post-show report

OFC 2018

The future of optical networking and communications

A MARKET OVERVIEW

Contents

15,500
ATTENDEES FROM

75 COUNTRIES

1/3
OF OFC ATTENDEES
are based outside
the United States

700+
EXHIBITORS

OFC 2018 GENERATED
20,599
NEWS ARTICLES
reaching an audience of
2 billion*

*as of 3/23/18
Source: OFC 2018 Survey and Registration Data

Introduction

The Optical Fiber Communication Conference and Exhibition (OFC) is the leading global venue for learning and discussing market trends, innovations, business opportunities, and industry-shaping technologies. OFC is a world class event that provides a unique global showcase of market direction across the networking and communications industry and adjacent sectors.

Companies and industry participants from around the globe convened at OFC 2018 to discuss, demonstrate, and share feedback on optical technology that will shape the growth of networking. Topics included using AI to manage and control networks, the impact of 5G networking across the supply chain, and what innovations are allowing the network to keep pace with the spectacular growth of cloud computing and services. Experts discussed numerous global trends, including advances in coherent optical transmission, developments in data center networking, and new approaches in disaggregating network design.

Occupying over 350,000 square feet of exhibit space, OFC 2018 featured 700+ exhibits from major international corporations such as Acacia, Alibaba, Broadcom, Ciena, Corning, Finisar, Huawei, Infinera, Inphi, Juniper Networks, Lumentum, Oclaro, Semtech, Sumitomo Electric Device Innovations and more. Technologies on display included new compact modular WDM equipment designed for the latest network architectures, 16nm semiconductors for 400Gbs transmission and beyond, network and test equipment, fiber cables and specialty fiber manufacturers and the latest Indium Phosphide and silicon photonics optical components.

The exhibition hall theaters featured business-focused programming with presentations by experts from major

global brands, including Tencent, AT&T, Arista, NTT, China Mobile, Google, Facebook, Microsoft and many others as well as key industry organizations such as the Ethernet Alliance, OIF and the Consortium for On-Board Optics (COBO) to name a few.

Over the past 40+ years, OFC has grown into the largest optical communications event in the world. It is the one must-attend show for analyzing the future direction of the industry. Each year, companies choose OFC to showcase the most noteworthy developments in the optical industry and make pivotal product and technology announcements. This report highlights and summarizes the 2018 developments in these areas.

- **Consolidation Buzz**
- **Compact Modular Equipment and Hardware Disaggregation**
- **Operator Perspectives**
- **Coherent Technology**
- **400G Inside the Data Center**

1 Consolidation Buzz

Consolidation Buzz

Each year, there is at least one announcement at OFC which surprises the industry and this year was no different. In 2016, the announcement was the introduction of Inphi's ColorZ, while in 2017 it was news of Ciena choosing to license the Wavelogic DSP to module vendors. And yet, OFC 2018 delivered a surprise that exceeded both: Lumentum will acquire Oclaro.

Industry consolidation was a subject of speculation during multiple Market Watch sessions held at OFC for the past decade. Frankly, these discussions became circular and tiresome after years of no action. That changed during OFC 2018 as Lumentum and Oclaro, the market's second and third largest optical component companies, announced their merger. Unlike the mergers in the 2000s, which were examples of the strong consuming the weak, this agreement was an alliance of choice made by management bent on realizing the benefits of consolidation. The move sparked excitement and fresh conversations at OFC.

Lumentum is paying a combination of cash and stock to acquire Oclaro for $1.8B. Lumentum ($1126M) has nearly twice the annual revenue of Oclaro ($606M), although both companies' telecom and datacom component businesses are roughly equal. Therefore, from the perspective of the customers at OFC, it is considered a merger of equals. Lumentum also indicated it expects to realize $60M in annual cost synergies from the combination, roughly a 3% improvement in operating margins for the combined entity.

Consolidation discussions in the industry pointed to Oclaro as a prime candidate for acquisition, but Finisar (not Lumentum) was the consensus buyer. Finisar has the least product overlap with Oclaro and therefore such a merger would retain the most value. Lumentum, on the other hand, already had deep expertise in indium phosphide manufacturing and high-performance client optics, so the perceived value was less.

So why then did Lumentum pursue Oclaro? First of all, Oclaro's R&D for the 400G generation of client and coherent optics was ahead of Lumentum's. Furthermore, Lumentum's revenue will be distributed equally between three separate end markets – telecom, datacom, and consumer/industrial after the merger. This diversification, combined with the company's size, will result in a more stable and manageable business—a new entity with total revenue that is greater than previous market leader Finisar.

HORIZONTAL VS. VERTICAL INTEGRATION

Hearing of Lumentum's bold move, OFC hummed with conjecture about other potential horizontal integrations. Missing from the discussions were vertical integrations – the combining of product lines that share a common application but do not have complementary production and design. Previous examples of vertical integration include Ciena's acquisition of Teraxion indium phosphide and silicon photonics component assets and Cisco's acquisition of Lightwire silicon photonics and CoreOptics DSP.

One fact highlighted by presenters during the conference was the staggering cost of 7nm silicon needed to deliver the next generation of coherent DSPs and PAM-4 devices. Arista Networks' CTO Andy Bechtolsheim stated that the first manufacturing run of 7nm silicon costs more than $10M, not including development costs.

There are six separate companies at OFC developing PAM-4 silicon, all of which will migrate to 7nm next year in order to remain competitive. How will these companies overcome such enormous up-front fixed costs? One possibility is vertical integration - selling complementary optical technology alongside the PAM-4 DSP. MACOM already has some in-house optical technology, as does Broadcom (acquired from Avago).

Horizontal integration and vertical integration are very different market strategies which entail unique benefits. Horizontal integration is concerned with saving R&D and SG&A costs, while vertical integration combines technologies to create superior and sustained competitive advantage. After Lumentum's acquisition, next year the market will probably show us more of both.

KEY TAKEAWAYS

- Lumentum's acquisition of Oclaro is a merger of equals if considering only telecom and datacom revenue.

- The perceived product overlap between Lumentum and Oclaro does not take into account the stronger position Oclaro has in 400G InP technology.

- Neophotonics, Fujitsu, and other suppliers may reap incremental benefits from second source activity.

- It is likely that the Lumentum move will inspire more horizontal consolidation among component companies.

> " We love OFC. It's such an interesting conference because of the trade floor, where we show products, but its also got this very strong academic, intellectual component. It's 15,000 people. We think it's on the way back to being the 40,000 it was at its peak because of the importance of optical networking going forward. And it just gets bigger and bigger for us. "

MARCUS WELDON, PRESIDENT, NOKIA BELL LABS

2 Compact Modular Equipment and Hardware Disaggregation

Compact Modular Equipment and Hardware Disaggregation

Compact modular equipment took center stage at OFC 2018. News included speed upgrades to existing systems, the emergence of new switch/router variants, and open line systems designed to address the growing interest in optical hardware disaggregation.

2017 was a period of exponential revenue growth for compact modular optical hardware. Products in this category include the well-recognized Infinera CX, Cisco NCS1000, and the Ciena Waveserver. All three of these hardware products were originally built for DCI applications, and as a result, some refer to these systems as "DCI hardware." To do so is inaccurate; DCI is not a type of equipment but an application. 'Compact Modular' more accurately describes these small 1 or 2 RU chassis systems that allow operators to build networks in a modular way.

