios. Compared with CWDM, LWDM has a wavelength spacing of 5 nm, and features a low dispersion penalty with a higher transmission performance. Therefore, it is the first choice for carrier-grade scenarios in the metro network. Take the 100G/lane solution as an example. After 10 km transmission, the CWDM's dispersion window and dispersion penalty (2.5 dB) is much greater than that of LWDM (1 dB). In the 400G era, CWDM cannot support long-haul transmission over 10 km and as such, LWDM transmitters will become the mainstream solution for metro integrated bearer networks.

- **Using High-Performance Receivers with Avalanche Photodiode (APD)**

Generally, the output power of a 25G transmitter is 0 – 3 dBm, and the sensitivity of a 25G PIN receiver is about – 7 dBm, which cannot meet the long-haul (40 km) transmission requirements of carrier-grade optical modules. A high-performance APD is therefore required to improve receiver sensitivity.

Table 4-3 Optical port specifications for optical modules

	Sensitivity	Receiver	Cost
400G LR8	–6.6 dBm	PIN	Low
400G ER8	–16.1 dBm	APD	High

- **Introducing Coherent Technologies**

Limited by component performance, the 400G PAM4 solution does not support long-haul transmission over 80 km. To overcome this challenge, mature coherent technologies that have been successfully deployed on long-haul transport networks should be introduced. In addition, SiP and InP integration technologies as well as the complementary metal-oxide semiconductor (CMOS) technology continuously evolve to support smaller coherent optical modules with lower power consumption. With compact ICT/ICR and low-power 7 nm oDSP, 400GE compact QSFP-DD coherent optical modules can be implemented. In 2017, the OIF 400ZR project was initiated, which defined the concatenated forward error correction (CFEC) mode and low-complexity 400G-16QAM modulation mode. Both performance and power consumption are considered to support metro 80 – 120 km and DCI applications.

With low power consumption and a compact size, the 400G ZR can be used in metro edge access scenarios. However, the performance defined by the original 400G ZR cannot meet the requirements of metro edge access scenarios. To resolve this, some optical module vendors are adopting higher performance algorithms based on the 400G ZR algorithm and the FEC algorithm to meet the 200 – 300 km transmission requirements. However, higher performance leads to higher power consumption, which in turn puts pressure on the system's heat dissipation. In response, some vendors are employing the CFP2 package size for ZR+ scenarios.

Table 4-4 Optical module specifications for different transmission distances

Optical Module	Modulation	Optical Component Baud Rate	Subcarrier Count	Transmission Distance	Module Package	Standard Compliance
400GE-LR8	PAM4	25 Gbaud	8	10 km	QSFP-DD	802.3bs

Optical Module	Modulation	Optical Component Baud Rate	Subcarrier Count	Transmission Distance	Module Package	Standard Compliance
400GE-ER8	PAM4	25 Gbaud	8	40 km	QSFP-DD	802.3cn
400GE-LR4-6	PAM4	56Gbaud	4	6 km	QSFP-DD	802.3cu
400G ZR	PDM-16QAM	61 Gbaud	1	30 km (w/o EDFA)	QSFP-DD	OIF 400ZR
				120 km (w EDFA)		
				120 km (w EDFA)	CFP2	/

4.3 Solution: 400G Optical Modules for Metro Integrated Bearer Networks

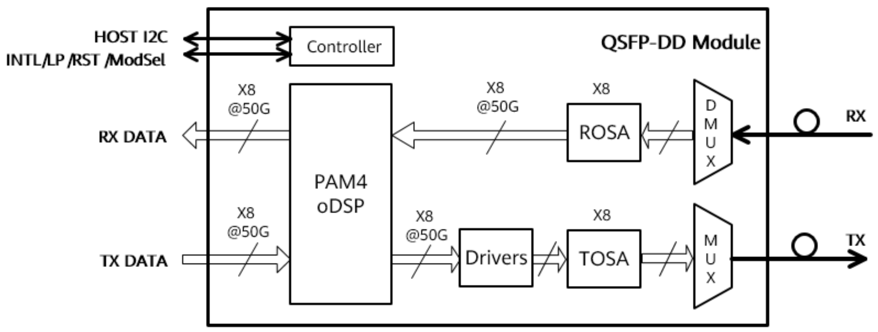
HiSilicon Optoelectronics provides three kinds of 400G optical modules for metro integrated bearer networks: 400GE-LR8, and 400GE-ER8/ER8 Lite. These modules comply with the 400GBASE-LR8/ER8 protocol defined in IEEE 802.3cn, fully meeting the application requirements of long-haul (10–40 km) high-speed optical interconnect. As more edge data centers are deployed to the metro access network, the interconnect demands between DCs in different metro networks increase. Additionally, HiSilicon Optoelectronics provides another optical module, 400G ZR, for long-distance DC interconnect.

Details about the design architecture and key technologies of optical modules are described in the following.

