Coherent 100 Gb/s PM-QPSK Field Trial

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ABSTRACT

The development of 100 Gb/s transponder technology is progressing rapidly to meet the needs of next-generation optical/IP carrier networks. Video-driven IP traffic growth continues together with the need for ever higher-speed ports on IP routers, Ethernet switches, and OTN cross-connects, thus driving the requirements for cost-effective client and line side 100 Gb/s transponders. For a short time to market, 100 Gb/s transponders should be deployable using 10 Gb/s link-engineering rules over existing fiber and DWDM infrastructure. In this article we describe the upgrade of an installed 10 Gb/s field system to 100 Gb/s using a real-time single-carrier coherent 100G polarization multiplexed quadrature phase shift keyed (PM-QPSK) channel. Performance sufficient for error-free operation after forward error correction was achieved over installed 900 km and 1800 km links, proving the viability of 100 Gb/s upgrades to most installed systems. Excellent tolerance to fiber polarization mode dispersion and narrowband optical filtering demonstrates the applicability of this technology over the majority of installed fiber plant and through existing 50 GHz reconfigurable optical add/drop multiplexers.

INTRODUCTION

Since 2005, to keep up with growing traffic demands in core networks, carriers have upgraded their existing 10 Gb/s designed links with 40 Gb/s channels [1]. As network demands continue to grow rapidly, carriers will have to explore the possibilities for further network upgrades. An important question is, with 100 Gb/s on the horizon, is it practical to upgrade these existing networks with 100 Gb/s channels? A critical enabler for the 40 Gb/s network upgrades was the introduction of advanced modulation formats, allowing the retrofit of 40 Gb/s data channels into existing 10 Gb/s dense wavelength-division multiplexed (DWDM) transport systems. Modulation formats such as optical duobinary (ODB), differential phase shift keying (DPSK), differential quadrature phase shift keying (DQPSK), and polarization multiplexed quadrature phase shift keying (PM-QPSK) have all been deployed in carrier networks. One common property of these modulation formats is the support of 50 GHz DWDM channel spacing. Earlier 40 Gb/s modulation formats that did not support 50 GHz channel spacing were not deployed, since a primary driver for deploying higher line rates is to improve spectral efficiency and thus maximize capacity on existing DWDM systems and fiber pairs. At 100 Gb/s, improved spectral efficiency to meet Internet and video traffic growth is again expected to be a key stimulus, with support of 50 GHz channel spacing still a key requirement. To facilitate ease of networking, tolerance to transmission through many reconfigurable optical add/drop multiplexer (ROADM) nodes is also essential, as express channels will often transit through a large number of these ROADM nodes. Each ROADM permits each wavelength channel to be added, dropped, or passed through at that node, completely in the optical domain (i.e.,, not converted to an electronic signal). Thus, each ROADM acts as an optical filter, constraining the bandwidth of the DWDM signals.

For 100 Gb/s, significant research has been done recently on advanced modulation formats (e.g., 8-PSK/quadrature amplitude modulation [QAM], 16-QAM, 36-QAM [2–4]). Coding more than 1 b/symbol is essential to reduce the spectral width of the signal. At 100 Gb/s, it is necessary to code at least 3 b/symbol to narrow the spectrum sufficiently to operate through 50 GHz filters. For this trial we use the PM-QPSK modulation format that codes 4 b/symbol (modulating each of two orthogonal polarization tributaries with both in-phase and quadrature-phase components). The spectral width of 100 Gb/s PM-QPSK is sufficiently narrow to allow use of powerful forward error correction (FEC) with a 20 percent overhead [5, 6]. Although the FEC increases the line rate, symbol rate, and spectral width of the signal, the signal can still propagate through multiple cascaded 50 GHz ROADMs with adequate performance. The FEC with higher coding gain enables improved optical signal-to-noise ratio (OSNR) sensitivity and thus longer reach (propagation distance) between optical-to-electrical-to-optical (OEO) regeneration points, thereby reducing the network cost.

Another advantage of PM-QPSK is the significant effort on implementation agreements undertaken recently by the Optical Interworking

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Forum (OIF) [7]. The OIF members are in or near agreement on many of the necessary hardware blocks and interfaces to support these modulation techniques. The OIF implementation agreements have not included FEC and the digital signal processing (DSP) following the coherent detection, for now leaving these two areas open for vendor innovation. Thanks to Moore's law, massive DSP functionality can be integrated today into a single chip [8], even at 100 Gb/s. Furthermore, using coherent detection, the full E-field of the signal can be measured in the receiver, leading to excellent tolerance to linear impairments, such as chromatic dispersion (CD) and polarization mode dispersion (PMD) [9]. These impairments can now be compensated in the electronic domain, making 100 Gb/s practical even on older fiber plant.

This article describes test results obtained in a laboratory and then in a field environment indicating the suitability of this 100 Gb/s PM-QPSK technology for upgrades of backbone DWDM networks. For clarity, while these transport systems are colloquially referred to as "100G," their purpose is to transport a payload of 100 Gigabit Ethernet across many kilometers. To do so they add some overhead (such as the FEC mentioned above and others), so the actual signaling rate (or line rate) is higher. In our case the line rate was 126.5 Gb/s.

SYSTEM DESCRIPTION

TECHNOLOGY ATTRIBUTES OF 100G B/S PM-QPSK

OSNR Sensitivity — Coherent PM-QPSK offers approximately 6 dB improvement in OSNR sensitivity compared to binary on-off keying (OOK) for the same bit rate. As 100 Gb/s is 10 times higher capacity than 10 Gb/s, any new 100 Gb/s modulation scheme would ideally offer a 10 dB performance improvement, providing a comparable OSNR sensitivity to 10 Gb/s OOK. Although difficult to achieve in practice, part of the performance shortfall can be recovered by the use of a high-coding-gain soft decision forward error correction (SD FEC) [10]. Depending on the particular algorithm, soft bit resolution, and overhead rate selected, another 2–3 dB gain can be realized compared to the typical 7 percent overhead enhanced FEC codes [11]. The rest of the shortfall can be made up by reduction in penalty allocations. In 10 Gb/s OOK systems, there is often a penalty of 1 dB or more allocated for imperfect CD compensation, and a similar penalty allocated for PMD. A key advantage of coherent detection is that the electromagnetic phase information is passed into the electronic domain, so powerful electronic dispersion compensation (EDC) in the DSP can mitigate the distortions with very low residual penalty. Therefore, by using 100 Gb/s PM-QPSK with SD FEC and EDC, there is a 6 dB improvement for coherent detection, a 2–3 dB improvement for SD FEC, and a 1–2 dB improvement due to reduced CD and PMD penalties. This results in a total improvement of 9–11 dB, approaching the OSNR sensitivity of 10 Gb/s OOK systems, thus allowing 100 Gb/s PM-QPSK to be deployed with a comparable reach to current 10 Gb/s OOK systems.

