All-Raman-Amplified, 73 nm Seamless Band Transmission of 9 Tb/s Over 6000 km of Fiber

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***Abstract*— We report wavelength-division-multiplexed transmission of ninety 128-Gb/s polarization-multiplexed quadrature-phase-shift-keyed channels in a seamless 73 nm band over 60 × 100 km of ultra-large-area fiber. Co- and counter-pumped all-Raman amplification in the fiber spans, single-stage discrete Raman amplifiers, and broadband wavelength selective switch and channel equalizer were utilized to achieve optical signal-to-noise-ratio margin of more than 3 dB after 6000 km transmission of the 9 Tb/s capacity.**

***Index Terms*— Optical fiber communication, optical fiber amplifiers, distributed Raman amplification.**

I. Introduction

As CARRIERS attempt to continue to lower the cost-per-transmitted bit, research and development have concentrated on maximizing the benefits of coherent detection, in terms of obtaining the highest possible spectral efficiency. In order to increase capacity beyond the 100G systems with 88 to 96 wavelength-division-multiplexed (WDM) channels currently being deployed, multi-band transmission systems may be considered. Typical C+L-band systems with erbium-doped fiber amplifiers (EDFA) utilize ~70nm of bandwidth and require guard bands of 8 nm or more near 1565 nm, as recently reported in [1]. A seamless transmission band enabled by distributed Raman amplification avoids the band splitters and combiners required by systems with C+L EDFAs, thus simplifying the system configuration and potentially lowering cost. In addition, the reduced number of loss elements along the transmission link and distributed amplification in the fiber spans result in higher received optical signal-to-noise ratio (OSNR).

In the early 2000's, there were several demonstrations of ultra-wide, continuous single-band transmission including 10G submarine systems with seamless transmission bandwidths up to 80 nm using all-Raman amplification [2] or hybrid Raman-EDFA repeaters [3]. For terrestrial applications, transmission of a 53nm continuous band with 2.5 Tbit/s (64 × 42.7 Gbit/s) capacity [4] and 90 × 42.7 Gb/s in a 73nm band [5] were each demonstrated over 4000 km of fiber. Both [4] and [5] utilized non-zero dispersion-shifted fiber in the spans and in-line, Raman-pumped dispersion-compensating fiber (DCF) modules. Since those demonstrations, the adoption of digital coherent detection has obviated the need for inline dispersion compensation, thereby eliminating nonlinear impairments arising from Raman-pumped DCF in all-Raman-amplified systems. In addition, digital coherent systems' tolerance to dispersion lends flexibility in the design of the Raman fiber utilized in discrete Raman amplifiers.

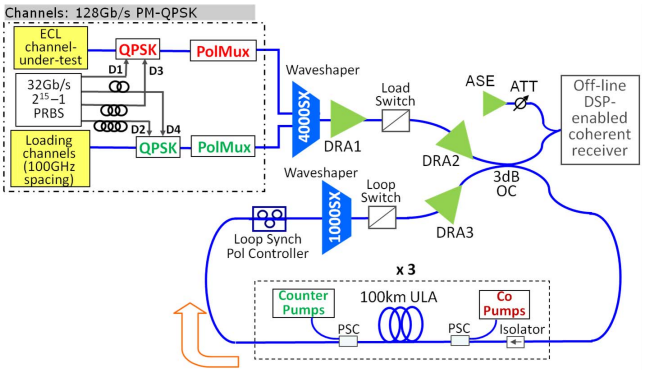

Fig. 1. Experimental setup: OC: optical coupler, PSC: pump-signal coupler. ATT: attenuator, ASE: amplified spontaneous emission.

Here we report transmission of ninety 128Gb/s polarization-multiplexed quadrature-phase-shift-keyed (PM-QPSK) channels in a seamless 73nm band over 60 × 100km of low-loss ultra-large-area (ULA) fiber. We employed all-Raman amplification in the fiber spans via co- and counter-pumping, along with simple, single-stage, counter-pumped discrete Raman amplifiers having noise figure as low as 6dB. Seamless wavelength-selective-switch functionality and equalization across the entire 73nm band were achieved by using commercial optical processors based on liquid-crystal-on-silicon. Although the experiment utilized 100GHz channel spacing, subsequent tests showed that transmission with 50GHz channel spacing, allowing 18Tb/s capacity in a single band, also could be feasible over similar distances.