4.3.1 400GE-LR8/ER8/ER8 Lite

A 400GE-LR8/ER8/ER8 Lite module consists of a transmitter optical subassembly (TOSA), a receiver optical subassembly (ROSA), EML drivers, a PAM4 service chip (oDSP), and a controller. As illustrated in Figure 4-3, a series of key HiSilicon-developed underlying components with proprietary IPR are used, including optical chips (EML, PD, and APD) and electrical chips (Driver, TIA, and oDSP). It is an end-to-end vertical integration solution.

Figure 4-3 400GE-LR8/ER8/ER8 Lite system diagram



Electrical-to-Optical Signal Conversion

(1) The module connector receives 8-lane parallel 26.5625 Gbps PAM4 electrical signals from the board. (2) The oDSP performs adaptive processing on the signals, which are then amplified by the driver to drive the 8-lane TOSA. (3) The 8-lane TOSA generates stable laser signals that are multiplexed by the multiplexer (MUX) for output, completing the 8-lane electrical-to-optical signal conversion.

Optical-to-Electrical Signal Conversion

(1) After receiving optical signals, the DeMUX demultiplexes the signals into 8-lane modulated optical signals, which are then sent to the ROSA. (2) The ROSA converts the optical signals into electrical signals, and sends them to the oDSP. (3) The oDSP chip then performs digital signal processing on the 8-lane parallel 26.5625 Gbps PAM4 electrical signals, completing the 8-lane optical-to-electrical signal conversion.

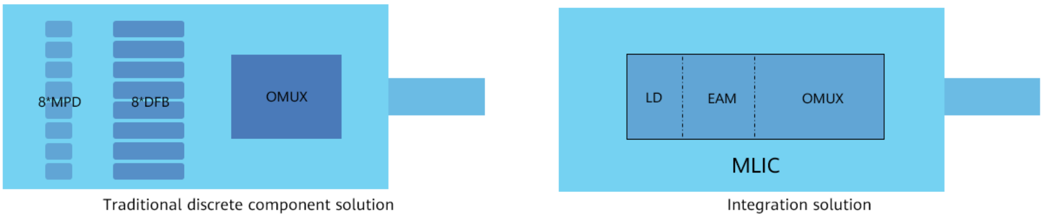
To ensure the optical modules are industry-leading, the following key technologies are used:

- **Multi-Laser Integrated Chip (MLIC)**

  100G and 200G optical modules use 4-lane lasers, while carrier-grade 400G optical modules use 8-lane lasers. The QSFPDD package requires components to be compact in size and consume minimal power. In addition, the Tx laser must have high luminous efficiency and low power consumption to meet the link budget requirements of LR8 and ER8.

  HiSilicon's carrier-grade 400G optical modules use the HiSilicon-developed MLIC, which integrates several building blocks, including multi-lane laser, monitoring photodiodes (MPDs), and MUX. Designs and processes suitable for multi-lane integration are adopted, including novel laser, complex multi-lane RF, and low-insertion-loss MUX. Compared with traditional discrete optical components, these designs and processes help lower the usage of discrete components by 80%, improve manufacturing by 70%, and achieve high luminous efficiency, as shown in the Figure 4-4. The MLIC works with a high-bandwidth EML driver developed by HiSilicon to implement 400G high-bandwidth transmission.

Figure 4-4 Comparing two solutions

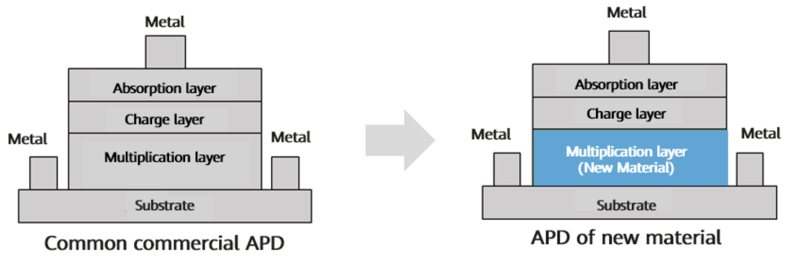


- **High-Performance Receiver**

  According to the definition in IEEE802.3cn, 400GBASE-LR8 and 400GBASE-ER8 should meet the link budget of 6.8 dB and 18.5 dB, respectively. As required, the LR8 receiver sensitivity should be less than or equal to –6.6 dBm, and the ER8 receiver sensitivity should be less than or equal to –16.1 dBm. High receiver sensitivity poses great challenges to the performance of core components (PIN and APD) of the receiver. The performance of a 25G PIN receiver is about –7 dB, which cannot meet the requirements for 40 km transmissions. Therefore, long-haul transmission requires an APD receiver with higher performance.

  HiSilicon's carrier-grade 400G optical modules are equipped with self-developed APDs. Compared with the traditional APD, the self-developed APD uses new ultra-low noise materials for the multiplication layer to reduce the system noise factor (NF) and improve receiver sensitivity by 2 dB. In addition, innovative structure designs and techniques are adopted to improve the APD bandwidth. Combined with the HiSilicon-developed high-bandwidth linear TIA, the new APD improves overall bandwidth and sensitivity, meeting the high performance requirements of 400G-ER8 optical modules.

