Spectrally Efficient Long-Haul WDM Transmission Using 224-Gb/s Polarization-Multiplexed 16-QAM

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Spectrally Efficient Long-Haul WDM Transmission Using 224-Gb/s Polarization-Multiplexed 16-QAM

A. H. Gnauck, *Fellow, IEEE*, P. J. Winzer, *Fellow, IEEE*, S. Chandrasekhar, *Fellow, IEEE*, X. Liu, *Senior Member, IEEE*, B. Zhu, *Member, IEEE*, and D. W. Peckham, *Senior Member, IEEE*

***Abstract*—We discuss the generation, wavelength-division-multiplexed (WDM) long-haul transmission, and coherent detection of 224-Gb/s polarization-division-multiplexed (PDM) 16-ary quadrature amplitude modulation (16-QAM) at a line rate of 28 Gbaud. We measure a required optical signal-to-noise ratio of 23.4 dB (0.1-nm reference bandwidth; 10^{-3} bit-error ratio), 3.4-dB off the theoretical limit. Using ultra-large-area fiber, we achieve 2000-km single-channel transmission. We also demonstrate 1200-km WDM transmission on a 50-GHz grid (4-b/s/Hz spectral efficiency), including three passes through a wavelength-selective switch.**

***Index Terms*—Coherent detection, optical networking, quadrature amplitude modulation (QAM), wavelength-division multiplexing (WDM), transmission, 100 G Ethernet.**

I. Introduction

SCALING per-channel transport bit rates beyond 100 Gb/s is important to accommodate the continuing increase in router interface rates, and is currently an area of intense research. Transmission approaches include orthogonal sub-carrier multiplexing [1], [2] and single-carrier multilevel modulation at high symbol rates [3]–[7]. While the two approaches are similar in many respects, the latter method allows for a simpler transmitter structure at approximately equal receiver and digital signal processing hardware [8]. For 100-Gb/s transmission, a promising approach is to use single-carrier 28-Gbaud polarization-division-multiplexed (PDM) quadrature phase-shift keying (QPSK) [9]. The line rate of 112 Gb/s supports a net information bit rate of 100 Gb/s, including overhead for Ethernet and forward error correction (FEC). Such signals can be operated on a 50-GHz frequency grid in wavelength-division-multiplexed (WDM) systems (spectral efficiency, SE, of 2 b/s/Hz), while still providing enough spectral margin for several passes through reconfigurable optical add/drop multiplexers (ROADMs). By moving to 28-Gbaud PDM 16-level quadrature amplitude modulation (16-QAM), 224-Gb/s channels could be sent over the same WDM grid, providing an SE of 4 b/s/Hz in an optically routed network environment, and carrying two 100 G Ethernet streams per WDM channel. Until recently, the highest line rate for single-carrier PDM 16-QAM transmission was 21.4 Gbaud (171 Gb/s) [4], where 432 WDM channels were transmitted through 240 km of low-nonlinearity pure-silica-core fiber (PSCF) using distributed Raman amplification. In addition, 20-Gbaud (160-Gb/s), single-channel transmission through 1 120 km of standard single-mode fiber (SSMF) was achieved using erbium-doped-fiber-amplifier (EDFA) repeaters [5], and 20-Gbaud single-channel transmission through 3123 km of PSCF was obtained using distributed Raman amplification [6]. We have since reported the generation of 28-Gbaud (224-Gb/s) PDM 16-QAM, and ten-channel WDM transmission through 1200 km of ultra-large-area fiber (ULAF) in a 400-km recirculating loop [10]. In order to demonstrate the capability for long-haul optical networking, the recirculating loop included a wavelength-selective switch (WSS), configured to emulate the filtering and crosstalk of a ROADM. In this paper, we expand upon the work reported in [10], and include results for single-channel transmission at distances up to 2000 km.