Compact Modular systems are now breaking out of DCI applications in cloud networks and finding new roles in cable MSO and incumbent networks around the world. Operators across all applications and regions are keenly interested in these systems, especially operators seeking a more disaggregated hardware design approach.

COMPACT MODULAR MARKET OVERVIEW

The compact modular segment is the fastest growing part of the optical hardware market and was a prominent focus of OFC 2018. Most of the major equipment companies in attendance showcased their compact modular systems in Market Watch presentations or through new product announcements. Cloud and colocation (colo), incumbent, and cable MSOs all identified these systems as a crucial technology for future network deployments.

One factor driving the popularity of the compact modular system is that the needs of network operators are rapidly diverging. Twenty years ago, a company such as AT&T would outline its requirements and most other operators would model their deployments accordingly. This is not the case today. The equipment and software requirements of AT&T are radically different from those of Google, Comcast, or even distant cousin Verizon. It is therefore difficult for OEMs to economically build systems that are designed just for one network operator segment.

COMPACT MODULAR SYSTEMS	
ADVA	Cloudconnect Teraflex
Ciena	Waveserver
Cisco	NCS1000
Coriant	Groove G30
Fujitsu	1Finity (T-Series, L-Series)
Huawei	OSN 902
Infinera	Cloud Xpress XT-500/XT-3300
Nokia	1830 PSI
ZTE	ZXONE 7000

This situation is where compact modular systems shine. Operators are moving toward a model where they can build a network tailored to its needs out of modular pieces from several vendors. The compact modular approach allows operators to mix and match components as needed to meet their application requirements.

COMPACT MODULAR HARDWARE REVENUE

Source: Cignal AI Optical Applications Report

The software to stitch these systems together will initially be built in-house. Going forward, groups like the Open Networking Foundation (ONF) are working to develop standardized APIs and software models for specific network functions.

Hardware adoption is white hot in this segment, and 2018 revenue tripled year over year to nearly

$500M. Companies are driving investment to capitalize on the compact modular trend. Cignal AI forecasts that revenue in this segment will nearly double in 2018 – yet even with this growth compact modular remains a small part of overall optical hardware spending.

OFC 2018 PRODUCT ANNOUNCEMENTS

Cisco, Coriant, and Fujitsu each chose OFC to announce new 600G capable compact modular platforms. These announcements follow those made last year by ADVA, Ciena, and Infinera regarding higher speed platforms.

Each of these systems now supports multi-haul operation; the ability for a single coherent port to operate at varying baud rates and modulations to maximize capacity on links spanning from 100km to 4000km+. Multi-haul operation is in almost all new coherent systems that reached the market in 2017. All three of these newly announced 600G capable systems are slated to be in production by the end of 2018.

CISCO NCS1004

Cisco announced a new member of the very successful NCS1000 series; the NCS1004. This family of systems only began shipping in late 2016, but it has been quite successful and earned the number two spot in compact modular market share in 2017. The NCS1000 provides a combination of CFP2-ACO design, 250G per lambda operation, and a flexible software model that appeals to cloud and colo operators.

Cisco's new NCS1004 takes the NCS1000 concept and adds in flex-coherent operation up to 600Gb/s per wavelength. Recognizing the industry-wide move away from CFP2-ACO as part of a transition to

400G speeds, the NCS1004 can use both silicon photonics and indium phosphide based discrete optics. Cisco is confident both technologies will work equally well.

CORIANT

Coriant introduced a follow-on module (CHM2T) to the Groove G30 platform which added 600G operation. The Groove was the first system to feature 'sleds'—cards that can be customized with certain features and allow the network operator to personalize any given system. The Groove's sleds allow the entire installed base to make the jump to 600G operation, where products from Cisco, Ciena, and others require users to install new chassis to support higher speeds. Users can purchase a CHM2T and deploy it in an existing G30 chassis – something no other vendor can do. It also gives the Groove a leg up in 2018 as its customers can deploy 200G coherent now and know the upgrade path is future proofed.

Coriant also offers a range of amplifiers, filters, and optical functions that can occupy the sleds – and the company is developing more. While the Groove hasn't had the same commercial success as the Ciena, Cisco, and Infinera platforms, it did pioneer features now being adopted by systems like Cisco's NCS1000.

FUJITSU T500, T600

Fujitsu announced new generations of its 1FINITYcompact modular product line – the T500 and T600. Like Cisco and Coriant, Fujitsu increases coherent wavelength speeds to 600G and uses the latest in DSP and discrete InP optical technology.

Fujitsu has made incumbent and cable MSO operators customers a central focus, which is not surprising considering its long relationships with AT&T and Verizon. The 1FINITY is designed to meet the needs of AT&T's network hardware disaggregation efforts, including Open ROADM hardware and CORD software architecture.

ADVA, INFINERA, AND CIENA

All three of these vendors announced new compact modular systems prior to OFC 2018 and they had live demonstrations or mock-ups of the new hardware on site. Ciena is already in production with its Wavelogic-based Waveserver Ai, capable of multi-haul 400G operation. Waveserver Ai will be the only 400G system to ship in volume during 2018, and it will be exciting to see what sort of market prominence this affords Ciena.

Infinera is in production with its 4th generation coherent optical engine and uses it in its CloudXpress 2. The engine (ICE4) is capable of

200G per wavelength operation but the company claims that it has a structural cost advantage when competing against other 200G solutions because of its vertical integration and use of photonic integration. Infinera also announced its technology roadmap which we discuss in the coherent technology section.

ADVA announced its 600G system – Teraflex – at OFC 2017, and it is based on much of the same technology as other 600G systems.

COHERENT + ETHERNET & IP

Ciena and Juniper announced new compact modular products that combine both coherent optical transport with Ethernet and IP switching & routing.

Ciena's new product is the 8180 coherent networking platform, a 6.4 Tb/s packet fabric based on off-the-shelf Ethernet switching silicon. Half of the switch bandwidth can be dedicated to four 'sleds' with coherent optics, each of which can currently operate up to 400Gb/s using Ciena's Wavelogic AI. The other 3.2 Tb/s of switch bandwidth is dedicated to 32 100GbE QSFP ports.

The 8180 is designed with a number of new applications. The first is the densification of future 5G mobile networks and the convergence of both mobile fronthaul and backhaul traffic into a common Ethernet interface. The second is fiber deep – the deeper penetration of Ethernet interfaces into Cable MSO access networks. Cable operators are moving from analog-DOCSIS-based interfaces to Ethernet and increasing the number of total interfaces by an order of magnitude. Both 5G and fiber deep require lots of Ethernet switching and low-cost coherent

backhaul, which the 8180 is designed to meet head-on.

Juniper announced the ACX6360, which is a derivative of its much larger carrier-class PTX router. The 6360 is essentially a single blade of the PTX, complete with its extensive L3 routing capabilities, paired with 8 x 200G coherent interfaces and 16 100GbE QSFP clients. Juniper plans to offer the hardware with a limited Ethernet switching feature set, and then sell additional software licenses that can leverage the extensive packet capabilities of the blade. The licenses could be application specific and include features specifically needed for Cable MSOs, content distribution networks, or wireless.