Figure 4-5 Comparing the two APDs



- **High-Performance oDSP**

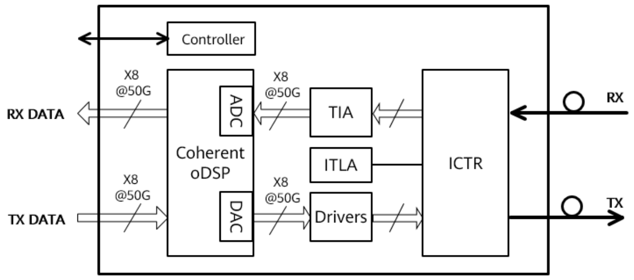
  Most PAM4 oDSPs in the industry use the 16 nm process. The 400GE-LR4/ER8/ER8 Lite optical modules use a HiSilicon-developed 7 nm PAM4 oDSP instead, reducing the overall size while lowering power consumption by more than 30%. The oDSP architecture combines the analog-to-digital converter (ADC) and digital signal processor (DSP), to implement refined link compensation and maximum interconnect compatibility. The oDSP provides rich and powerful features, including SNR monitoring, link transfer function inference, and bit error rate (BER) monitoring, improving the O&M efficiency of fiver links. In addition, the oDSP measures delay with a precision of 1 ns, achieving high-precision 1588 timing. This enables high-precision synchronization for certain mobile services, greatly improving the applicability of optical modules.

4.3.2 400G ZR

HiSilicon provides a colored 400G ZR QSFP-DD optical module, which:

- complies with the OIF 400ZR multi-source agreement (MSA).
- uses the QSFP-DD Type2 package.
- complies with the 400G CAUI-8 electrical port specification.
- uses the PDM-16QAM modulation mode.
- supports tunable 48 C-band wavelengths (100 GHz lane spacing) or 64 C-band wavelengths (75 GHz lane spacing).
- supports DWDM single-span 80-120 km transmission.

Figure 4-6 400G ZR system diagram

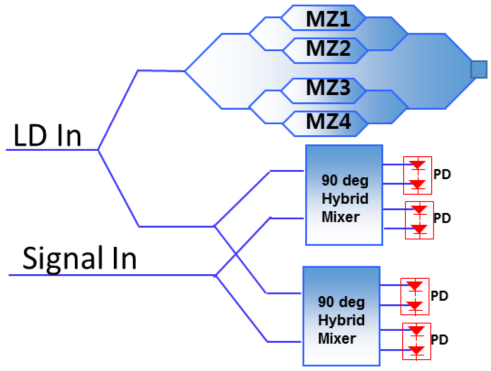


Ultra-compact size and ultra-low power consumption was made possible by the 7 nm oDSP developed by HiSilicon. Specifically, HiSilicon's silicon photonics integrated coherent transmitter receiver (ICTR) enables the design to be ultra-compact in size. The ICTR integrates the driver, PDM-QPSK modulator, and ICR, increasing the bandwidth and performance. Furthermore, a unique high-power Pico laser is used to provide Tx and Rx narrow-linewidth laser signals.

- **Silicon Photonics ICTR**

  Because of their unique optical characteristics, silicon photonics has greater light field limitations, resulting in a more compact waveguide structure. Moreover, silicon photonics supports polarization processing, which can implement the modulation of dual-polarized 16QAM signals and coherent detection while minimizing the size of the ICTR chip.

Figure 4-7 Silicon photonics ICTR

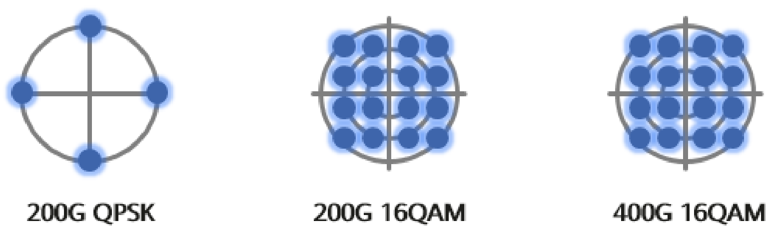


- **Low-Power oDSP Technology**

  A variety of unique oDSP algorithms are used for QSFP-DD applications. Converting time-domain algorithm processing to the frequency domain greatly reduces algorithm complexity. For 80 – 120 km applications, the CD capability of the oDSP is deleted, significantly reducing the number of taps and oDSP power consumption. By using the advanced 7 nm process to make the oDSP, power consumption is further reduced.

  The oDSP supports the flex rate and 100G/200G/400G modulation formats, which can be selected based on the service mode. The 100G and 200G modes support DWDM multi-span transmission over a longer distance.

Figure 4-8 Flexible code pattern based on oDSP



- **Photo-electric Component Packaging**

  Performance of the RF link from the oDSP to the optical modulator is optimized to reduce the requirement on the driver, thereby lowering power consumption. Additionally, optical chips and electric chips are packaged together to reduce the physical size. HiSilicon offers both an oDSP and optical chips, making photoelectric packaging possible.