Optical Filtering Tolerance — Due to their 10 Gbaud symbol rate, 10 Gb/s OOK channels have a much narrower spectral width than the 50 GHz channel filters used in DWDM systems. This provides excellent tolerance to cascades of ROADMs (i.e., with negligible penalty after transmission). Similarly, to ensure good ROADM tolerance at 100 Gb/s, a sufficiently low symbol rate is required, since the spectral width of the signal scales with the symbol rate. Using 100 Gb/s PM-QPSK (~25 Gbaud) provides a clear advantage over higher symbol rate formats. Coding even more bits per symbol results in a denser signal constellation and leads to reduction in OSNR sensitivity. A 100 Gb/s PM-QPSK signal can tolerate filter bandwidths below 30 GHz with minimal penalty, significantly better than direct detection DQPSK and OOK formats. This exceptional filtering tolerance allows deployment through a large number of ROADMs. Using a higher-level coding scheme, with a resulting drop in OSNR performance, is not necessary. Reducing the symbol rate has other practical advantages, such as easing the implementation of the modem in a complementary metal oxide semiconductor (CMOS) chip, and reducing the bandwidth requirements for the electro-optic components. However, using higher complexity constellations to further lower the symbol rates places more stringent requirements on signal and local oscillator laser line widths and reduces nonlinear phase noise tolerance. All of these trade-offs must be considered when choosing a modulation format.

With EDC inside the modem chip, CD can be compensated without optical tunable dispersion compensators. The amount of CD that can be compensated inside the chip is a function of the number of taps in the Finite Impulse Response (FIR) adaptive filter and the time delay of each tap.

Chromatic Dispersion Tolerance — With EDC inside the modem chip, CD can be compensated without optical tunable dispersion compensators. The amount of CD that can be compensated inside the chip is a function of the number of taps in the finite impulse response (FIR) adaptive filter and the time delay of each tap. Installations of 10 Gb/s DWDM systems primarily utilize dispersion compensating fiber (DCF) deployed throughout the network to limit the residual CD at the 10 Gb/s OOK receiver to within ±400 ps/nm (typically) for long-haul systems. It is quite straightforward to meet this range in a 100 Gb/s PM-QPSK EDC with a small number of taps. However, if the system could be designed without DCF, it could have significant improvements in performance. Usually a small spool of DCF, built in a dispersion compensating module (DCM), is installed with each optical amplifier. DCF is special fiber with larger CD than the transmission fiber and of opposite sign. As a result it has higher loss per unit length and a smaller core diameter. Given these characteristics, a line system with DCF needs more amplification (adding more noise) and will introduce more penalties due to nonlinear interactions within the DCMs than a system without DCF. Since each DCM must be matched to the specific length and type of transmission fiber in the preceding span, installation and maintenance of DCF-free systems would also be simplified. In

PMD-mitigating algorithms can handle very fast changes in either the received state of polarization or the instantaneous value of the PMD because the tap coefficients are updated at a rate on the order of the clock frequency of the DSP.

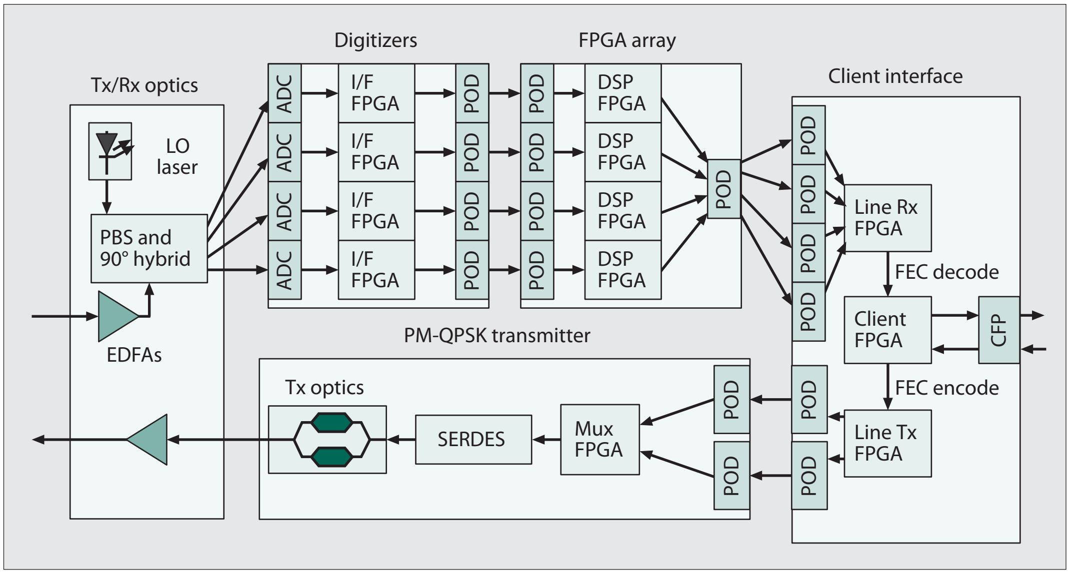

Figure 1. Block diagram of transponder. LO = local oscillator, PBS = polarization beam splitter, POD = parallel optical (interface) device, I/F = interface.

addition, carriers are interested in reducing latency in their networks to improve the performance of delay-sensitive telecommunications applications, such as Internet gaming and network storage.

For these reasons, carriers would prefer to eliminate DCF for next-generation transport networks. Eliminating DCF greatly increases the required dispersion tolerance, particularly for standard single-mode fiber (SSMF, G.652) links, and greatly impacts the EDC complexity, as a large number of taps are now required to fulfill the required dispersion tolerance. Higher EDC complexity increases the chip gate count, which in turn increases chip power consumption and reduces yield.

Polarization Mode Dispersion (PMD) Tolerance — The EDC can also mitigate PMD without optical PMD compensators. The number of taps needed for PMD mitigation is relatively small, as the pulse energy distortion from PMD only spills into a few adjacent time slots. One key parameter for PMD mitigation is that it must be fast enough to track the rapid polarization dynamics that can occur in carrier networks [12]. This is in contrast to CD compensation, which is more static, changing very slowly and by small amounts due to variations in the fiber temperature. Fortunately, PMD-mitigating algorithms can handle very fast changes in either the received state of polarization or the instantaneous value of the PMD because the tap coefficients are updated at a rate on the order of the clock frequency of the DSP.