OPEN LINE SYSTEMS

For some time now, companies have claimed to offer open line systems, but the equipment has come with some inherent limitations. Some systems required custom pilot tones or placed performance restrictions on the wavelengths from other vendors. All of them failed to operate with maximum spectral efficiency.

Now, there is a new class of optical common equipment coming to market with the goal of eliminating those issues and building truly open optical line systems. Ciena announced the 6500 RLS (Reconfigurable Line System) while Cisco presented the NCS1010. Both are designed to have the hardware flexibility (flexible-grid ROADMs, independent closed loop subsystems) and the software interfaces (North/Southbound NETCONF/YANG data models) needed to adapt to disaggregated hardware environments. Cisco's hardware is even capable of running 3rd party applications written by the network operator itself.

As is typical with the first iteration of any new technology, all of this flexibility comes at a premium cost. If one were to tear down the hardware of the 6500 RLS, NCS1010 (or any of the other systems that follow) you'll find top-of-the-line components end-to-end. Users who automatically expect open hardware and open line systems to be cheap will be in for a surprise.

In order to accommodate a range of potential transponder vendors and network designs, truly open equipment must be designed to handle every possible situation. This necessitates the elimination of fixed grid AWGs and replacing them with flex-grid ROADMs. It requires sophisticated amplifier power balancing techniques and embedding OTDR testing hardware in each node. The result is a Ferrari, not a Ford, and the price tag reflects this.

The open systems announced by Cisco and Ciena are just a first step in trying to meet these needs. There will be some improvements at the component level that reduce the cost of these systems. Ultimately though, the market for open line systems is likely to split into two markets.

Large network operators seeking open line systems will find ways to constrain their network architectures to avoid needing maximum flexibility. They will then seek out the lowest cost modular equipment to build these line systems – a vision that Google clearly outlined during its Market Watch presentation.

There will also be other customers who place a premium on network and vendor flexibility. Most of the operators who want to move towards open systems have highlighted flexibility, not cost reductions, as the reason. They want to build application-specific networks and solve the problems unique to their business – and maximum flexibility always comes at a price.

KEY TAKEAWAYS – OFC 2018 & COMPACT MODULAR EQUIPMENT

- Compact modular systems are the fastest growing segment of the optical market, as growth extends beyond the initial cloud and colocation customers who used these systems for DCI.

- These systems form the building blocks for operators with unique requirements who seek to build an application-specific optical network.

- Cisco, Coriant, and Fujitsu announced systems which do not have much hardware differentiation between them, but they do take different architectural and software approaches. These three systems join those already announced previously by ADVA, Infinera, and Ciena.

- Ciena and Juniper announced combined Ethernet/IP platforms with coherent interfaces. Cable MSOs and 5G networks are the target applications for these systems.

- Ciena and Cisco announced open line systems which are extremely impressive but costly. Large operators with big networks are likely to constrain the requirements of their line system in order to cut costs. These new open line systems are likely to evolve further to meet these needs.

3 Operator Perspectives

Operator Perspectives

Each year at OFC, we have the valuable opportunity to hear from the network operators themselves to better understand their vision for the future network. This year, there were some excellent presentations and discussions involving operators from several network verticals – Incumbents, Cable MSOs, and of course the ever-expanding cloud and colocation operators.

CLOUD & COLOCATION OPERATORS

MICROSOFT

Microsoft made several presentations during OFC; in fact, more than any other cloud operator. Mark Filer, part of the Azure optical network architecture group, outlined the current connectivity topology of Microsoft's data centers and discussed its plans for transitioning to 400GbE. The company consistently messaged that it designs primarily for power, not cost. Often the indirect savings from lower power consumption will outweigh the direct costs of purchasing more expensive and exotic technology.

Inside the data center, Microsoft has already invested in parallel fiber and plans to leverage this with DR4 optics. The company currently uses 100Gbs direct attach cabling (copper twinax) for intra-rack communication, but anticipates a move to active optical cables (AOCs) for 400GbE.

Outside of the data center, Microsoft indicated it had deployed at least 15,000 ColorZ direct detect modules from Inphi. Microsoft is pleased with this solution and the savings it entails by integrating WDM optics into its switching equipment. The ColorZ plugs directly into the layer 2/3 equipment and eliminated standalone optical transport equipment from Infinera, Ciena, and others. Microsoft uses this solution for connections between data centers in a metro area (less than 80km) to create a relatively cheap mesh computing solution.

Microsoft holds that the ColorZ won't scale to 400G and anticipates moving to the upcoming 400G ZR standard, which should plug into its Ethernet switches just like ColorZ does. For longer distances, Microsoft is looking at conventional WDM equipment but is also considering the possibility of coherent optics directly embedded in its equipment.

GOOGLE

Google continues its network design based on simple building blocks that allow it to scale seamlessly. These "blocks" can be purchased from multiple vendors, which allows Google to make choices based on who is currently offering the best performance. Compact modular equipment is designed to serve this model, and Google said it prefers the fast innovation cycles it has observed from vendors of this equipment.

Google presented plans for implementing optical open line systems (OLS) during OFC's Network Operator Summit. Open line systems are already in its long-haul transport networks, but Google wants to improve the operational model and implement the preferred modular approach. The company wants "open, modular

> **"** OFC once again provided a superb conference and exhibition for meeting with the leaders and start-ups in the optical communications industry. I was able to see a proliferation of PON types, reflecting the individual strategies of Communications Service Providers as they prepare for 5G networks and the growing demands on xHaul (mobile backhaul, mobile fronthaul) while striving to contain capital expenditures. **"**

JULIE KUNSTLER, BROADBAND ACCESS ANALYST, OVUM

line systems to unlock the best in breed building blocks."

It envisions three discrete blocks: an in-line amplifier, a colorless, directionless, contentionless (CDC) ROADM for signal routing, and a drop-side ROADM for connecting transponders. CDC is fundamental, as the company wants to add and remove transponders and optical links without having to touch the cabling infrastructure.

TENCENT
Tencent, a Chinese cloud provider with market capitalization comparable to Facebook, gave one of the best presentations of the Data Center Summit. Tencent operates
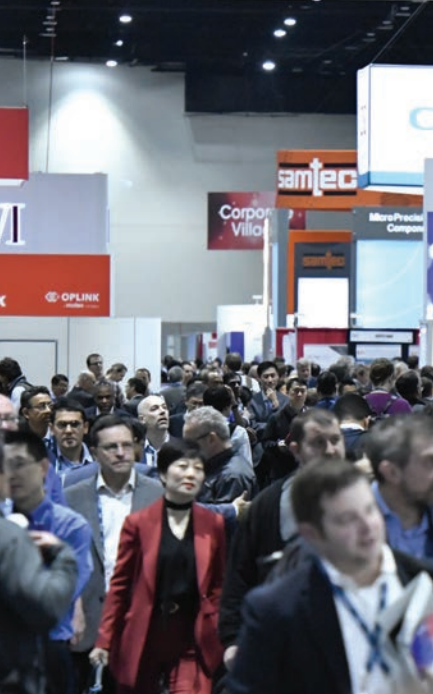
80 data centers worldwide with over 1M servers and 70k network devices and provides numerous consumer services in China including the omnipresent WeChat.