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P. J. Winzer, A. H. Gnauck, S. Chandrasekhar, and X. Liu are with Bell Laboratories, Alcatel-Lucent, Holmdel, NJ 07748 USA (e-mail: alan.gnauck@alcatel-lucent.com).

B. Zhu and D. W. Peckham are with OFS Labs, Somerset, NJ, 07974USA.

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II. Experiment

The experimental setup is shown in Fig. 1. Ten C-band distributed-feedback (DFB) lasers were operated on a 50-GHz frequency grid extending from 192.50 THz to 192.95 THz (1553.73 nm to 1557.36 nm). The odd and even channels were separately combined using arrayed-waveguide grating routers (AWGs), and the two sets were combined in a 3-dB optical coupler. A second 3-dB optical coupler was used to add the output from an external cavity laser (ECL). The ECL, with 100-kHz linewidth, replaced the channel under test during measurements, due to the required narrow linewidth for 16-QAM [11]. The ten channels were modulated using an integrated $LiNbO_3$ double-nested Mach–Zehnder modulator (MZM) with 35-GHz 3-dB bandwidth and V_π of 2.3 V. The biases of the sub-MZMs were manually adjusted to the nulls by minimizing the carrier component in the modulated spectrum, and the $\pi/2$ phase shifter was manually adjusted to produce a square signal constellation. The in-phase (I) and quadrature (Q) branches of the modulator were driven by 28-Gbaud four-level, 2.5-V_{pp} electrical signals. Each four-level signal was derived from two copies of a 28-Gb/s true pseudo-random bit sequence (PRBS) of length $2^{15}-1$, decorrelated with a relative delay of 35 bit periods. The four-level drive signals were significantly smaller than the modulator 2 V_π of 4.6 V. Therefore, the modulator operated in a semi-linear regime and produced good signal constellations for equally spaced drive levels. In addition, the amplitudes of the binary signals from which the four-level signals were constructed could be fine-tuned by adjusting the supply voltage of the driver amplifiers to compensate the residual modulator nonlinearity. Passive Gaussian low-pass electrical filters with bandwidths of 14 GHz (chosen due to availability) were used for transmit pulse shaping to reduce

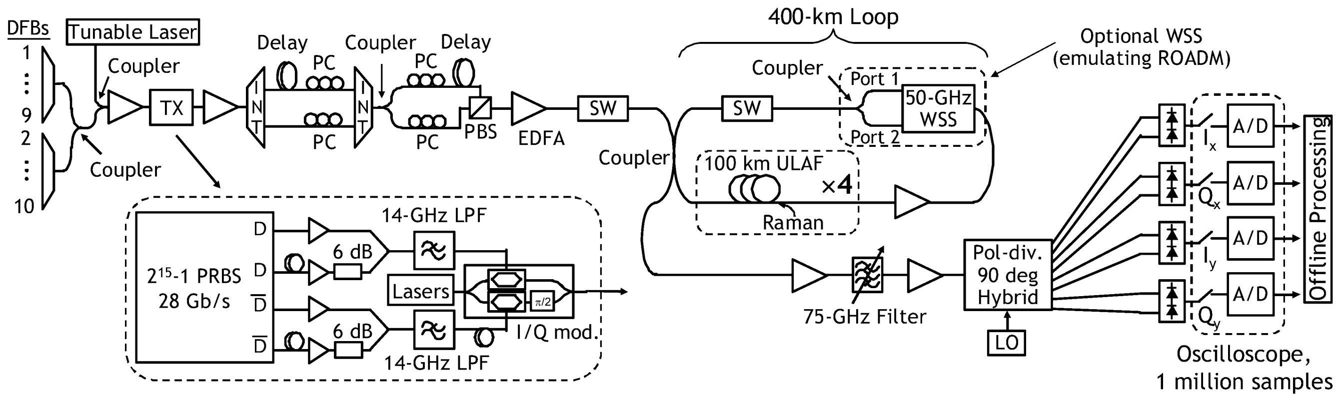

Fig. 1. Experimental setup. TX: transmitter, INT: interleaver, PC: polarization controller, SW: switch, LO: local oscillator, LPF: electrical low-pass filter. The 14-GHz LPFs are used for pulse shaping to reduce the spectral overlap of WDM channels (cf. Fig. 2).