FPGA-Based Prototype

A prototype development system using existing high speed analog-to-digital converters (ADCs) from digital sampling oscilloscopes and a field programmable gate array (FPGA) farm for digital data processing was built to assist in product development and enable early testing. Key functional blocks were included such as carrier frequency and timing recovery, carrier phase estimation, EDC of CD and PMD, and high-coding-gain FEC. The primary purpose of this system was to test and iterate the modem logic prior to taping out an application-specific integrated circuit (ASIC) chip, as using FPGAs allows the designer to optimize and reprogram the logic to optimize performance prior to finalizing the ASIC net-list. FPGAs offer the next level of performance evaluation beyond using offline processing techniques that capture a short data sequence on an oscilloscope and post-process on a personal computer. A key challenge for the FPGA-based prototype system was to stream the data at 126.5 Gb/s in real time and fully process all data at the line rate in the modem, requiring advanced synchronization of the ADCs and FPGA farm. The real-time single-carrier coherent PM-QPSK system block diagram is shown in Fig. 1. The symbols were carved into 67 percent duty-cycle return-to-zero (RZ) pulses. Using an RZ-pulse format rather than non-return-to-zero (NRZ) provides greater tolerance to single-channel fiber nonlinear effects, improving propagation performance. The coherent receiver system consisted of four high-speed ADCs to digitize the data followed by an FPGA farm to perform the DSP [9]. A single 2 × 2 equalizer, consisting of 8 taps, was used for polarization state demultiplexing and CD and PMD compensation. The equalizer size was limited by the FPGA implementation. The reduced number of taps in the equalizer means that the FPGA-based prototype had lower CD tolerance (approximately 400 ps/nm) than an ASIC-based solution, so system testing did require the use of dispersion compensation fiber (DCF). The data rate used in the trial was 126.5 Gb/s (31.625 Gbaud), corresponding to the 100GE payload, mapped into the OTU4 frame plus 20 percent overhead for high-coding-gain FEC [5, 6]. Both $2^{15} - 1$ and $2^{31} - 1$ pseudo-random bit sequences (PRBS) were used, and negligible pattern dependency was observed after transmission. Bit error rate (BER) data was collected via an integrated BER analyzer measuring the aggregate 126.5 Gb/s signal after the DSP block. Differential encoding and decoding was utilized for the results presented here to improve the performance in the presence of on-off-keyed signals.

Figure 2 shows the measured BER vs. OSNR taken back to back where the amplified spontaneous emission noise loading has been added between two optical filters (mux and demux) each with a 3 dB bandwidth of 40 GHz. The OSNR is reported with a 0.1 nm noise bandwidth. The OSNR sensitivity of the FPGA-based prototype has some additional implementation penalties compared with the estimated performance of an ASIC-based solution. The prototype system implementation penalties are a result of poorer ADC performance and lower gate count available in the FPGA farm to implement the DSP compared to an ASIC. The prototype performance does allow for testing of fiber propagation and the modem algorithms at full line rate, which is its primary purpose. The FPGA-based prototype is managed by a dedicated PC using a MatLab graphical user interface (GUI). The system has several integrated automation processes implemented to facilitate simple turn-up and automatic calibration. These include data path skew alignment, relative ADC delay synchronization, core frequency adjustment, gain control, and recombining line-side data stream in real time. The application software is capable of software/firmware management of all modules in the system.

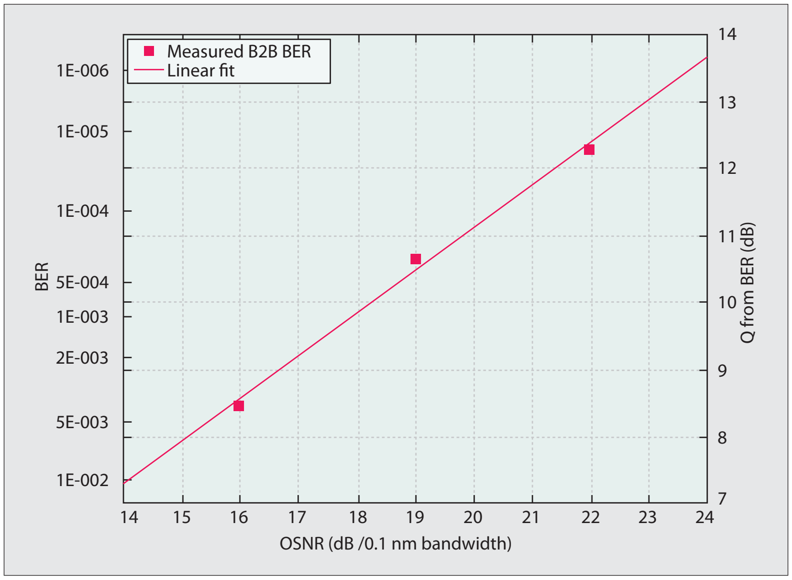

Figure 2. Measured back to back BER performance versus OSNR of the 126.5 Gb/s coherent PM-QPSK system.

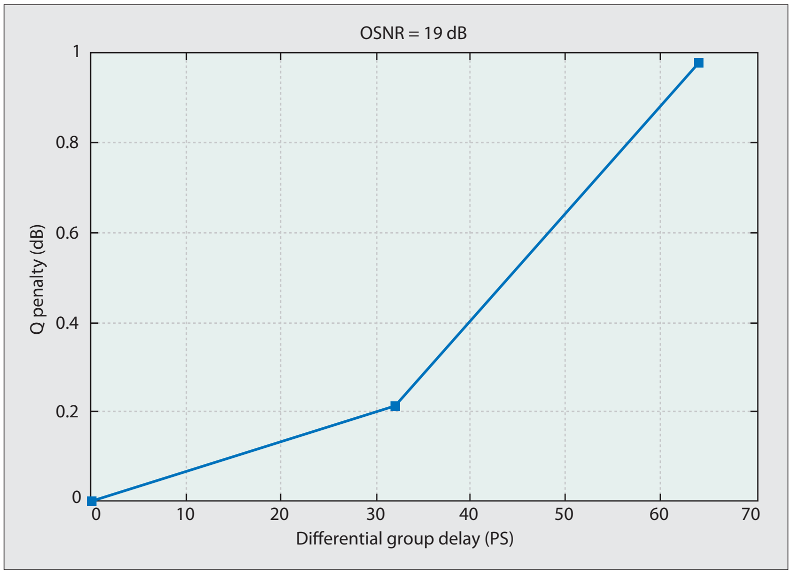

Figure 3. PMD tolerance of a 100 Gb/s PM-QPSK system.