Like its western counterparts, Tencent sees the fastest growth in its internal machine-to-machine networks, particularly in metro networks that mesh data centers in a Chinese province capital region. Inside the data center, the company uses a combination of 100G SR4 and CWDM4 for intra-building and intra-campus connectivity while relying on AOCs for intra-rack connections. Tencent is just beginning a transition to 100G optics inside the data center and doesn't anticipate a move to 400G until after 2019.

Microsoft and Tencent share a similar vision for IP and optical convergence for WDM connections. Tencent highlighted the popularity of standalone OTN switching and transport equipment in China among the incumbent Chinese carriers. The company went on to say that this approach would not work for it and therefore it would build its own IP networks with coherent optics inside the routers.

INCUMBENTS

VERIZON
For many years, Verizon operated separate, balkanized WDM transport and access networks; one for Fios broadband, another for Verizon wireless, another for enterprise connectivity, and even more because of mergers. The company recognized the enormous cost and complexity of this approach and sought to unify these networks – a project Verizon calls Unified Transport (UT).

Cisco and Ciena are the suppliers of the Packet-OTN switching equipment that Verizon is using

to build out this network. Verizon still expects more deployment activity for UT in 2018 than 2017 but commented that a rapid ramp in deployment is not possible. In the words of one Verizon engineer: "we only have so many people and so many trucks to do the work."

Verizon will also eliminate 90% of the edge routers from the network – a truly staggering number. Just as there were separate WDM networks for each Verizon division, there were also specialty edge routers designed to handle the traffic for that network. New router design with network function virtualization allows one piece of equipment to support a multitude of protocols, unifying this disparate traffic.

AT&T
AT&T provided a brief update on its plans to disaggregate the design of its optical network. Like Google, the company wants to adopt a network equipment deployment model that provides more flexibility.

To do so requires solving several longstanding problems that most incumbent operators have: a lack of optical vendor interoperability, vendor lock-in, an inability to rapidly switch vendors to take advantage of innovation, and a requirement to build overlay networks when vendors are mixed.

AT&T outlined a 4-phase plan that will use white box hardware, first with client transceivers, then WDM transponders, followed by solving the WDM interoperability problem. The last phase is the deconstruction of the common equipment and implementation of an open line system. The company announced it would begin deploying hardware conforming to its Open ROADM initiative by the end of 2018, although this is later than originally planned.

OFC

HAS BEEN ON A STEEP GROWTH TRAJECTORY OVER THE LAST THREE YEARS, INCREASING IN OVERALL SQUARE FOOTAGE BY

44%

AND EXPERIENCING A

21%

GROWTH IN
EXHIBITORS
AND ATTENDESS

Ultimately, AT&T believes these changes will not just give it better leverage over suppliers, but that they will allow it to build networks that are viable for longer periods of time and can adapt to the rapid pace of network technology.

CABLE MSO

COMCAST

Comcast also participated in the Network Operator Summit and reflected on how its network has changed over the past 20 years as optical fiber penetrated deeper into its access networks. Comcast is on the cusp of another change; the implementation of distributed access architecture (DAA) commonly referred to as "fiber deep."

The company is active within the ONF to remake the hardware and software that comprises its network; moving from hardware with dedicated functions to virtualized hardware running on servers. Comcast is a big supporter of the ONF's Open and Disaggregated Transport Network (ODTN) and plans to build its new transport network in this image, with transport and layer-2 switching components being essentially interchangeable from multiple vendors.

Absent from the Comcast discussion was a discussion of the enormous increase in the amount of Ethernet optics it will need as part of driving Ethernet-based protocols deep into its network. The exact size of this opportunity is not yet clear, but an initiative spearheaded by CableLabs (the Cable MSO technology working group) is underway to standardize 100G coherent optics, essentially a slower speed variant of 400G ZR.

KEY TAKEAWAYS

- Cloud and colo companies like Google, Microsoft, and Facebook are all moving to disaggregate the hardware components of their transport networks. Compact modular equipment should meet these needs – it is not evident that they will build WDM equipment in-house, yet.

- Microsoft has deployed at least 15k ColorZ units from Inphi and is pleased with the network model it enables. The company wants to build on this success and integrate longer reach WDM optics and its layer 2/3 switches.

- Google outlined a network model to build open line systems with three discrete building blocks and plans to deploy CDC ROADMs exclusively.

- Tencent, a major Chinese cloud company, has networks and requirements that mirror the west. Like Microsoft, the company favors tighter IP and optical integration.

- Verizon expects a slight ramp in the deployment of its Unified Transport metro-WDM network in 2018. It also will reduce the number of routers in its metro network by a staggering 90%.

- Quantitative details on cable MSOs' fiber deep deployments are still sparse, but the companies are embarking on a path that will eliminate specialty hardware wherever possible and rely on generic Ethernet and optical transport components.

4 Coherent Technology

Coherent Technology

Trends in coherent technology generated enthusiasm among the participants at OFC 2018, and 400G ZR applications were of particular interest. Nokia and Infinera outlined next-generation coherent roadmaps, and Acacia and NTT Electronics showcased silicon fresh back from the fab. Many component companies announced smaller, lower cost devices to enable new WDM applications.

COHERENT IN THE METRO EDGE

While the Lumentum/Oclaro news was the hot topic of the week, 400G ZR was the most discussed technology at OFC 2018. Even though there were no specific announcements regarding the ongoing development of the OIF 400ZR (120km) specification, multiple presentations illustrated broad anticipation of the benefits expected. 400G ZR is intended to address high volume optical metro-edge applications connecting data centers, 5G wireless, and cable MSO access nodes.

Coherent optical transmission is not the niche technology it was a decade ago. According to the operators and component makers presenting at OFC 2018, it will continue to spread into new optical networking applications as coherent speeds increase and price and power decrease.

Recall that 400G ZR is designed to bring interoperability to coherent interfaces for reaches up to 120km and at speeds of 400G. The target module form factor is QSFP-DD or OSFP, though every component maker we spoke with is working towards QSFP-DD.

Coherent 400G technology in the QSFP-DD format pushes the limits of space and DSP power consumption. Vendors are also hesitant about the high cost of developing the required 7nm DSP silicon - estimated by Arista to cost $10M to fab and $50M total to develop.

The addressable market for 400G ZR is growing, boosting the business case for this sizable investment. A year ago at OFC, 400GZR was perceived as useful only for data center interconnect. This year illustrated a myriad of new applications and speeds that could extend volumes by an order of magnitude.

NEW APPLICATIONS

120km was the original application 400G ZR was intended for, but discussions at OFC 2018 indicated that there are other applications both shorter and longer than this specification.