- **High-Power Tunable Laser**

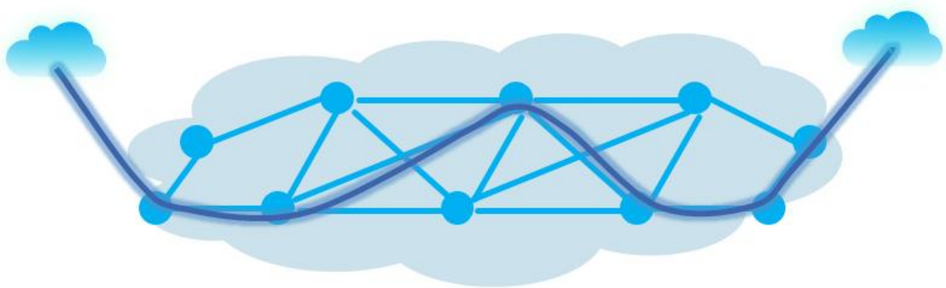
To realize a compact design with low power consumption for the QSFP-DD package, the Tx and Rx share a laser, using one less laser in the process. Additionally, the distributed Bragg reflection (DBR) laser is integrated with the highly reliable and high-gain semiconductor optical amplifier (SOA) to achieve high output optical power. In terms of component design, an efficient optical path and optical coupling are adopted, reducing the insertion loss introduced by component packaging. In this way, a tunable laser with high output optical power can be obtained.

5. 400G Optical Module Solution for DWDM Networks

5.1 Background: Traffic Growth Adds Bandwidth Pressure on Long-Haul Transmission

The growth of network traffic is leading to the increase of port bandwidth on transport networks. For long distance and high bandwidth transmissions, coherent transmission technology based on the wave division multiplexer (WDM) offers the optimal solution.

Figure 5-1 Long-haul transmission diagram

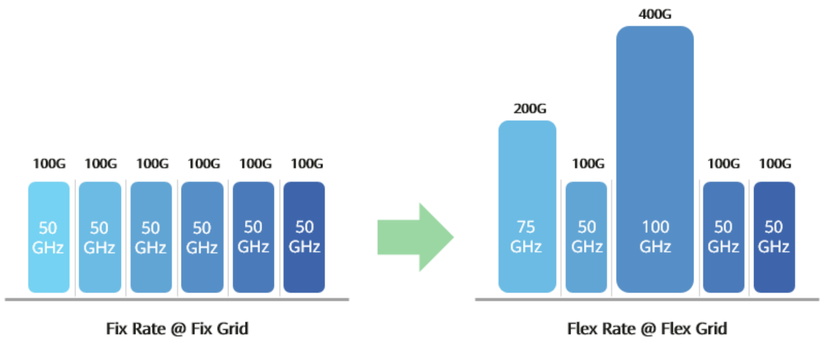


As the 400G coherent solution becomes mature, demands for 400G coherent ports will increase rapidly after 2020. There are two driving forces for the increase of coherent 400G ports: network bandwidth growth and the increasing number of client-side 400GE ports. Using one 400G wavelength to carry 400GE services proves to be the most cost-effective method. According to LightCounting's forecast report, 400G coherent ports will be employed in a growing number of networks and will see the fastest growth in the next 5 years.

As the network traffic, total number of wavelengths, and the number of wavelengths in one network continue to increase, network carriers will also increase the flexibility requirements of network management and scheduling, thus promoting the large-scale deployment of the reconfigurable optical add-drop multiplexer (ROADM) and optical cross-connect (OXC). With wavelength selective switching (WSS) technology, carriers can dynamically configure wavelength paths as required, implementing point-to-point connection through optical paths and reducing latency and power consumption. A growing number of carriers are embracing this solution because of these benefits. For example, in 2017, carrier T in China constructed a ROADM network with up to 364 wavelengths along the middle and lower reaches of the Yangtze River.

Flex rate modulation and flex grid technology enable DWDM networks to be more flexible and elastic, while traditional DWDM systems use fixed 50/100 GHz grids, center frequency, and lane width. If flex modulation and grid technologies are available, the modulation format and lane width of each port can be customized based on the capacity and transmission distance, improving the spectral efficiency and transmission capacity.

Figure 5-2 Flex rate and grid for flexible network configuration



Changes in network architecture require more flexible line-side optical modules that support Flex Rate and Flex Grid

5.2 Trend: Higher Spectral Efficiency, Approaching the Shannon Limit

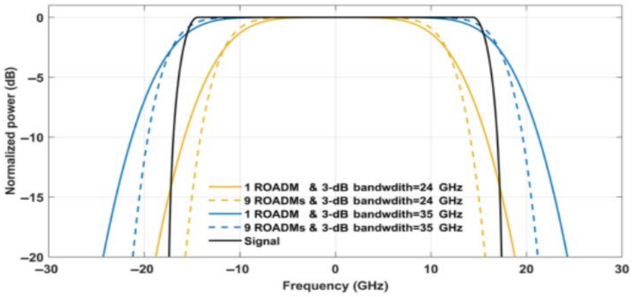
Coherent optical modules evolve in three directions:

- Spectral efficiency: Improves the spectral efficiency and single-fiber capacity based on the progress of the oDSP algorithm.
- Baud rate: Increases the single-wavelength baud rate for higher single-port bandwidth, reducing the per-bit cost and power consumption.
- Smaller size and lower power consumption: Use integrated optoelectronic components, advanced manufacturing processes, and dedicated oDSP algorithm.