LABORATORY RESULTS

PMD TEST RESULTS

In order to test the PMD tolerance of the 100 Gb/s prototype system, two lengths (32 ps and 64 ps) of polarization maintaining fiber (PMF) were used to vary the differential group delay (DGD) in the laboratory testbed. The launch state of polarization was set at the worst case of 45° to equally split the power between the fast and slow axes. The resulting penalty was derived by monitoring the pre-FEC BER and comparing the result with DGD = 0ps. The 100 Gb/s PM-QPSK signal was noise-loaded to an OSNR of 19 dB/0.1 nm for each test case. The results are shown in Fig. 3. Although the FPGA based 100Gb/s prototype does have a somewhat larger residual PMD penalty than that expected with the ASIC-based product, these results still demonstrate very high PMD tolerance, larger than 10 Gb/s OOK signals, and therefore show the applicability of this 100 Gb/s technology for older generations of fiber plant with up to 20 ps of mean PMD, assuming a PMD outage probability of 10^{-5}.

OPTICAL FILTERING TEST RESULTS

To test the suitability of 100 Gb/s PM-QPSK for networking applications with multiple cascaded ROADMs, it is important to understand the optical filtering tolerance. The testbed was reconfigured to replace the PMD elements by a tunable-bandwidth optical filter. The optical filter shape approximates a second order super-Gaussian profile and the full width at half maximum (FWHM) was varied over a range of 25–44 GHz. For each test case, noise-loading was used to keep the OSNR constant at 19 dB/0.1 nm and the penalty derived from the resultant pre-FEC BER. The results are shown in Fig. 4. These results indicate that the optical filtering bandwidth can be as low as 30 GHz with negligible penalty, and at 26 GHz FWHM the penalty measured was approximately 0.5 dB. This indicates that 100 Gb/s PM-QPSK signals are thus suitable for 50 GHz DWDM systems and have sufficient filter tolerance to enable cascading multiple 50 GHz ROADMs in carrier networks [13].

FIELD TRIAL LINK DESCRIPTION

While many tests can be adequately performed in the laboratory, field trials impose more rigorous requirements on the equipment. For example, the only communication between network

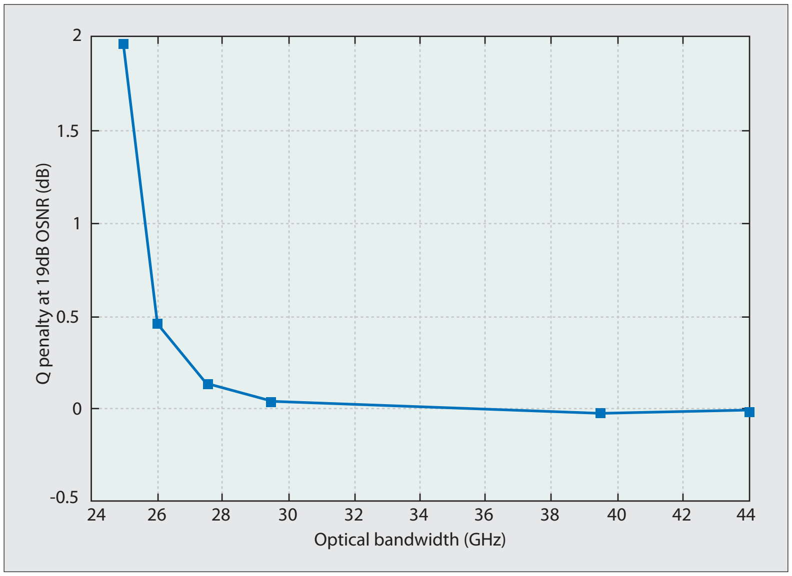

Figure 4. Optical filtering tolerance of a 100 Gb/s PM-QPSK system.

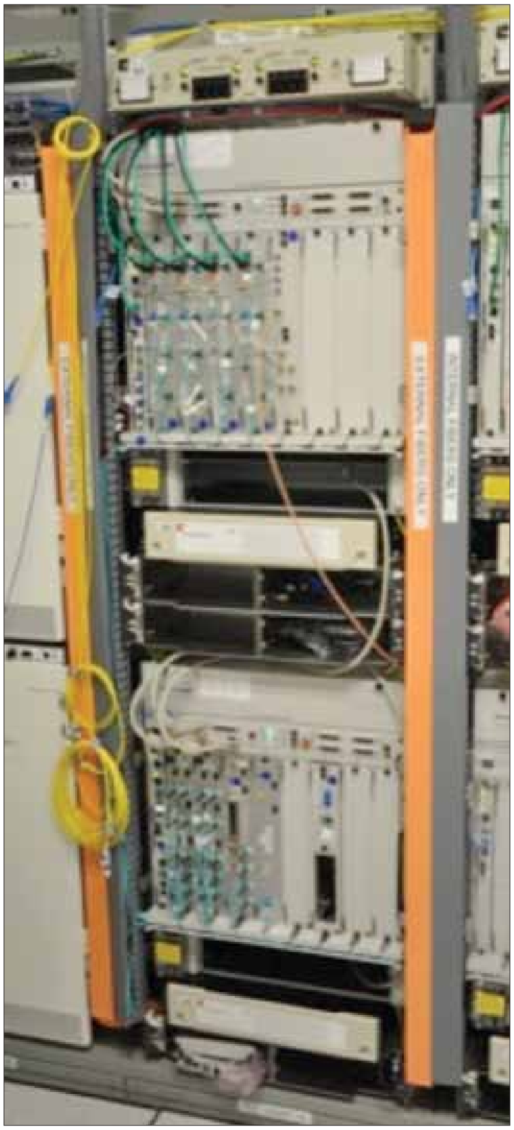

Figure 5. Photograph of the 100 Gb/s PM-QPSK prototype system in the field.

elements must be over the transmission link; no management signaling over side channels can occur, and no clock or other synchronization signal can be shared by the two ends. The turn-up procedure, which with a DSP-based coherent receiver includes blind equalization of CD and PMD, must deal with the unknown characteristics of the transmission line. During operation, the system must automatically adjust for changes in the CD (and therefore the propagation delay) and PMD, both slow and fast. And finally, many aspects of the high-speed optoelectronic components and circuits vary with temperature. By housing each end of the system in different cities, the temperatures are not only different, but vary independently, further stressing the hardware design.

This field trial was conducted over a portion of the existing AT&T network between Florida and Louisiana. This 900 km link consisted of 12 spans of SSMF, where the average span length was 78 km and the average span loss was 16.5 dB, typical of fiber spans in a long-haul terrestrial network. The line system deployed on the link is optimized for 10 Gb/s and 40 Gb/s, and began carrying real service in the AT&T network soon after the trial was completed. In other words, the link was not installed or optimized in any way for the purpose of the 100 Gb/s trial. In addition, the optical link control ran in automated mode, dynamically adjusting the amplifiers to be at the optimum operating point. Standard two-stage C-band Erbium-doped fiber amplifiers (EDFAs) were used to compensate for the fiber loss. The CD of the transmission line was compensated with a DCM at the mid-stage of each EDFA to provide approximately 96 percent compensation for each fiber span. There was no precompensation for the CD at system input or further optimization for the CD before the receiver using optical dispersion compensation. The average PMD of the transmission line was measured to be 0.04 ps/(km$^{1/2}$). With 0 dBm launch power for the 100 Gb/s channel, after 900 km, the received OSNR was approximately 21 dB, and approximately 18 dB for the 1800 km optical loopback link. Figure 5 shows a photograph of the 100 Gb/s PM-QPSK prototype system in the field.