For example, Inphi now offers a 20km version of its 100G non-

DEPLOYED COHERENT BANDWIDTH BY SPEED

Y-axis: % Total Bandwidth Deployed (0% to 100%)
X-axis: 2014, 2015, 2016, 2017, 2018, 2019, 2020, 2021

Legend: 100G, 200G, 400G
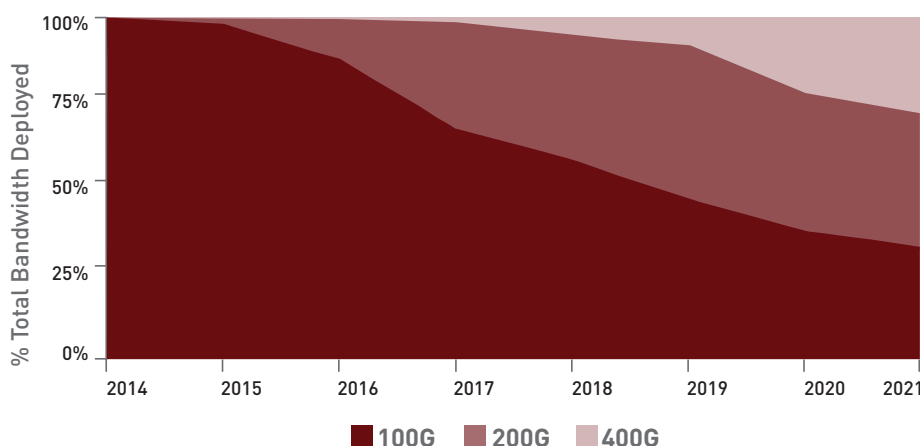
coherent ColorZ—a product based on interest from several large cloud customers. These customers appear to need only a fraction of the 120km capabilities of 400G ZR. Options like 400G versions of LR4 or ER4 don't meet needs for WDM capabilities. Microsoft presented a histogram of fiber lengths in its metro networks, and almost all of its links were under 40km. Clearly, a dedicated shorter reach version of 400G ZR could have a significant market.

In the case of long reaches, Huawei made a Market Watch presentation outlining its research on 400G ZR capabilities and indicating that the low-power potential of the technology extended to reaches as far as 600km in form factors larger than QSFP28, such as 2x400G ZR in a CFP8.

COHERENT CLIENT OPTICS

Other vendors at OFC discussed modifying 400G ZR to provide an alternative to LR 10km optics. The current IEEE 400G LR8 specification is perceived as high cost and power, as it uses 8 separate wavelengths. The 100G Lambda MSA group proposed a more optimized 400G LR4 solution using 4 wavelengths.

A coherent implementation re-using the 400G ZR DSP and lower cost/power optics could be a competitive alternative to both of these solutions even at 10km distances, a strategy highlighted by Arista and Huawei. Acacia proposed that coherent technology coupled with silicon photonics might even be viable at 2km for 400G client operation. As one might expect, not everyone agreed. Fujitsu Optical Components felt a 400G LR4 module using 7nm PAM-4 silicon could be built both cheaper and lower power than a modified 400G ZR coherent solution.

Short reach coherent technology is still in its infancy but it is expected

to encroach on 10km applications. Operators with a need to reach between 10km and 40km are almost certainly going to migrate to coherent 400G, and non-coherent solutions will not be competitive at distances greater than 10km.

Looking forward to 800G, there was the general consensus that coherent is the only solution for reaches beyond 2km. It's just a matter of time until many client optics go coherent, and the ZR based DSP is the enabling technology.

5G AND FIBER DEEP

Both cable MSOs and mobile operators will need more capacity than 10G optics can provide by 2020. 400G ZR is one possible solution, but in many cases, 400G provides more capacity than necessary. Such situations create an opportunity to repurpose the technology for 100G coherent operation.

Cignal AI estimates that 500,000 10G WDM pluggable modules are still sold each year, yet no viable technology exists today to migrate these 10G applications to 100G. Coherent optics have been too bulky, expensive, and powerful to replace the incredibly compact 10G tunable SFP+ solutions in use. A higher bandwidth solution will be needed soon.

Instead of upcoming 400G ZR solutions, alternatives using lower cost and power 100G coherent would provide an upgrade path for the 500k tunable 10G interfaces sold each year. Comcast detailed its shift to distributed access architectures (or 'fiber deep') in which high capacity digital optics are needed deeper in the network. Bottom line, 100G coherent optics could displace 10G at the right price and power.

Wireless network operators migrating to 5G need to deploy high bandwidth links to connect remote

radios & antennas to centralized baseband units. Operators without plentiful fiber require cheap, low power, high capacity WDM solutions, as highlighted by China Mobile's presentation. 100G coherent for wireless fronthaul/backhaul would be an ideal solution.

600G DSP TECHNOLOGY

Many component and equipment companies unveiled upgrades to coherent DSPs or updates to their technology roadmaps.

ACACIA AND NEL

Acacia and NTT Electronics (NEL) demonstrated new DSP technology in private. Both DSPs support 600G operation and are designed in 16nm silicon, but public details on performance and specifications are allusive. One equipment vendor had the new Acacia DSP in a private system demo. Most notable about this vendor is that it intends to pair the DSP with both silicon photonics and indium phosphide (InP) based solutions for the optics, and it does not see any major differences in performance between the two.

Acacia's DSP is at the heart of several new compact modular systems as well as Acacia's own AC1200 optical module. NEL has equipment and component partners who will bring systems as well as modules to market. Both companies demonstrated working silicon in partner and equipment customer booths and expect to have production silicon by the end of this year. Inphi also announced production availability of its 200G DSP.

NOKIA

Nokia had a major announcement with the arrival of the PSE-3s, its new in-house DSP. Like the products of Acacia and NEL, it supports 600G operation. It differs, however, by incorporating a new technology - Probabilistic Constellation Shaping (PCS). Nokia states that PCS adds an additional optical dB of performance beyond the hybrid-modulation approaches used in the past.
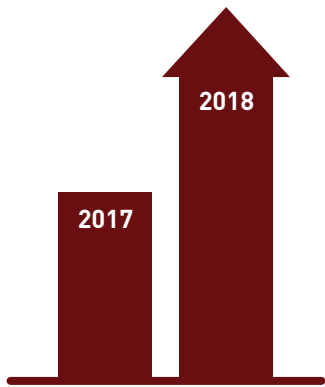
133

EXHIBITOR NEWS RELEASES RESULTED IN

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MEDIA PLACEMENTS — A

66% increase

OVER OFC 2017

It is notable that Nokia has chosen to continue designing its own DSPs rather than purchasing them from Acacia, Inphi, or NEL. Nokia feels doing so enables it to bring to market technology unique from that of other vendors sharing common hardware. This proved true with 200G coherent, as Ciena, Cisco, and Nokia designed their own DSPs and shipped most of the 200G hardware used outside of China during 2017. Each company states that vertical integration and control of the design cycle led to market success.

INFINERA

Infinera announced its fifth generation of coherent technology - the Infinite Capacity Engine or ICE5, also capable of 600G operation. Paired with the Infinera InP photonic integrated circuit (PIC), ICE5 supports 2.4 Terabits of capacity over 4 wavelengths.

Infinera was late in releasing the previous generation ICE4 product, which took longer than planned to bring to volume production. The ICE4 boosted speeds to 200G per wavelength and added much-needed flexibility to its tightly integrated multi-wavelength InP component, but the complexity was a development risk for Infinera.