II. Experimental Setup

Figure 1 shows a schematic of the experiment. A tunable external cavity laser (ECL) having less than 100kHz linewidth served as the channel-under-test and was

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TABLE I
DISCRETE RAMAN AMPLIFIER CHARACTERISTICS

	Raman Fiber				Avg Gain (dB)	Avg Noise Figure (dB)	Output Power (dBm)	Total Pump Power (dBm)	Number of pump wave-lengths
	length (km)	Aeff (sq um)	1550nm atten (dB/km)	1550nm Dispersion (ps/nm/km)					
DRA1	9.1	26.3	0.39	12.1	14.8	6.5	18.5	29.8	5
DRA2	10.0	30.9	0.70	9.3	7.8	7.3	23.4	32.2	6
DRA3	7.0	26.3	0.39	12.1	15.0	6.0	21.5	31.1	5

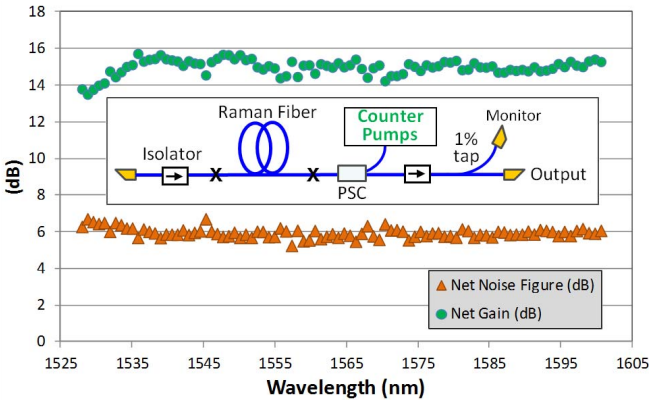

Fig. 2. Measured gain and noise figure of DRA3 in the loop. Inset shows the basic configuration of all three DRAs. (PSC: pump-signal coupler)

modulated with 32Gbaud QPSK via an I-Q modulator driven with $2^{15}-1$ pseudo-random-bit sequences (PRBS) with suitable inversion and delay to assure decorrelation of the I and Q data. The channel-under-test was then polarization multiplexed by splitting the signal, delaying one arm by 990 symbols, and recombining in a polarization beam combiner. A commercial 1×4 Finisar Waveshaper WS4000SX was used as a wavelength selective switch to combine the channel-under-test with a band of 100GHz-spaced loading channels, which were separately PM-QPSK modulated (similar to the channel-under-test) to provide decorrelation of the WDM channels adjacent to the channel-under-test. The resulting signal was comprised of ninety 128Gb/s channels at 100GHz spacing in a continuous band from 1528.0nm to 1600.6nm.

Before the recirculating loop, the signals were boosted by two counter-pumped, single-stage discrete Raman amplifiers (DRA1 and DRA2), whose characteristics are listed in Table I and whose configuration is shown in the inset of Fig. 2. The WS4000SX was used to replace the loading channel with the channel-under-test as the ECL was tuned across the band, and to adjust the individual channel attenuations to flatten the spectrum at the output of DRA2 to within $+/-0.25$dB, thereby providing a flat spectrum at the loop input.

The prototype ULA fiber had, at 1550nm, $150\mu m^2$ average A_{eff}, 21ps/nm/km dispersion, and 0.175dB/km average attenuation. The peak Raman gain efficiency was measured to be 0.20/(W-km) at 1455nm, where the fiber attenuation was 0.215dB/km. (Typical standard single-mode fiber has 0.39/(W-km) peak Raman gain efficiency [6] and attenuation of $\sim$0.25dB/km near 1450nm.) Three ULA spans were configured for all-Raman amplification, as shown in Fig. 1, resulting in total span losses (fiber + components) of between