Due to the Shannon limit, a 64 Gbaud 400G wavelength cannot achieve the performance required by long-haul optical transmissions. It is necessary to use a higher baud rate and a more complex and powerful oDSP algorithm to meet the requirements of inter-city (regional) and long-haul backbone networks. For example, for a long-haul link (> 1000 km), the baud rate of a 400G wavelength should be above 90 Gbaud, and the ADC and DAC rates in the oDSP need to be increased simultaneously.

However, with the increase of the baud rate, the fiber transmission penalty is higher and even more difficult to be compensated. Therefore, a stronger compensation algorithm is required for compensating the physical lane impairment. Given that ROADMs have been widely used, an end-to-end wavelength link needs to pass through several or even dozens of ROADMs, which contain wavelength selective switches (WSSs). The WSS filtering superposition effect narrows the effective bandwidth of the link, resulting in even higher requirements for the compensation algorithm in oDSP.

Figure 5-3 Multi-level ROADMs' impact on the optical channel bandwidth



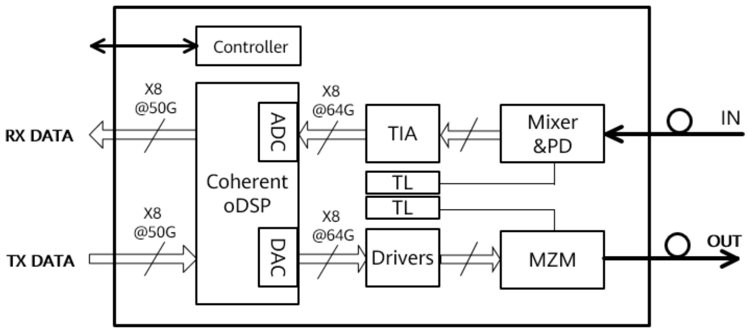
Furthermore, many carriers want to flexibly configure modulation formats and baud rates based on the port rate and transmission distance. For example, deploying 400G 16QAM for 400G long-haul transmission, and deploying 800G 64QAM for metro datacenter interconnect over tens of kilometers to improve spectral efficiency and reduce per-bit costs. With this flexible modulation technology and flex grid at an optical layer, the fiber capacity can be maximized, saving optical cable investments.

5.3 Solution: 400G Optical Modules for Long-Distance Large-Capacity Transmission Network

HiSilicon Optoelectronics' long-haul and large-capacity 400G coherent optical module solution meets the needs of different customers, with each module supporting flex rate modulation (100G/200G/400G) and adopting CFP2 and micro packages. To satisfy customers' large-capacity requirements, both the 40 nm C-band spectrum width and the 48 nm Super C-band are supported, with up to 120 wavelengths. Small-sized silicon photonic components or high-performance high-bandwidth InP components are used to meet a range of different application scenarios.

400G coherent optical modules of different packaging have the same principles. The Tx end of a 400G coherent optical module consists of an oDSP, data driver, wavelength-tunable laser, and PDM-I/Q modulator. First, data from the motherboard is mapped and encoded. Then, the Tx-oDSP performs spectrum shaping and compensation on the data link bandwidth. After that, the data driver amplifies the amplitude and inputs the amplified data to the modulator. The modulator then converts the data into optical signals for output. On the Rx side, optical signals enter the ICR, which interferes with wavelengths of the local oscillator to implement optical-to-electrical conversion. After electrical signals are sampled by the high-speed ADC, compensations to chromatic dispersion (CD), state of polarization (SOP), and polarization mode dispersion (PMD) are performed to restore data signals.

Figure 5-4 Block diagram of a coherent optical module



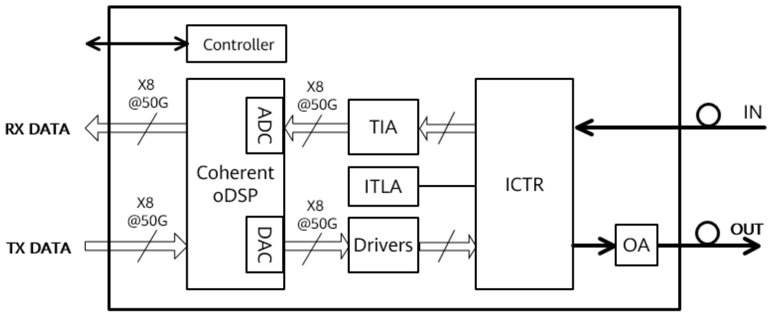
5.3.1 400G CFP2

Used for 400G large-capacity and long-distance transmission, the 400G CFP2 optical module:

- complies with the CFP2 protocol (MSA).
- uses the CFP2 package.
- compiles with the 400G CAUI-8 and FlexO interface specifications.
- supports multiple modulation formats, including QPSK and 16QAM.
- supports 400G 16QAM 500 km @ 75 GHz, and 200G QPSK 2000 km @ 75 GHz.