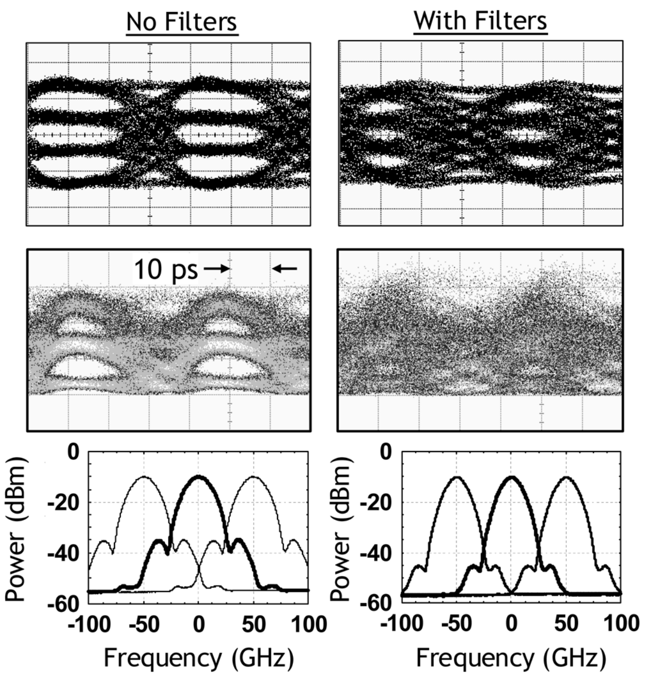

Fig. 2. Effect of no electrical low-pass filtering (left) versus 14-GHz filtering (right) on a single-channel single-polarization signal. Top: electrical four-level drive. Middle: directly detected eye pattern. Bottom: optical spectrum (dark trace) showing overlap with adjacent 50-GHz WDM channels (light traces).

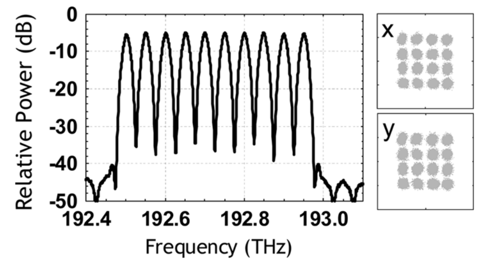

Fig. 3. Transmitted spectrum at the output of the polarization multiplexer (0.1-nm resolution bandwidth), and the recovered signal constellations for both polarizations of the WDM channel at 192.8 THz.

the spectral overlap between adjacent WDM channels. The two four-level signals were decorrelated by 16 symbol periods before being applied to the modulator. After modulation, the odd and even channels were decorrelated using a pair of 50-GHz/100-GHz optical interleavers with a differential delay in the two paths of several hundred symbols. The -3-dB bandwidths of the interleaver-pair passbands were 40 GHz. Note that the use of this single-transmitter optical-decorrelation technique is possible provided that WDM crosstalk is negligible, which we measured to be the case owing to the use of low-pass electrical pulse shaping. Fig. 2 shows the effect of electrical filtering on the four-level drive waveform, the directly detected (three-level) eye pattern, and the optical spectrum of a single channel. Much of the distortion seen in the eye pattern is compensated by the adaptive equalizer that is included in the receiver signal-processing algorithm [11]. Polarization multiplexing was achieved by 3-dB splitting the WDM signal, delaying one copy by 20 ns (560 symbols), and recombining them in a polarization beamsplitter (PBS), using manual polarization controllers (PCs). Fig. 3 shows the ten-channel optical spectrum at the output of the polarization multiplexer, as well as the recovered signal constellations for the WDM channel at 192.8 THz. Since no optical noise was added to the signal in this case, the spread of the symbols reflects a combination of transmitter and receiver imperfections (such as inter-symbol interference and impairments from analog-to-digital conversion) that the adaptive equalizer was unable to compensate for.