The new ICE5 represents a more incremental R&D effort with minimal changes to existing InP components. The major difference is the electronics - a new outsourced DSP that supports higher baud rate operation and more complex modulations. The performance of the existing ICE4 PIC can support much higher baud rate operation and can be paired with the latest generation of DSPs to facilitate higher bandwidth. ICE5-based products will be announced later this year and are expected to reach production in 2019.

Infinera also outlined the technology direction of ICE6, which will make use of even higher baud rate operation. The company presented a paper on 100Gbaud coherent operation last fall that provides detail on what the company is working towards. While Infinera outsourced development of the DSP for this generation, speeds exceeding 100Gbaud will still require internal DSP development. The company anticipates a need for tighter integration of the photonics and electronics and expects that the ICE6 will require co-packaging of the DSP and InP based optics.

ADDITIONAL TRENDS AND NEWS

COHERENT COMPONENTS

Several companies announced new components designed to make coherent optics cheaper, smaller and faster. Each either announced or demonstrated monolithic InP devices that incorporate most or all of the optical components needed to build an optical sub-assembly (OSA). These devices are tested and calibrated in the factory, reducing the test and assembly complexity of equipment or module manufacturer customers. One point of annoyance is that none of the companies agree on what to call these devices, which are so similar.

Finisar announced its ITTRA (Integrated Tunable Transmitter and Receiver Assembly) which incorporates a tunable laser, optical amplifier, modulators, coherent mixers and driver electronics. It can support up to 200G 16-QAM operation and is clearly a solution for Huawei's effort to build in-house 200G CFP-DCOs. The device will sample in 2Q18.

Neophotonics claims to be the only company currently shipping 400G discrete coherent optical

components in production. It also announced a COSA (coherent optical sub-assembly) that integrates all of the needed coherent components (except the laser). The Neophotonics COSA is capable of 64Gbaud operation and is designed to pair with 400G ZR DSPs that will prototype late this year.

Oclaro's demonstrated 400G and 600G components including a TROSA (transmit and receive optical sub-assembly) similar to the Neophotonics part, except it includes the narrow linewidth laser. These are follow-on components to its tremendously successful CFP2-ACO designs.

Silicon photonics continues to incite sharp opinions among the component crowd, with every company firmly believing either InP or silicon will be the medium of choice for upcoming 400G ZR solutions.

L-BAND AMPLIFICATION

Once an esoteric technology, L-Band amplification is now moving into the mainstream. Coherent speeds are increasing but at the expense of using more and more optical spectrum. The amount of capacity supported by the C-band is topping out, and fiber-constrained network operators view L-Band as an additional optical spectrum that can delay purchasing or trenching new fiber. Cloud and colo networks are the first targets for L-Band amplification, but companies are seeing strong interest from Cable MSOs as well.

Infinera, Cisco, Ciena, and others are on board, and they used OFC to announce equipment supporting this additional optical spectrum. Specific features mentioned will minimize the additional hardware and complexity needed to work with L-Band. The result should be

new amplifiers, WSS modules, and transponders that can work across the spectrum.

KEY TAKEAWAYS

- 400G ZR interest and investment is increasing as the addressable market for shorter reach coherent links grows. A year ago this technology was generally considered useful only for connecting large data centers, but now it is viewed relevant for links as short as 10km as a replacement for 400G LR4. Even lower cost and power 100G variants for cable MSO fiber deep and 5G backhaul applications are feasible.

- Acacia, NTT Electronics, and Nokia announced or demonstrated 600G DSPs. Acacia prototypes were fresh back from the fab while NTT Electronics devices were already integrated and running in optical modules and equipment.

- Finisar, Oclaro, and Neophotonics announced highly integrated coherent optical assemblies for 600G, 400G ZR, and low-cost 200G DCO coherent module applications.

- Several companies announced L-Band capable components and systems as operators struggle with diminishing gains in optical fiber capacity, even as speeds increase. Cloud and colo, as well as cable MSO operators, received the most interest.

5 400G Inside the Data Center

400G Inside the Data Center

When the conversation at OFC turned to short reach client optics, faster speeds were the central focus. Several companies announced products and gave demonstrations of 400G-capable technology. The 100G speeds and production ramp that had been such a hot topic at OFC 2017 had little follow-on during 2018.

100G QSFP MARKET MATURES

A common belief at last year's OFC was that there would be a shortage of 100G QSFP28 client optics for the remainder of 2017. Hyperscale operators were all migrating simultaneously to 100G inside the data center, and in March 2017 there was not enough supply to meet demand.

And yet, the shortage was not to be. Contrary to all presentations, discussions, and write-ups from last year, the 100G QSFP28 shortfall reversed itself by the end of 2017. At that point, supply of the modules outstripped demand and pricing collapsed as component suppliers strove to move excess inventory.

At the same time, customer preferences shifted away from LR4 and towards lower cost CWDM optics. Some of the shift was due to the more widespread availability of silicon with IEEE 802.3 KR forward error correction (FEC). CWDM optics coupled with KR FEC enabled at the physical layer could reach as far as 10km, thus eliminating the need for LR capable optics. Since CWDM optics cost about a third of the price of LR optics, large cloud operators had a compelling incentive to abandon LR.

At OFC 2018, 100G QSFP28 discussions focused on how individual companies could use their existing technology or market edge to be profitable in today's fiercely competitive market. Oclaro stated that it would focus on selling sub-components to other module assemblers, while Intel turned up the heat by shipping 100G CWDM4 modules in volume. Overall, OFC 2018 attendees acknowledge that the technology for 100G QSFP is mature and harder to differentiate than it is for emerging 400G applications.

400G CLIENT TECHNOLOGY TRENDS

All of the OFC announcements and discussions on short reach interfaces revolved around the various ways to deliver 400G optics. Production is targeted to commence by the end of 2018, with new products designed to reduce cost following 12 months later. Two enabling components are required for 400G speeds to reach high volumes in the data center: Ethernet switch silicon and 2km client optics in a compact form factor.

Ethernet switch silicon will be ready this year and samples have already reached the market. Broadcom arrived first with its Tomahawk 3 (BCM56980) in December 2017, a 12.8Tbs Ethernet switch with 256 integrated 56G-PAM4 I/O. There are also other switch suppliers such as Innovium and Barefoot Networks. Given the relatively mature supply situation of 400G capable Ethernet switches, OFC attendees felt that the determining factors of when 400GbE volumes would ramp would be the availability of optics and the underlying PAM-4 silicon.

PAM-4 SILICON

For decades, all optical signaling was performed using non-return to zero (NRZ) modulation; the direct translation of binary information into the presence or absence of voltage or light. Electrical and optical signals were modulated on and off more and more quickly as speeds increased. This approach eventually broke down in the optical domain at 40Gbs, and the entirely new technique of coherent optical modulation (borrowed from the world of radio) was first introduced by Ciena commercially.

A similar transition is now underway in the electrical domain. PAM-4 uses multilevel electrical signaling to transmit two bits per period with the electrical voltage signaling four levels (0,1,2,3 volts for example) rather than two (on/off). This modulation increases the information rate of an electrical signal operating at 25GBaud from 25 to 50 billion bits a second. The PAM-4 modulation takes place in the I/O of the Ethernet switch chip or in a standalone PHY chip inside, or adjacent to, the optical module.