400G CFP2 is a pluggable optical module and provides optimal performance, incorporating multiple innovative technologies to improve the 400G transmission performance.

Figure 5-5 Block diagram of 400G CFP2



- **High-Performance and Low-Power oDSP**

  To increase the transmission distance, the Turbo Product Codes (TPC) FEC technology — with high performance and low power consumption — is used to continuously approach the Shannon limit. A flex rate ranging from 200G to 400G is also supported. In addition, the low-power IP/DSP architecture is adopted to implement pluggable and low-power features.

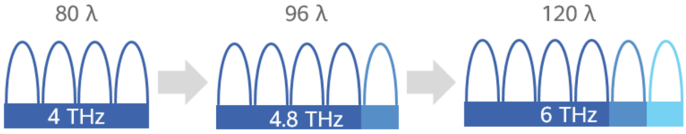
  For 400G CFP2, multiple modulation formats are supported, including 400G 16QAM, 200G QPSK, and DQPSK. For large-capacity transmission, 16QAM is recommended to implement single-wavelength 400G@75 GHz transmission. For a new network, QPSK is recommended for 200G@75 GHz transmission over a distance of 2000 km. Conversely, DQPSK is suitable for existing networks with mixed scenarios to reduce on-linear impact.

- **Super C-Band Capability**

  In a WDM system, the single-fiber system capacity is directly influenced by the number of transmission wavelengths. This CFP2 module is the industry's first Super C-band optical module, supporting 400G@75G with 80 wavelengths and implementing a single-fiber optical transmission capacity of 32T. The implementation of Super C-band depends on other capabilities, including the underlying laser, ICTR, and built-in optical amplifier (OA).

  To realize a compact design with low power consumption for the CFP2 package, the Tx and Rx share a laser, using one less laser in the process. Additionally, HiSilicon's unique laser design features a compact Nano laser with high output optical power.

Figure 5-6 Ultra-broadband spectrum (120 wavelengths)



- **Large Adjustment Range for Output Optical Power**

  In long-haul transmission, the output optical power needs to be finely adjusted for better performance. The output optical power of 400G CFP2 can be precisely adjusted in the range of +1 dBm to +4 dBm to meet the input power requirements of different optical layers.

- **Silicon Photonics Integrated ICTR**

  The silicon photonics ICTR technology is used in the 400G CFP2 optical module to minimize the physical size. Because of their unique optical characteristics, silicon photonics has greater light field limitations, resulting in a more compact waveguide structure. Moreover, silicon photonics supports polarization processing, which can implement modulation of dual-polarized 16QAM signals and coherent detection while minimizing the size of the ICTR chip.

- **Photoelectric Multi-Chip Packaging**

  Performance of the RF link from the oDSP to the optical modulator is optimized to reduce the requirement on the driver, thereby lowering power consumption. Additionally, optical chips and electric chips are packaged together to reduce the physical size. HiSilicon offers both an oDSP and optical chips, making photoelectric packaging possible.

- **High-Performance Compact OA**

  Silicon photonics ICTR technology is used to achieve a compact size but it results in a relatively large insertion loss. To meet the requirements of high-performance optical transmission, a small HiSilicon-developed OA is used to amplify the optical signals at the output end. In addition, the NF of the OA is optimized for high-quality amplified optical signals.

5.3.2 400G MSA

For 400G long-haul and ultra-large-capacity transmission, HiSilicon Optoelectronics' 200G–800G MSA optical module:

- uses the HiSilicon-developed oDSP and high-bandwidth optical components.
- supports 200G－400G long-haul transmission and 600-800G metro/DCI transmission.
- has a built-in OTN framer and clock synchronization processing unit.
- supports 400GE, 100GE, 200GE, OTU4, OTUCn, FlexO, FlexE, and hybrid service access.
- supports OTN alarm reporting and overhead processing, and high-precision clock synchronization for 1588 timing.

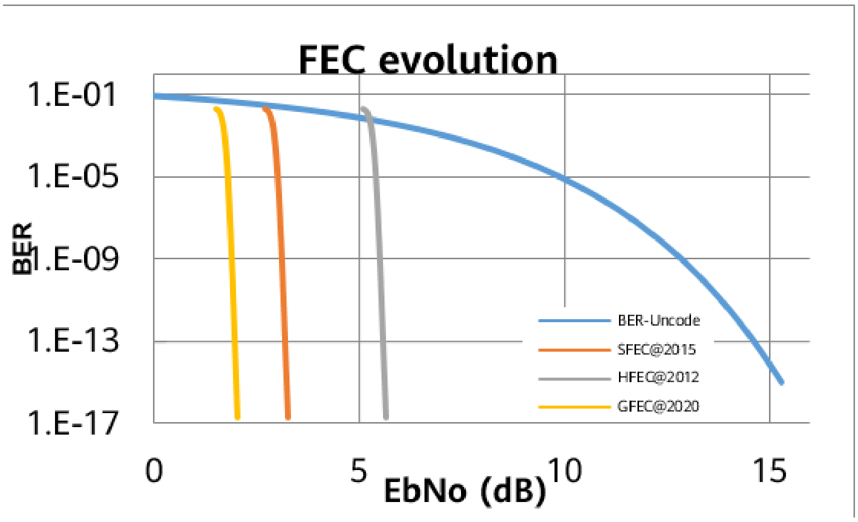
With these features, the MSA optical module meets customers' requirements for high-quality transmission in multiple application scenarios.