Transmission was performed in a recirculating loop similar to that described in [2], which consisted of 4 backward-Raman-amplified 100-km ULAF spans, pumped to near transparency. At 1555 nm, the fiber loss, dispersion, and dispersion slope were 0.185 dB/km, 20 ps/nm/km, and 0.08 ps/nm^2/km, respectively. The fiber effective area was 120 μm^2, and the nonlinearity coefficient was 0.81 W^{-1} km^{-1}. The low loss and low nonlinearity of this fiber may make it preferable to standard single-mode fiber in future long-haul deployments. Span amplification was provided solely by backward Raman pumping. One EDFA was used to compensate for the remaining loss in the loop. In order to evaluate the performance of the signals in optically routed networks that deploy ROADMs, the loop optionally contained a flexible-bandwidth WSS (Finisar WaveShaper 4000S) configured for 50-GHz channel spacing. To emulate the impact of filtering and coherent crosstalk, we configured the WSS output port 1 to pass the even channels and port 2 to pass the odd

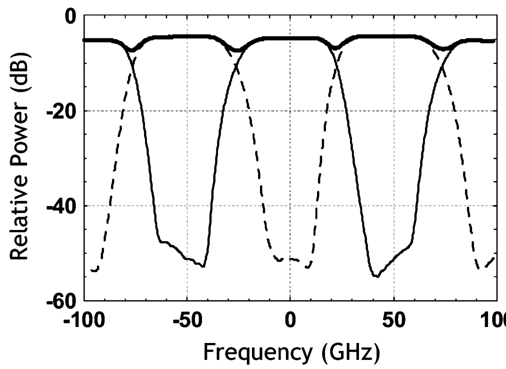

Fig. 4. Response of the WSS. Thin solid line: response of port 1. Dashed line: response of port 2. Heavy solid line: combined response of both ports.

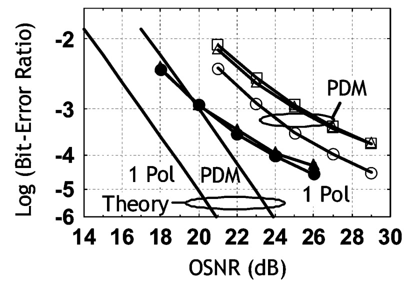

Fig. 5. Back-to-back BER curves. Without electrical filters and optical interleavers: solid circles and triangles (single x- and y-polarization) and open circles (PDM). PDM with electrical filters and optical interleavers: open triangles (1 channel) and open squares (3 channels).

channels, and recombined the two outputs with an arbitrary relative polarization and delay in a 3-dB coupler before the signals went on to the next loop round trip. In this configuration, the -3-dB bandwidths of the port passbands were 45 GHz, and the crosstalk rejection (ratio of total signal power received at the correct port to that received at the wrong port) was >35 dB. Fig. 4 shows the WSS amplitude characteristics. The response of port 1 is shown by the thin solid line and the response of port 2 is given by the dashed line. The heavy solid line is the combined response of both ports.

At the receiver, the channel under test, including a portion of its neighbors, was selected using a 75-GHz-bandwidth optical filter. The signal was then combined with a free-running ECL local oscillator (LO), tuned to within ± 20 MHz of the signal carrier, in a polarization-diversity 90-degree hybrid, followed by 4 balanced detectors. The 4 signal components $(\mathrm{I_x}, \mathrm{Q_x}, \mathrm{I_y}, \mathrm{Q_y})$ were sampled asynchronously and digitized using a 4-channel 50-GSamples/s real-time oscilloscope with 16-GHz bandwidth, resulting in two complex sample streams. We note that the 16-GHz bandwidth eliminated most residual power from the neighboring WDM channels. The remaining interference was removed by digital filtering as part of the digital signal processing algorithms forming the intradyne receiver's back-end. All results are based on offline processing of 10^6 samples per polarization and quadrature.