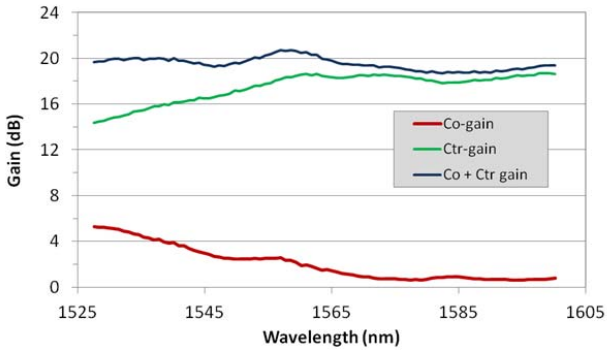

Fig. 3. Measured co-, counter-, and total gain for a typical 100km ULA fiber span.

19.1 and 20.1dB. For each span, counter-pumps at 1429, 1447, 1465, and 1495nm with 490, 427, 440, and 466mW, respectively, provide 14dB on-off Raman gain at the shorter wavelengths, and 19dB gain at the longer wavelengths. Co-pumps at 1425 and 1455nm with 365 and 114mW, respectively, provided a maximum of 5.8dB on-off Raman gain at the shortest wavelengths, with co-gain less than 1dB from 1570 to 1600nm, as shown in Fig. 3. The Raman-pumped ULA span noise figure, as defined in section IV(D) of [7], was estimated to be less than 16dB at all channel wavelengths, consistent with the low noise figure of all-Raman-amplified large-A_{eff} fiber spans reported in prior publications (e.g. [6]). After the third span, the peak-to-peak variation of the channel powers was less than 5dB across the band. A loop-synchronous polarization controller to accurately emulate the polarization effects of a straight-line system was followed by a commercial Waveshaper WS1000SX for channel power equalization. The WS1000SX and WS4000SX each have an operating frequency range of 1527.4 nm to 1600.8 nm and optical transfer function [8] of 16 to 18GHz, compared to $\sim$11GHz for a Waveshaper covering C-band only. DRA3 compensates for the attenuations of the WS1000SX, polarization controller, and loop components. As shown in Fig. 2, DRA3 had measured gain of 13.5 to 15.7dB and average noise figure of 6.0dB. Note that only DRA3 was optimized in terms of Raman fiber length; DRA2 used a new prototype fiber having larger A_{eff} but higher than expected loss. All three DRAs had positive dispersion at the signal wavelengths and thus provided no pre-dispersion compensation or inline dispersion compensation, as is optimal for coherent systems [9].

After 20 loops (6000km), each channel was independently received using a tunable optical filter with $\sim$0.6nm -3dB bandwidth, followed by a polarization- and phase-diverse coherent receiver with balanced photodiodes having -3dB bandwidth of 40GHz. A four-channel real-time oscilloscope (with 80GSa/s and 33GHz bandwidth) performed the sampling and digitization function, followed by post-transmission offline digital signal processing of the captured data, as described in [10]. Errors were counted over 1×10^6 bits of information for each WDM channel.

III. TRANSMISSION RESULTS AND DISCUSSION

Optimization of the transmission system was carried out experimentally. First the launch power into the ULA spans

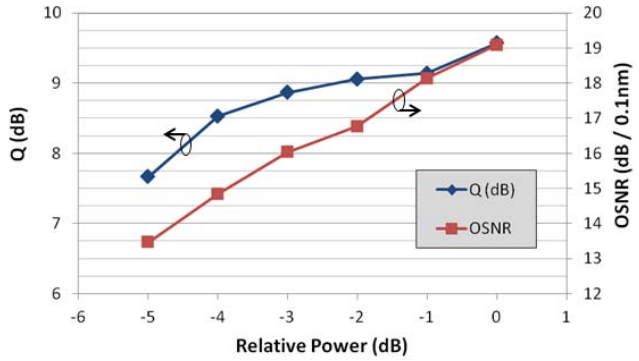

Fig. 4. 20 log (Q) and OSNR of the center channel after 6000km as a function of launch power, where 0dB relative power corresponds to −1.5dBm/ch at the input to each span.