Field Trial Results

900 km Link

We measured the transmission performance of the single 100 Gb/s channel for both directions of the 900 km link, and as expected based on the very similar properties of the fiber spans and EDFAs, the performance was almost identical. For the single 100 Gb/s channel, as shown in Fig. 6, we measured the BER after 900 km transmission as the launch power into each SSMF span was varied. The launch power into each DCM was held constant at 0 dBm, which is known to be suboptimal, but was a limitation of the trial. Figure 6 shows that the optimal fiber launch power was around 1 dBm, with the range of 0–3 dBm resulting in similar performance. Performance at a pre-FEC BER level below 1e-2 yields error-free post-FEC operation using the latest 20 percent overhead hard- or soft-decision

FEC algorithms [5,6]. For the 900 km link, the 100 Gb/s channel passed through three ROADM nodes (one at each terminal site plus one in the middle). Previous testing using offline processing had shown that the 100 Gb/s PM-QPSK signal can pass through a large number of ROADMs (> 10) with minimal penalty [13].

In addition to testing the tolerance of the single 100 Gb/s channel to launch power variation, it is important to understand the impact of nonlinear impairments caused by adjacent channels, as could occur in a DWDM system with channels carrying 10, 40, or 100 Gb/s. Figures 7 and 8 show the effect of adjacent 50 GHz symmetrically spaced 40 Gb/s DPSK and 10 Gb/s OOK channels on the 100 Gb/s channel in the center of the group, respectively. The launch power for all channels was 0 dBm/channel for these measurements. Pre- and post-compensation of –80 ps/nm and –200 ps/nm, respectively, were added to the link to optimize the 10 Gb/s and 40 Gb/s channel performances, resulting in a nominal 0 ps/nm residual dispersion after 900 km. With up to four neighboring 40 Gb/s DPSK channels at 50 GHz spacing, the Q penalty of the 100 Gb/s channel was within 0.6 dB of its single-channel performance. However, the impact of the 50 GHz spaced 10 Gb/s OOK channels on the 100 Gb/s PM-QPSK channel was severe and can be attributed to the strong nonlinear cross-phase modulation. Increasing the channel spacing to 100 GHz alleviated the degradation somewhat, as shown in Fig. 8. A carrier phase estimation (CPE) filter length of 20 symbols was used for all measurements discussed above. It is expected that reducing the CPE length would improve the 100 Gb/s performance with adjacent 10 Gb/s and 40 Gb/s channels [14]. We also measured the impact of a 100 Gb/s channel placed between two 100 GHz spaced 40 Gb/s DPSK or 10 Gb/s OOK channels for the 900 km link. As summarized in Table 1, the results indicate that the 100 Gb/s channel has little impact on either 10 Gb/s or 40 Gb/s neighboring channels.

1800 km Optical Loopback Link

We also measured the performance of the 100 Gb/s channel over an 1800 km link with five ROADM nodes by optically looping back the signal in Louisiana. Pre- and post-compensation of –480 and –450 ps/nm, respectively, were used for the link, resulting in a nominal residual dispersion of 0 ps/nm. The results are summarized in Figs. 9–11. Figure 9 compares the measured BER of the single 100 Gb/s channel at one launch power to simulation results for many launch powers. The launch power for the 1800 km link, restricted by the fixed 0 dBm launch power into the DCM, was set to be around 0.5 dBm, resulting in the best measured BER of 4E-3. We also simulated the single 100 Gb/s channel performance over the 1800 km link and varied the channel launch power into each fiber span while holding the DCM launch power to 5 dB lower than the fiber launch power. As can be seen from Fig. 9, simulation predicts a > 1.5 dBQ improvement in performance of the 100 Gb/s channel over this 1800 km link with the optimization of both fiber and DCM launch power. Figure 10 shows the measured BER of the 100 Gb/s channel with 0.5 dBm fiber launch power over a two-hour observation window. During that time, the BER was stable around 4.5E-3; such a pre-FEC BER will yield error-free performance after FEC decoding. Finally, Fig. 11 shows the constellation at the modem output after 1800 km transmission (at 0.5 dBm fiber launch power).

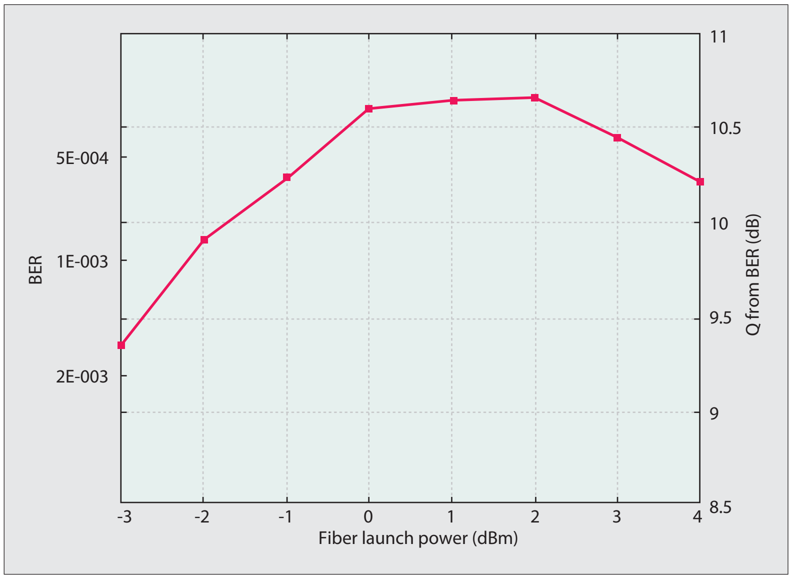

Figure 6. Single channel BER performance of the 126.5 Gb/s coherent PM-QPSK signal as a function of channel launch power into the transmission fiber for the 900 km link.