Our intradyne-receiver algorithm [11] first corrected for front-end imperfections, e.g., sampling skew and hybrid phase errors [12], adjusted to minimize the bit-error ratio (BER), and performed chromatic-dispersion compensation in the frequency domain. The subsequent clock recovery oversampled the signal by a factor of 3 using zero-padding in the frequency domain and extracted the tone at the symbol rate (1/T) from the spectrum of the magnitude-squared signal. Using the recovered clock, we synchronously upsampled the signal from $\sim$1.8 to 2. The original x and y polarizations of the signal were recovered using a 16-tap, T/2-spaced adaptive butterfly FIR filter. As detailed in [11], filter pre-convergence was achieved with the constant modulus algorithm, followed by maximum-likelihood frequency- and phase-estimation. Final filter adaptation was done using a decision-directed algorithm interleaved with a decision-directed phase-locked loop. Every measured sample sequence was only processed once throughout our experiments, whereby the first $\sim$14000 symbols were used for convergence of all receiver loops, and a few thousand symbols were discarded at the end of the record to avoid edge effects. The remainder of $\sim$544000 symbols per polarization, corresponding to a total of $\sim$4.4 million bits, was used for error counting. The symbols were mapped to a 16-QAM constellation using Gray coding. Throughout our experiments, we did not observe any cycle slips that would have necessitated differential QAM encoding. Compensation algorithms for fiber nonlinearities were not used in these experiments.

III. Results and Discussion

A. Back-to-Back Performance

Fig. 5 shows the back-to-back BER as a function of the optical signal-to-noise ratio (OSNR, 0.1-nm reference bandwidth, noise in both polarizations) for several cases. First, the performance of a single channel (192.80 THz) was measured without the 14-GHz electrical low-pass filters and without the interleaver pair for both single-polarization (solid circles and triangles for x- and y-polarizations) and PDM operation (open circles). The required OSNRs to achieve a BER of 1×10^{-3} are 20.3 dB and 23.4 dB, respectively. The theoretical limits for both single-polarization and PDM signals are also shown. For single-polarization and PDM, our results are 3.3 dB and 3.4 dB off the theoretical limit, respectively. At full OSNR ($\sim$40 dB) a BER floor at $\sim 1 \times 10^{-6}$ is reached for both single-polarization and PDM signals. We then added the electrical filters and optical-interleaver pair, and measured single-channel PDM performance. An additional penalty of 1.7 dB was incurred due to the narrow electrical and optical filtering (open triangles). Finally, in three-channel WDM operation, almost no additional penalty ($\leq$0.3 dB) was observed on the central channel (open squares), indicating that linear crosstalk was negligible, and justifying our interleaver-based WDM decorrelation method.

B. Single-Channel Transmission

We performed single-channel transmission in the recirculating loop, both without and with the 14-GHz electrical low-pass filters. For these measurements, both the interleaver pair and the WSS were removed. Fig. 6 shows the BER obtained after three, four, and five loop circulations (1200, 1600, and 2000 km) as a function of the power launched into the first fiber span. The received OSNRs at these distances are also shown. As expected from the back-to-back measurements,