Inphi was an early technology leader for PAM-4 chips and is in production with 28Gbaud (56G-PAM4) PHY silicon. Broadcom, as well as FPGA companies Xilinx and Altera, also support these speeds. These companies will provide the first generation PAM-4 silicon designed to support 400GbE QSFP56 DD modules with eight optical channels – 400BASE-FR8 (2km) and LR8 (10km). These PAM-4 chips also enable an upgrade of the QSFP28 to 200GbE, a format of interest solely to Google.

Since the costs of optical modules tend to scale with the number of optical channels, one can make the approximation that an eight

lambda module costs about twice what a four lambda module costs. If 400GbE is to be widely adopted, it needs to match the cost of existing 100G QSFP28-based solutions that are four lambdas. The current generation of PAM-4 doesn't allow this, and the consensus is that FR8 and LR8 optical formats are not destined to be high volume solutions as a result.

> OFC is very important for the OIF and for the OIF members because it is the largest global event in the world. It's that annual event where everybody gets together. If you want to communicate the latest thing that you're doing, if you want to understand the market needs or gaps, this is where you come to find that out. This is where all your customers are, all your suppliers are.

NATHAN TRACY, TECHNOLOGIST, SYSTEM ARCHITECTURE TEAM AND MANAGER OF INDUSTRY STANDARDS, TE CONNECTIVITY; VICE PRESIDENT OF MARKETING, OPTICAL INTERNETWORKING FORUM (OIF)

There was a lot of buzz at OFC 2018 over announcements and technology demonstrations for the next speed iteration of PAM-4, which enables 400GbE over four lambdas. This iterative step requires doubling the baud rate on the optical side from 28Gbaud to 53Gbaud, thereby allowing a single lambda to carry 100Gbs of information. Bringing production grade silicon and optics to market over the next year is imperative for companies who want to be part of the transition to high volume 400GbE speeds at the end of 2019.

At least six companies are actively developing 53Gbaud PAM-4 silicon: Broadcom, IDT, Inphi, MACOM, Maxlinear and Semtech. Maxlinear

announced sampling of this silicon in January and Inphi announced the same at OFC this March. MACOM is also currently sampling, and it's a safe bet that at least several companies will have working production silicon by the end of 2018. PAM-4 silicon availability should allow 400GbE solutions based on single lambda 100G to hit the market in 2019, thereby kicking off the next high volume transition of Ethernet speeds to 400G.

400G OPTICAL MODULES

A host of companies demonstrated first-generation 400G optical modules in FR8 and LR8 formats at OFC 2018. These optics rely on readily available 28Gbaud PAM-4 silicon that transmits eight wavelengths using directly modulated lasers (DMLs). Finisar states that DML technology is a low-power, low-risk solution designed to get 400GbE to market this year, and other companies like Applied Optoelectronics would readily agree. Examples of this format were rampant on the show floor in both QSFP-DD and the larger CFP8 format. Several companies such as Kaiam and Finisar demonstrated active optical cables as well. All of these modules will be in production later this year and will allow data center operators to begin deploying 400GbE.

Remember, the four lambda client is now the low-cost, high volume endgame for 400GbE optics. Two target standards are the FR4 (2km) and LR4 (10km). Aside from the challenge of available low-power PAM-4 silicon to support the necessary 53 GBaud rate, there are significant hurdles with the optics. The requisite signal bandwidth of 53Gbaud PAM-4 eliminates the possibility of using DML lasers and requires the use of externally modulated lasers (EMLs).

EML's higher performance comes with greater power and complexity and is difficult to implement within the small confines of a QSFP-DD optical module.

Companies made use of OFC to demonstrate the ways in which they would overcome these challenges. Applied Optoelectronics, long a purveyor of DML solutions, presented its new EML laser technology designed to bridge its 100G-focused product line into the 400G era. Neophotonics announced a new module that integrates EML lasers, laser drivers, and receiver circuits as an all-in-one solution for companies seeking to assemble QSFP-DD LR4 modules. Finisar, Lumentum, Oclaro, Mitsubishi, and many more also had working prototypes of FR4 and LR4 QSFP28 modules.

Intel presented an interesting twist that leverages its silicon photonics heritage. It is championing an eight lambda CWDM solution for 400GbE called CWDM8 and has formed a consortium including companies like Applied Optoelectronics, Rockley Photonics, and Hisense. Intel feels its silicon photonics expertise lends itself to a low cost eight lambda solution with the performance to potentially reach as far as 10km. The design leverages its 100G CWDM4 product but uses a higher bandwidth design, adding in PAM-4 modulation and doubling the number of wavelengths.

Intel's approach illustrates the rising competition between silicon photonics and InP based designs, and it will be exciting to see which technology ultimately succeeds. Four lambda 400GbE optical technology is transitioning out of the lab and into customers' hands for evaluation, and by OFC 2019 it will be more apparent which companies and technologies have an edge.

QSFP-DD VS OSFP: SETTLED

The question of which module format – QSFP-DD or OSFP – would win out for 400GbE sparked debate at OFC 2017. Today, considering the investments already made and the work underway, it appears that QSFP-DD has won the debate. As long as QSFP-DD can deliver 400GbE operation across a variety of reaches and formats (which it now appears it can), companies and customers are hesitant to switch formats to OSFP.

Every module company is now working towards QSFP-DD for its 400GbE designs, including the toughest specification of them all—400G ZR. Companies commented that OSFP had more space and thermal margin and converting to that format would be easier than initially designing for OSFP and then having to then squeeze into a more constrained QSFP-DD module. Additionally, the QSFP-DD MSA group chose OFC to release a new thermal study indicating that QSFP-DD could operate as high as 15W. Even Arista CTO Andy Bechtolsheim, a long time supporter of OSFP, conceded the performance of QSFP-DD would suffice for 400GbE, with the exception of applications using AWG26 copper cable interconnect.

Yamaichi, a prominent connector manufacturer, said that the next speed transition – 800GbE – will obsolete QSFP-DD because the electrical specifications won't be able to handle another speedup to 100 GBaud. 800GbE is the opportunity for OSFP to enter the market, though such a transition is probably at least three years away.

KEY TAKEAWAYS

- Despite enthusiasm at OFC 2017 for an extended run of positive returns, challenging profit margins arrived quickly in the 100GbE optics market. Companies are now trying to gain better leverage on existing investments, including exiting some product types and consolidating businesses.

- Eight lambda LR8 and ER8 400GbE solutions will reach the market this year, but a cost reduction is needed to trigger a mass migration from 100GbE in hyperscale applications. The four lambda LR4 and ER4 formats are the likely formats.

- There is an abundance of investment in PAM-4 DSPs with at least six companies developing silicon for the high volume LR4 and FR4 400GbE formats. This abundance will be positive for accelerating availability though it is clear not all these companies can get a return on their investment.

- Intel and others are trying to find other ways to solve the 400GbE client optics problem. Intel's approach leans heavily on its 100G CWDM solution that is now in production. There is a lot of room for further innovation in this market.

- The OSFP vs. QSFP-DD format war is over. QSFP-DD won, but future 800GbE speeds will require a new approach.