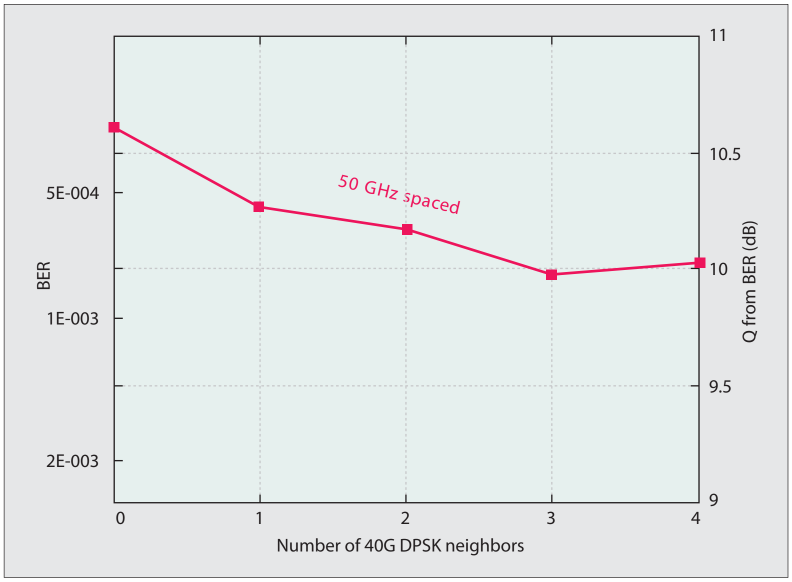

Figure 7. Performance of the 126.5 Gb/s PM-QPSK channel after 900km transmission as a function of the number of adjacent 40Gb/s DPSK channels spaced at 50GHz. The fiber launch power was 0dBm/channel.

Summary

We have discussed the primary drivers for transmission systems operating at 100 Gb/s per wavelength channel and summarized the advantages of the polarization-multiplexed QPSK modula-

BER	10 Gb/s OOK @ 194.45 THz	10 Gb/s OOK @ 194.55 THz	40 Gb/s DPSK @ 194.45 THz	40 Gb/s DPSK @ 194.55 THz
Without 100 Gb/s	8.20E-9	2.80E-8	4.00E-11	6.00E-9
100 Gb/s @ 194.5 THz	4.30E-8	2.50E-8	1.20E-10	4.30E-7

Table 1. BER performance of 10 Gb/s or 40 Gb/s channels over the 900 km link with and without an adjacent 100 Gb/s channel.

tion format as a cost-effective and practical 100 Gb/s transponder technology. We prototyped a pair of real-time single-carrier coherent 100 Gb/s PM-QPSK transponders using existing high-speed ADCs from digital sampling oscilloscopes and an FPGA farm for digital signal processing.

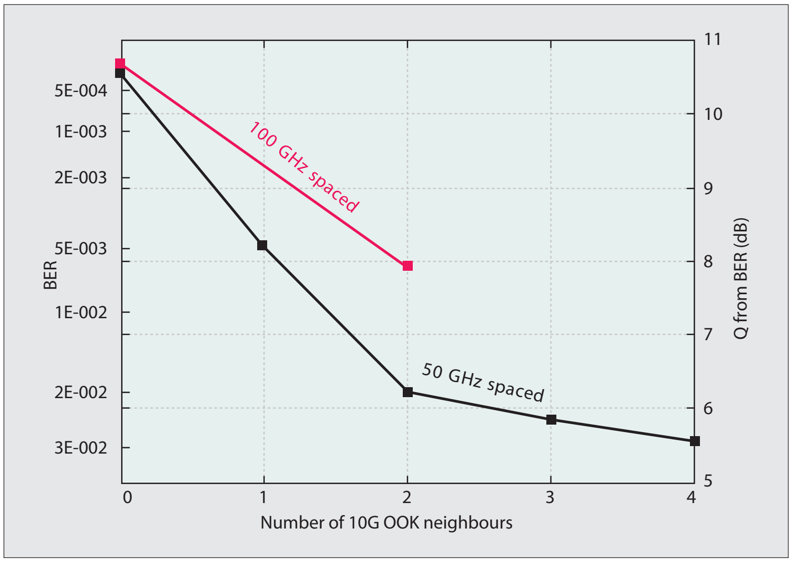

Figure 8. Performance of the 126.5 Gb/s PM-QPSK channel after 900 km as a function of the number of adjacent 10 Gb/s OOK for both 50 GHz and 100 GHz spacing. The fiber launch power was 0 dBm/channel.

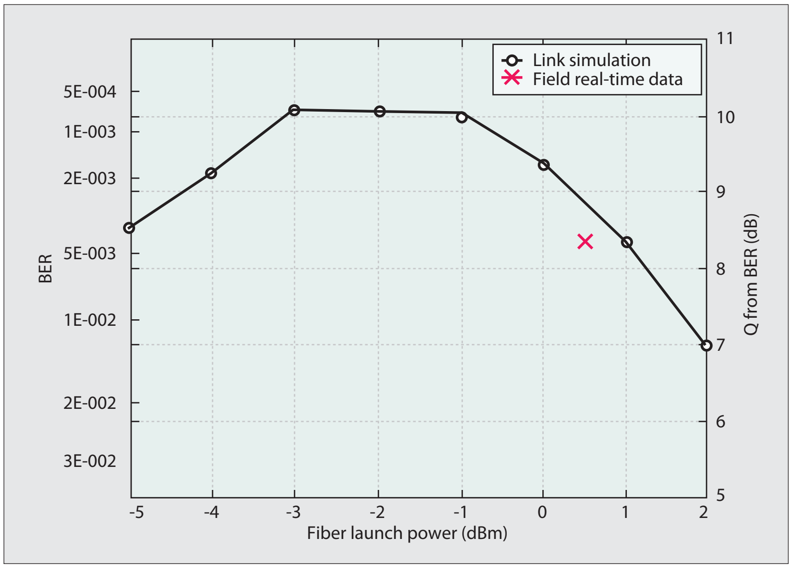

Figure 9. Measured BER versus fiber launch power of the 126.5 Gb/s PM-QPSK channel over the 1,800km loopback link overlaid on simulated performance.

Key functional blocks included carrier and timing recovery, carrier phase estimation, EDC of CD and PMD, and high-coding-gain FEC. We have presented laboratory measurements of the tolerance of the real-time 100 Gb/s PM-QPSK channel to polarization mode dispersion and optical filtering. Finally, we have discussed the results of the first demonstration of a network upgrade of an existing 10/40 Gb/s terrestrial link with a real-time single-carrier coherent 100 Gb/s PM-QPSK channel. The measured pre-FEC bit error rates were sufficient over 900 and 1800 km links in AT&T's installed network for error-free performance after FEC, proving that 100 Gb/s channel upgrades to existing 10 and 40 Gb/s DWDM systems are possible and practical in most cases.

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BIOGRAPHIES

Martin Birk (birk@att.com) received his M.S. and Ph.D. degrees from Germany's University of Ulm in 1994 and 1999, respectively. Since 1999 he has been with AT&T Labs in New Jersey, working on high-speed fiber optic transmission at data rates of 40 Gb/s and above.