Based on an oDSP and optical components with the highest performance, the 400G MSA module delivers the optimal performance for 400G long-haul transmissions, and a flexible 200–800G DWDM system.

- **High-Performance oDSP**

  To increase the transmission distance, high-performance FEC technology is used to continuously approach the Shannon limit, while supporting a 200－800G flex rate. When the number of ROADMs and that of cascading filters increase in an all-optical network architecture, the faster-than-Nyquist (FTN) algorithm is used to enhance the filter pass-through capability and ensure that multi-level filters cause no penalties. The fiber link data collection and analysis modules are integrated into the network management system, improving O&M during the lifecycle.

Figure 5-7 400G MSA transmission performance



- **High-Performance Laser**

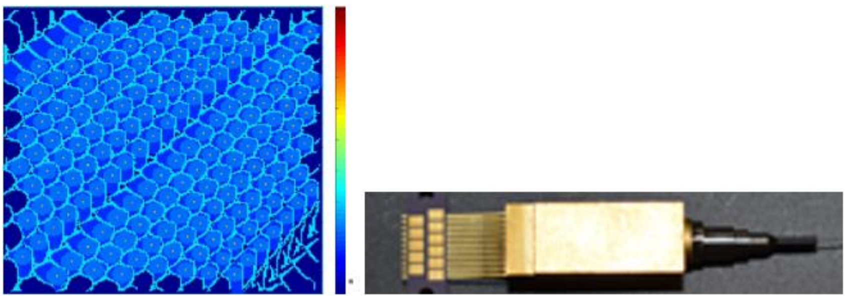
In a coherent 400G system, an adjustable laser provides optical signals at the Tx for modulation. At the Rx, another adjustable laser provides optical signals to serve as the local reference signal for coherent detection. The laser should have the following features:

(1) High output optical power, ensuring high incident optical power for the module and to improve transmission performance.

(2) Narrow line width. Nonlinear phase noise is introduced after optical signals are transmitted over optical fibers and the line width is directly related to the phase noise. It is especially true for high quadrature amplitude modulation (QAM) transmission which raises the requirements on the line width even further.

A unique InP integrated laser with SOA is used to ensure high output optical power. In addition, a unique grating design and wavelength control scheme are adopted to implement ultra-narrow line width and high-stability wavelength locking. Moreover, adjustable lasers of the Super C-band are covered by optimizing the gain medium and adjustable grating of the laser.

Figure 5-8 High-performance laser

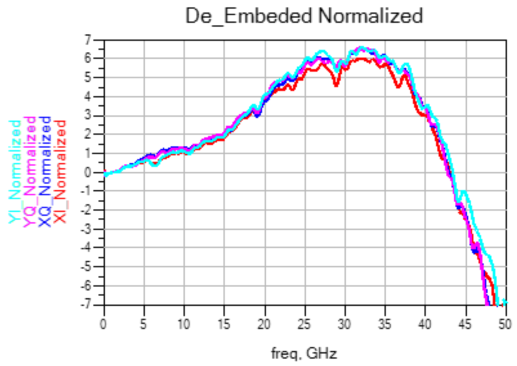


- **High-Performance Modulator**

Generally, a modulator is created by using one of the three technologies: lithium niobate ($LiNbO_3$), indium phosphorus (InP), or silicon photonics technology. Each has its own strengths and weaknesses. $LiNbO_3$, a mature optical component platform, can implement high bandwidth and low drive amplitude, but the component size is relatively large. InP supports high-bandwidth modulation, and can integrate SOA to realize high output optical power. However, InP is sensitive to temperature, and TEC is required for temperature control. On the other hand, the silicon photonic modulator minimizes the physical size while integrating a polarization multiplexing function unit at the chip level, but it requires a relatively large drive voltage.

400G MSA uses a semi-insulated substrate and a unique Mach-Zehnder modulator, implementing high-bandwidth InP I/Q-MZ and SOA integration. In this way, high modulation bandwidth and high output optical power are achieved.

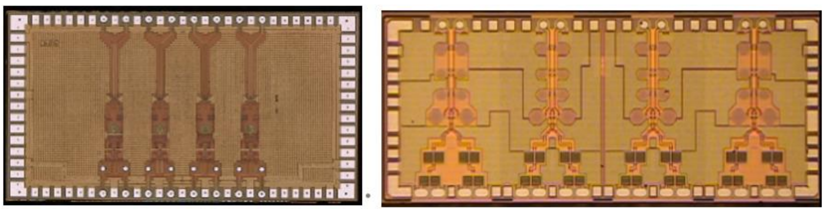
Figure 5-9 High modulation bandwidth supported by an InP modulator



- **High-Performance Optoelectronic oRFIC**

At the Tx of a coherent optical receiver, a driver is required to amplify electrical signals to drive the optical modulator. At the Rx, a TIA is required to convert current signals into voltage signals and amplify the voltage signals. The coherent system adopts the QAM; therefore, Driver and TIA are required to have higher bandwidth and better linearity. Based on the innovative circuit architecture and active equalization design, a linear driver and TIA with ultra-high bandwidth, ultra-high linearity, and ultra-low noise are implemented. By working with HiSilicon-developed optical chips, the coherent driver modulator (CDM) and ICR also deliver high-bandwidth.