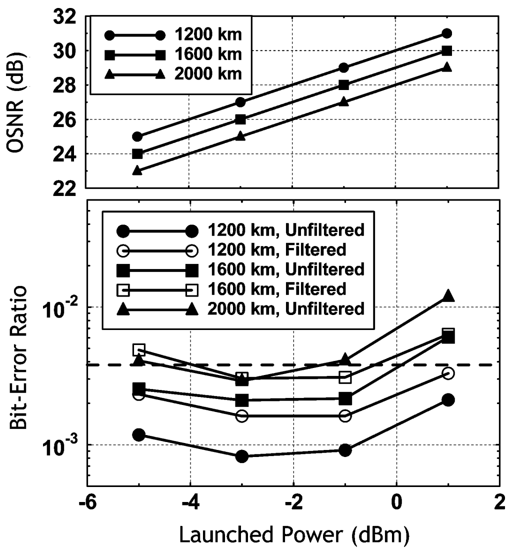

Fig. 6. Single-channel transmission performance at 1200 km (circles), 1600 km (squares) and 2000 km (triangles) as a function of the power launched into the first span of the recirculating loop. The upper plot shows the received OSNR for the three cases. The lower plot shows BER results. Solid symbols are without electrical filtering of the drive signals. Open symbols are with 14-GHz electrical low-pass filtering.

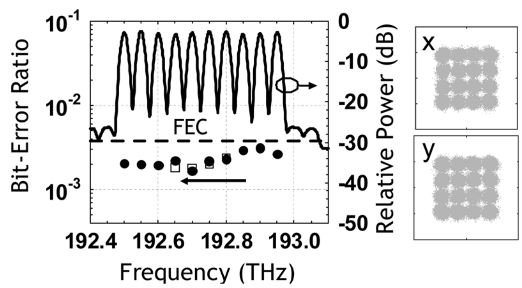

Fig. 7. BER results (solid circles) and received spectrum for 10-channel 1200-km transmission, including 3 WSS passes. Open squares: BER results without WSS filtering. Right: recovered signal constellations of the WDM channel at 192.8 THz.

better BER performance is achieved without the electrical filters (solid symbols), as opposed to with the electrical filters (open symbols). The dashed line at a BER of 3.8×10^{-3} shows the threshold for operation with advanced FEC with 7% overhead [13]. At the near-optimum launched power of -3 dBm, 2000 km can be bridged in the case of the unfiltered transmitter, while 1600 km can be spanned using the filtered transmitter.

C. WDM Transmission

We next re-installed the electrical low-pass filters, the interleaver pair, and the WSS, and performed ten-channel transmission over three circulations of the recirculating loop (1200 km). The total launched power into the first span was 7 dBm (-3 dBm/channel), the near-optimal value found in single-channel transmission. The average OSNR after three loops was 25 dB. Note that this is 2 dB lower than the 1200-km single-channel result of 27 dB obtained when using -3 dBm launched power (see upper portion of Fig. 6). The reduced OSNR in WDM operation is due to Raman-pump depletion at the higher total launched power of 7 dBm. Fig. 7 shows the BER measurements for each channel (solid circles), as well as the received optical spectrum (0.1-nm resolution bandwidth). The BERs of all channels were less than the FEC limit of 3.8×10^{-3} (shown by the dashed line). A comparison with the back-to-back three-channel WDM results shown in Fig. 5 discloses a transmission penalty of up to about 2 dB. BER measurements were also made on the four central channels with the WSS reconfigured to pass all frequencies to port 1 (and the output of port 2 disconnected), thus removing filtering and crosstalk effects. The results (open squares in Fig. 7) were almost identical to the initial results, indicating that the transmission penalty is due mainly to nonlinear effects and not due to optical filtering or crosstalk in the WSS.

IV. Conclusion

We have reported the generation and transmission of 28-Gbaud PDM 16-QAM signals at a line rate of 224 Gb/s, supporting two 100 G Ethernet streams per WDM channel. A single channel was transmitted through 2000 km of low-loss, low-nonlinearity ultra-large-area fiber. Ten channels (2-Tb/s total), operating on a 50-GHz frequency grid (spectral efficiency of 4 b/s/Hz) were successfully transmitted over 1200 km of the same fiber, including three passes through a 50-GHz ROADM emulated with a WSS. It was also demonstrated that the three ROADM passes did not contribute any measurable filtering or crosstalk penalty.