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Robert Curto's biography was not available at the time this issue went to press.

Lynn E. Nelson received her Sc.B. degree in engineering from Brown University, Providence, Rhode Island, and M.S. and Ph.D. degrees in electrical engineering from the Massachusetts Institute of Technology, Cambridge. From 1997 to 2000 she was with Bell Laboratories, Lucent Technologies, Holmdel, New Jersey, where she worked on fiber nonlinearities, WDM, and polarization mode dispersion. In 2000 she became technical manager of the Fiber Systems Testing Group for the Optical Fiber Solutions (OFS) business unit of Lucent and remained with OFS after its acquisition by Furukawa in 2001. Since 2007 she has been with AT&T Labs-Research, Middletown, New Jersey, where she is focusing on 40 and 100 Gb/s transmission, modulation formats, and polarization issues for AT&T's long-haul network.

Xiang Zhou [SM] received his Ph. D degree in electrical engineering from Beijing University of Posts and Telecommunications in 1999. From 1999 to 2001 he was with Nangang Technological University, Singapore, as a research fellow, doing research on optical CDMA and wideband Raman amplification. He has been a senior member of technical staff with AT&T Labs-Research since October 2001, working on various aspects of long-haul optical transmission and photonic networking technologies, including Raman amplification, polarization-related impairments, optical power transient control, advanced modulation formats, and digital signal processing at bit rates of 100 Gb/s and beyond. He has authored/co-authored more than 90 peer-reviewed journal and conference publications, and holds 20 U.S. patents. He currently serves as an Associate Editor of *Optics Express*. He is a member of OSA.

Peter Magill received his B.S. in physics from the University of Dayton, Ohio, in 1979 and his Ph.D. in physics from the Massachusetts Institute of Technology in 1987. He joined AT&T Bell Labs a month later, working at the Crawford Hill Laboratory on the characterization of advanced lasers, optical access networks, and data-over-cable access protocols. He then went with Lucent Technologies as it was spun out of AT&T in 1996 to head their access research department. He managed the R&D of passive optical network (PON) systems and cable modem head-end equipment. In 2000 he returned to AT&T and is now executive dDirector, Optical Systems Research, Middletown, New Jersey, concerned with advancing fiber communication technologies for the entire network (intercity, metro, and access) including 100 Gb/s transmission systems and dynamic wavelength networks. Since 2007 he has also been working on assessing, with a goal of reducing, AT&T's electricity consumption.

Theodore J. (Ted) Schmidt [SM'99] (tschmidt@opnext.com) received his B.Sc. degree in engineering physics from North Dakota State University, Fargo, in 1992 and his Ph.D. degree in physics from Oklahoma State University, Stillwater, in 1998. His doctoral research centered on the nonlinear optical properties of wide-bandgap semiconductors. He has authored two book chapters and more than 20 archival journal articles on the subject. From 1999 to 2000 he was a staff engineer in the Network Architecture division at Williams Communications Group, Tulsa, Oklahoma, responsible for evaluation and selection of Raman-based ultra-long-haul transport products for deployment in Williams' nation-wide fiber optic network. From 2000 to 2002 he was a senior optical engineer and technical manager at OptiMight Communications (now part of Huawei Technologies), responsible for development of optical subsystems within OptiMight's ultra-long-haul 10G transport product portfolio. Since 2002, he has led optical systems research and development for StrataLight Communications, now part of Opnext, concentrating on 40G and 100G long haul DWDM optical communications technologies. His research interests include high-speed optical communications systems, optical networking, and semiconductor optical devices. He has authored over 50 articles on his research interests ande has 14 patents granted or pending in the area of optical communications.

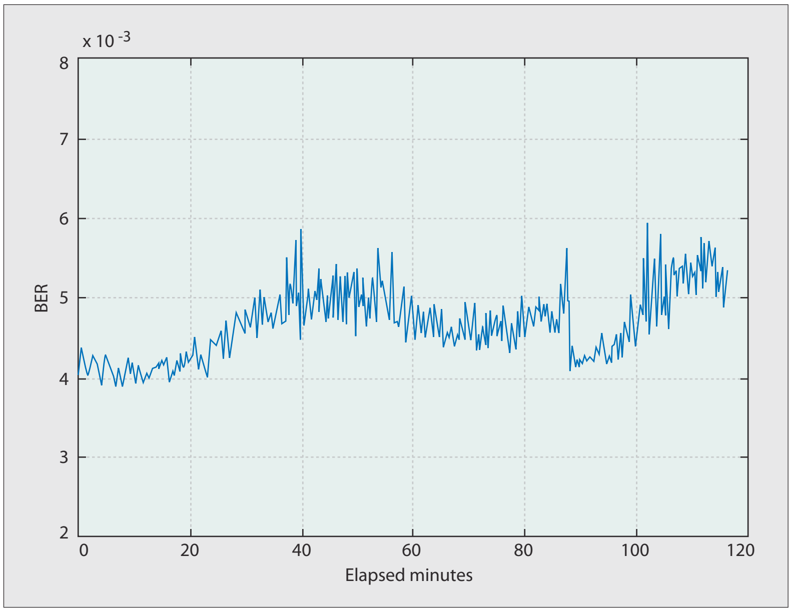

Figure 10. Measured BER variation of the 126.5 Gb/s PM-QPSK channel over 2 hours for the 1800 km loopback link, operating at 0.5 dBm channel power.

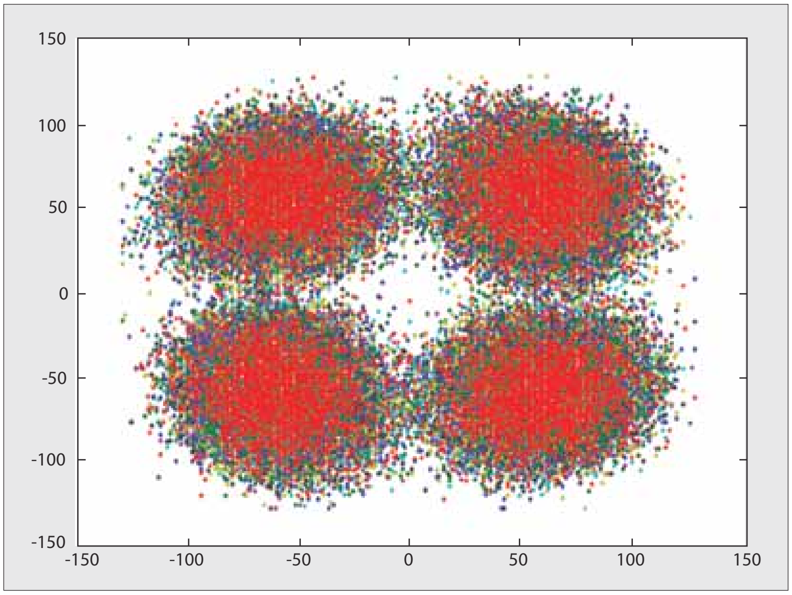

Figure 11. Measured constellation of the 126.5 Gb/s PM-QPSK modem (prior to the slicer) after 1800 km transmission, with a fiber launch power of 0.5 dBm/channel.