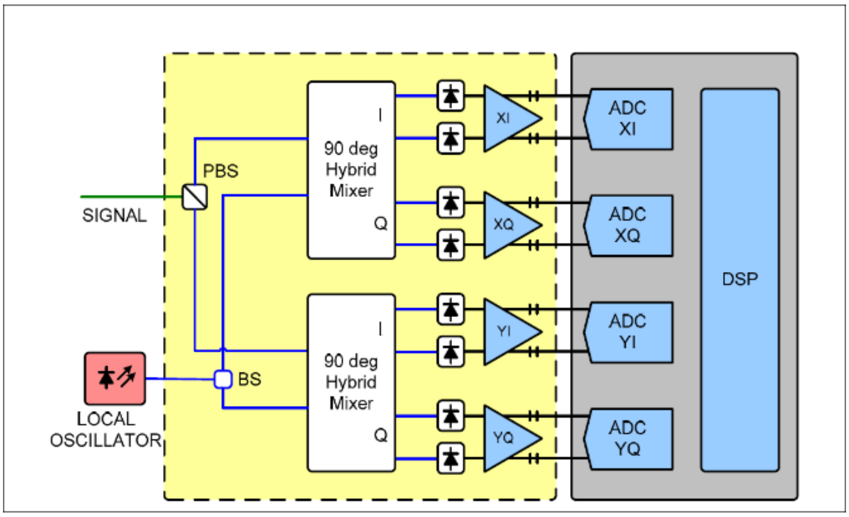
Figure 5-10 TIA and driver



- **High-Performance ICR**

In a coherent optical receiver, an ICR is used at the Rx to receive optical signals. This process also involves an optical mixer and a PD for converting optical signals into electrical signals. ICR-related technologies include: silicon-on-insulator (SOI) technology for ICR integration; planar lightwave circuit (PLC) technology for the optical mixer; and an InP PD. Based on unique techniques involving SiN and PD, HiSilicon Optoelectronics developed an industry-leading ICR. The optical mixer based on SiN technique can be used to achieve good fiber coupling and polarization processing for the optimal optical mixing effect. The InP PD, which boasts high bandwidth and high sensitivity, is mounted to the SiN chip through unique flip chip packaging, producing a highly integrated, high-performance, and small-size ICR.

Figure 5-11 ICR diagram



- **High-Performance Packaging**

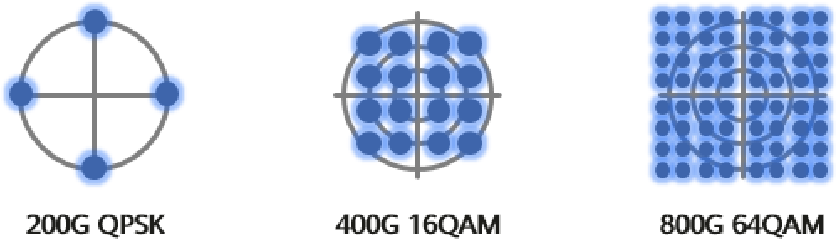
  400G MSA uses the high-performance charge device model (CDM) package. The high-bandwidth driver and modulator are packed into one component, reducing the trace length of high-speed RF signals, which in turn ensures the integrity of the high-speed signal and the component's high bandwidth. Some electrical ports use pins to ensure the stable connection and bandwidth of access signals, thereby improving the performance of CDM components.

Figure 5-12 High-performance component package

- **200－800G Flex Rate and Single-Wavelength 800G Large-Capacity Transmission**

  With powerful oDSP and high-bandwidth optical components, the micro module supports higher-order QAM. Meanwhile, the constellation shaping 2.0 is used to support 200－800G adjustment. In addition, the built-in OA can ensure the output optical power in higher order modulation.

Figure 5-13 Flexible modulation formats



6. Conclusion

The demand for higher capacity, lower per-bit cost, and lower power consumption are driving the transmission rates of optical modules ever higher. As the mainstream technology in the previous generation, 100G has entered the mature and stable phase of its lifecycle where unit cost reduction is extremely limited. Compared with 400G, 200G is less competitive in terms of standardization, the industry chain, and technologies, making 400G the better mainstream transmission rate for next generation devices.

Currently, mainstream 400G optical modules have been used in various network scenarios, such as DC networking, metro integrated bearer networks, and large-capacity and long-haul transmission networks. With over 10 years of investment and R&D, HiSilicon Optoelectronics has become the provider of end-to-end 400G optical module solutions that are fundamental for building ultra-broadband pipelines to carry the heavy traffic flows in the ICT industry.