Outlook for 2018

Through its many meetings, discussions, and presentations among customers, vendors, and engineers, OFC sets the stage for the coming year. Here's what you should watch:

- **Open transponders and line systems.** Some operators, particularly cloud and data center providers, continue to move in the direction of disaggregating the optical networking hardware in their networks. Equipment and component vendors have adapted their products to meet these requirements and are now bringing hardware and software solutions tailored to these markets. These suppliers will need to remain agile and adjust to the changing network deployment models used by operators of all types.

- **Evolving technology for 400G client optics.** 400GbE optics are on track for production this year, but more work is needed to bring the cost down to a point where they can displace 100GbE. Reducing costs may involve additional power, space and price improvements as well as moving PAM-4 silicon to 7nm. Companies will seek out any edge they can to position their solution favorably for the transition to 400GbE in late 2019.

- **Coherent innovation in the metro access and edge.** 400G ZR is an area to watch in optics as more applications become apparent for this nascent technology. The business case for expensive 7nm DSP developments is improving,

and optical component vendors have an opportunity to address multiple markets beyond data center interconnect. The technology is on track to provide a 100G upgrade path for 10G at the edge of the network and potentially displace the venerable 10km LR client optics standard.

- **Vertical and horizontal consolidation.** Challenging profit margins have already arrived in the relatively new 100GbE optics market, forcing industry participants to look hard at next-generation investments. Unlike other parts of the networking ecosystem where a handful of vendors account for most of the market, the optical components and equipment market is fragmented. Fragmentation leaves companies without the critical mass to make the increasingly larger up-front investments in 7nm silicon and new fab and test processes. Expect to see more vertical and horizontal consolidation so that companies are better assured a return on the risks they take.

- **Impact of 5G on optical communications.** A new topic this year was the evolution and development of optical networking component, equipment, and service assurance technologies in order to make wireless 5G deployment a

reality. Ericsson, Huawei, Nokia and ZTE are all shipping pre-standard 5G technologies for evaluation, testing and field trials. Because 5G mobile network technologies offer the potential of 30 to 50 times faster speeds than 4G, the development and deployment of 5G requires substantial deployment of more optical networking technology than previous wireless generations. Air-interfaces and radio access network (RAN) architectures must be completely redesigned to accommodate 5G and because of bandwidth and latency requirements, new optical backhaul and front haul network architectures will be required to service more closely distributed microwave points of presence. Companies will develop new technologies that can meet the rigorous environmental and economic requirements of this challenging but sizable market.

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Ltd. • Ningbo Zhantong Telecom Equipment Co., Ltd. • Nippon Electric Glass Co., Ltd. • Nissin Kasei USA Corp. • Nistica, Inc. • Nitto Optical Co., Ltd. • Nokia • Norland Products, Inc. • Notice Co., Ltd. • Novoptel GmbH • nPoint, Inc. • NTT Advanced Technology Corporation • NTT Corporation • NTT Electronics America, Inc. • NTT Electronics Corporation • Nuferm • Nuphoton Technologies Inc. • nVoloro, Inc. • OE Solutions, Co., Ltd. • OFS • O2Mentum, Inc. • O-Net Communications (Shenzhen) Ltd. • Open-Silicon • Opneti Communications Co. • Opt Gate Co., Ltd. • OpTek Systems, Inc. • Optelian Access Networks • Optella, Inc. • Optient, Inc. • OptiGalaxy, LLC • Optic River Communication, Ltd. • Optical Connections • Optical Fiber Test & Measurement Center • Optical Internetworking Forum • OptiLab, LLC • Optivave Systems, Inc. • OptiWorks, Inc. • Opto Marine Co., Ltd. • OPTOKON • Optoplex Corporation • OptoScribe Ltd. • OptoTest Corporation • Optoway Technology, Inc. • Optqwell Co., Ltd. • Optwide Technologies Co., Ltd. • Optronics Co., Ltd. • The Optrum Technology • Opwill Technologies (Beijing) Co., Ltd. • Orte Photonics Co., Ltd. • OSA – The Optical Society • OSA – The Optical Society Research & Program Development • OSI Laser Diode Incorporated • OSI Optoelectronics, Inc. • Otrans Communication Technologies (Hangzhou) Co., Ltd. • Oxcent Technologies Co., Ltd. • OXC Technologies Co., Ltd. • Oxford Fiber, Ltd. • Oz Optics • Pacific Microchip Corp. • PacketLight Networks Ltd. • Palomar Technologies, Inc. • Passive Plus, Inc. • PE Fiberoptics Limited • Peak Optoelectronics (Suzhou) Co., Ltd. • PETRA • PFC Flexible Circuits Ltd. • Philips GmbH U-L-M Photonics • PhoeniX Software • Phononic • Photon Delta • Photon Design • Photon Kinetics, Inc. • Photonic Lattice, Inc. • Photonics Media/Laurin Publishing • PI (Physik Instrumente) LP • Piconics • Piezoelectric Technology, Co. 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Ltd. • Tri-light Wuhan Electronics Technology Co., Ltd. • TRS-RenTelco • U-Flex Co., Limited • ULTRA TEC Mfg., Inc. • Unioriental Optics Co., Ltd. • US Conec, Ltd. • Vectrawave • Veex, Inc. • VERTILAS GmbH • VI Systems GmbH • ViaSat, Inc. • Viavi Solutions • Viking Technology a Division of Sanmina Corp. • Vishay Intertechnology • Vitex LLC • VLC Photonics S.L. • Vlink Optics Corporation • VPIphotonics • W2 Optronics, Inc. • Wanjun Engineering SDN BHD • Waveoptics • Way Optics • Wen Global Solutions • WingComm • Woonro Co., Ltd. • Wuhan Aroptics-Tech Co., Ltd. • Wuhan HuaGong Genuine Optics Tech Co., Ltd • Wuhan RayOptek Co., Ltd. • Wuhan Yi Valley Optoelectronic Technology Co., Ltd. • Wuhan Yilut Technology Co., Ltd. • Wuhan Yusheng Optical Devices Co., Ltd. • Wuxi Taclink OptoelectronicsTechnology Co., Ltd. • XDK Communication Equipment (Huizhou) Co., Ltd. • Xelic • XFS Communications, Inc. • Xgiga Communication Technology Co., Ltd. • Xiamen Beogold Technology Co., Ltd. • Xiamen San-U Optronics Co., Ltd. • Xilinx, Inc. • XTXH Precision Tooling (Shenzhen) Co., Ltd. • Yamamura Photonics Co., Ltd. • Yangtze Optical Fibre & Cable Joint Stock, Ltd.,Co. • Yelo Limited • Yenista Optics • Yokogawa Corporation of America • Yueqing Reepure Technology Co., Ltd. • Yuetsui Seiki Co., Ltd. • Yuyao Huijia Communication Equipment Co., Ltd. • Zeus, Inc. • ZGT Optical Comm Limited • Zhejiang Guangda Pute Communication Technology • Zhejiang Guangsu Communication Technology CO. • Zhejiang Jiawei Communication Equipments Co., Ltd. • Zhongshan Meisu Technology Co., Ltd. • Zhuzhou Jiabang Refractory Metal Co., Ltd. • ZTE Corporation • ZTT International Limited

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San Diego, California, USA