Christian Malouin [SM'09] received his Ph.D. degree in physics and optics from the Université Laval, Québec, Canada, in 1996 and his postdoctoral degree from the Université Paris XI, Orsay, France, where he focused on the characterization of magneto-optical recording media using ultra-fast second order nonlinear effects. During his Ph.D. dissertation, he developed a novel geometry of four-wave mixing to characterize fast optical nonlinear media. In 1998 he joined Nortel Networks, where he worked on high-capacity transmission systems from 40 to 100 Gb/s. In September 2000 he joined Innovance Networks, where he helped in the design and development of an ultra-long-haul all-transparent optical network. Since August 2005 he has been with Opnext Subsystem (formely StrataLight Communications), Los Gatos, California, where he is currently responsible for the modeling, verification, and prototyping of the optical architecture of existing and forward-looking products. In particular, his research focuses on transmitter and receiver design/modeling, and the study of advanced modulation formats at high speed using direct detection and coherent schemes.

BO ZHANG [S'03, M'08] received his B.S. degree from Zhejiang University, China, in 2003, and his M.S. and Ph.D. degrees in electrical engineering from the University of Southern California, Los Angeles, in 2005 and 2008, respectively. He is currently a member of technical staff within the Advanced Optical Systems Technology group at Opnext Subsystems, Inc. (formerly StrataLight Communications). He is mainly focused on the design and development of coherent optical communication networks at 100G and beyond, including the engineering of optical transport systems as well as the prototyping of coherent optical transponders. He is a member of the IEEE Photonics Society and the Optical Society of America (OSA). He serves as a frequent reviewer for several IEEE and OSA journals, including *Optics Letter*, *Optics Express*, *Journal of Lightwave Technology*, *Photonics Technology Letters*, and *Journal of Selected Topics in Quantum Electronics*. He has authored and coauthored more than 65 journal and conference papers, including one book chapter and four invited papers. He was the recipient of the Dr. Bor-Uei Chen Memorial Scholarship Award from the Photonics Society of Chinese-Americans in 2008. In 2009 he won the Honorable Mention award from the Corning Outstanding Student Paper Competition held by Corning Inc., OSA, and OFC/NFOEC.

EDEM IBRAGIMOV [M'00] received B.E. and M.S. degrees in 1977 and a Ph.D. degree in physics and mathematics in 1985. He held positions at Michigan Technological University, Houghton; the University of Maryland, Balitmore; YAFO Networks, Inc., Hanover, Maryland; and Scintera Networks, San jose, California. He is currently working for Opnext Subsystems, Los Gatos, California, with a focus on high-speed coherent optical subsystems. He is an author of five U.S. patents and has over 50 publications in major technical journals.

SUNIL KHATANA [M'98] received a B.S. in electrical engineering in 1993, an M.S. in physics in 1995, and an M.S. in electrical engineering in 1997 from the Indian Institute of Technology, Delhi. He held positions at Centre for Development of Technology, New Delhi, Altamar Networks, Mountain View, California, and JDS Uniphase, San Jose, California. He is currently working for Opnext Subsystems with a focus on high-speed coherent optical subsystems.

MIRKO GLAVANOVIC is marketing sales engineer at Opnext Subsystems. He has 12 years of experience in telecommunications and the network equipment industry. Prior to joining Opnext (when it was StrataLight), he was a systems engineer at Altamar Networks responsible for an integrated ULH transport system. Previously, he was marketing engineer at Optimight Communications responsible for ULH transport. He previously held a transport development engineering position at WorldCom. He received a B.S. degree in electrical engineering from the University of Arizona.

ROB LOFLAND has 34 years of experience in the design of flight simulation, optical networking, and long-haul optical transport. He holds a B.S. degree in electrical engineering from the University of Delaware.

ROBERTO MARCOCCIA received his engineering degree in 1988 and has focused on digital communications using advanced modulation techniques and protocol development. In the past decade he led the team that developed the first field deployed 40G core network optical transmission system and most recently led the team in the development of the first 127 Gb/s single-wavelength coherent optical transmission system.

Ross Saunders worked in Nortel Networks high-capacity transport R&D group for six years on 10, 40, and 100 Gb/s DWDM system design. He has spent the last 12 years working in DWDM Product Management for Nortel Networks, Pirelli Optical Systems (now Cisco), Ceyba Inc., and Opnext Subsystems. He currently runs Sales and Marketing for Opnext Subsystems. He graduated with a B.Eng. degree from Napier University, Edinburgh, United Kingdom, and has 18 U.S. patents granted in optical communications and approximately 100 journal/conference papers published to date.

GARY NICHOLL (gnicholl@cisco.com) is a principal engineer in the Core Routing business unit at Cisco Systems, where he is responsible for the definition and development of high-speed optical interfaces for the CRS-1 core router, including the recent integration of OTN and DWDM technologies. He is currently leading Cisco's efforts in the development of 100GE technology, and was actively involved in defining the 100GE standard as a member of the IEEE 802.3ba Task Force. He also represents Cisco at various industry standards organizations and industry fora, and in the past has been an active contributor in the development of several 10G and 40G standards in the IEEE, OIF, and ITU. Prior to joining Cisco in 1997, he spent 10 years at Nortel Networks, Ottawa, Canada, working in various R&D roles on the development of SONET/SDH transport products. He holds a B.Sc. in electrical engineering from the University of Manchester, United Kingdom.

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FABRIZIO FORGHIERI is currently a principal engineer with Cisco Photonics Italy, Monza. He has been with Cisco Photonics since the initial acquisition of Pirelli Optical Systems in 2000, working with the Engineering team on current and next-generation DWDM optical systems, optical fiber transmission, high-speed interfaces, and network design. Prior to the acquisition, he was with Pirelli Optical Systems since 1997 as R&D manager for DWDM Transmission Systems, and with AT&T Bell Labs, Crawford Hill, New Jersey from 1993 to 1996 doing research on modeling DWDM optical systems and fiber-induced transmission impairments. He received a D.Eng. degree in electrical engineering, summa cum laude, from Pisa University, Italy, and M.A. and Ph.D. degrees in electrical engineering from Princeton University. He has authored or coauthored more than 60 journal and conference papers and one book chapter, and has given tutorial presentations at both OFC and ECOC. He holds several patents in the field of DWDM optical transmission.

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