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Alan Gnauck (M'98–SM'00–F'09) joined Bell Laboratories, Holmdel, NJ, in 1982, where he is currently a Distinguished Member of Technical Staff in the Transmission Systems and Networks Research group.

He has performed record-breaking optical transmission experiments at single-channel rates of from 2 to 200 Gb/s. He has investigated coherent detection, chromatic-dispersion compensation techniques, CATV hybrid fiber-coax architectures, wavelength-division-multiplexing (WDM) systems, and system impacts of fiber nonlinearities. His WDM transmission experiments include the first demonstration of terabit transmission. More recently, he has demonstrated 25-Tb/s transmission. He is presently involved in the study of WDM systems with single-channel rates of 100 Gb/s and higher, using various modulation formats. He has authored or co-authored over 180 journal and conference papers, and holds 23 patents in optical communications.

Mr. Gnauck is a Fellow of the Optical Society of America (OSA), a Fellow of the Institute of Electrical and Electronic Engineers (IEEE), and former Associate Editor for IEEE PHOTONICS TECHNOLOGY LETTERS (2000–2009).

S. Chandrasekhar (M'90–SM'00–F'01) received the B.Sc., M.Sc., and Ph.D. degrees in physics from the University of Bombay, Bombay, India, in 1973, 1975, and 1985, respectively.

He was at the Tata Institute of Fundamental Research, Bombay, India, from 1975 to 1985 and at AT&T Bell Laboratories (later called Lucent Technologies, Bell Laboratories and more recently called Bell Labs, Alcatel-Lucent), Crawford Hill Laboratory, Holmdel, NJ, from 1986 to the present. He initially worked on compound semiconductor devices and high-speed optoelectronic integrated circuits (OEIC's). Since January 1999, he has been responsible for forward looking research in WDM Optical Networking at 40 Gb/s and 100 Gb/s. His current interests include coherent optical orthogonal frequency division multiplexed systems for high spectral efficiency transport and networking beyond 100 Gb/s, multi-carrier superchannels, and electronic digital signal processing for software-defined transponders.

He is a DMTS at Bell Labs, a member of the IEEE Photonics Society, and was an Associate Editor of IEEE PHOTONICS TECHNOLOGY LETTERS for over ten years. He has been a member of the technical program committees of the IEDM, the DRC, and the OFC conferences. He holds nineteen US patents. He was awarded the IEEE LEOS Engineering Achievement for 2000 and the OSA Engineering Excellence Award for 2004 for his contributions to OEICs and WDM systems research.

Xiang Liu (M'00–SM'05) received the Ph.D. degree in applied physics from Cornell University, Ithaca, NY, in 2000.

Since joining Bell Labs as a Member of Technical Staff in 2000, Dr. Liu has been primarily working on high-speed optical communication technologies including advanced modulation formats and detection schemes, fiber nonlinearity and dispersion management, and coherent optical OFDM. He has authored/coauthored more than 190 journal and conference papers, and holds over 35 U.S. patents in the field of optical communications and nonlinear optics.

Dr. Liu is a Senior Member of the OSA.

David W. Peckham received the B.S. and M.E. degrees in electrical engineering from the University of Florida, Orlando.

He started his career at the Bell Labs Transmission Media Laboratory in 1982 working on optical fiber measurement techniques. Since 1989 he has focused on the design, process development and commercialization of optical fibers for high capacity transmission systems at Bell Labs, Lucent and currently OFS. He is currently a Consulting Member of Technical Staff/Research Fellow in the Optical Fiber Design Group at OFS, Norcross, GA.

Dr. Peckham received the 2002 OSA Engineering Excellence Award recognizing his contributions in the design and commercialization of fibers enabling high speed, wideband WDM networks.