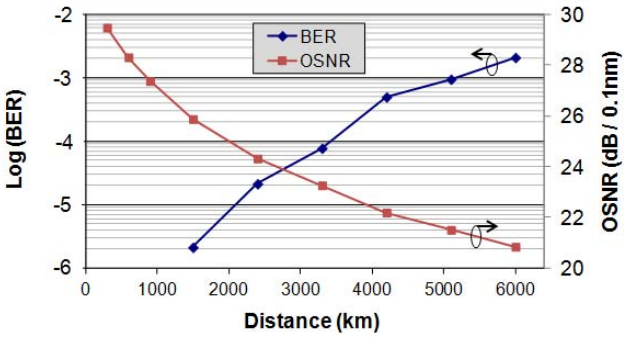

Fig. 5. Bit-error-ratio and OSNR of the center channel (at 1563.06nm) as a function of distance.

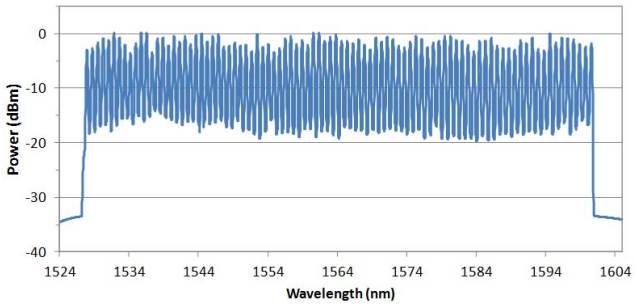

Fig. 6. Optical spectrum of the ninety 128Gb/s channels after 6000km transmission, measured with resolution bandwidth of 0.2nm.

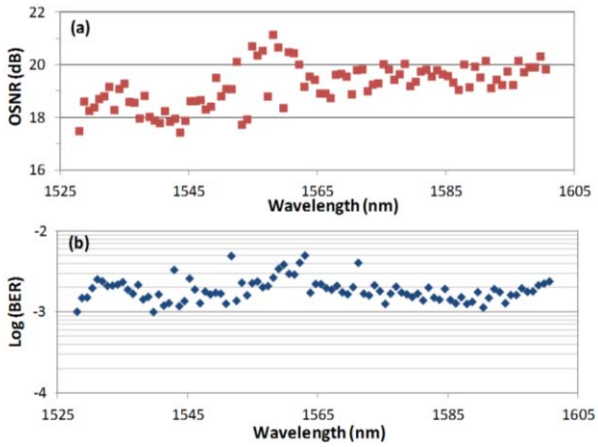

Fig. 7. (a) Measured OSNRs (in 0.1nm) and (b) bit-error-ratios for all 90 channels after 6000km transmission.

was set at +18.0dBm (−1.5dBm/ch), which was the maximum available launch power due to the limited available pump power for DRA3 in the loop. Then the Raman pumps were adjusted to achieve transparency in each span and optimum flatness across the spectrum. In order to evaluate the launch power sensitivity without significantly affecting the spectral flatness, the launch power of the center channel (1563.05nm) and its ten nearest neighbors were attenuated in 1dB steps using the WS4000SX, as the bit-error-ratio (BER) of the center channel was measured after 20 loops (6000km). Fig. 4 plots 20log(Q) (where Q is inferred from BER) and OSNR versus the relative launch power. Due to the complexities of the loop setup and per-channel equalization, one can see variations from a slope of 1 for the OSNR. For the interval from −5 to −4dB relative power, the OSNR increases by 1.4dB, while Q increases by 0.9dB, thus indicating that the system was operating in a slightly nonlinear regime at the lowest channel power measured. However, Fig. 4 indicates that Q continues to improve with launch power, and the maximum available launch power provides the lowest BER at 6000km. Note that the optimal launch power for the ULA spans is significantly higher than the −6dBm/ch optimum span launch power for the experiment of Ref [5]. Fig. 5 plots the evolution of the bit-error-ratio and optical signal-to-noise ratio for the center channel (1563.05nm) as a function of transmission distance with launch power of −1.5dBm/ch. The optical spectrum after 6000km is shown in Fig. 6, where the peak-to-peak channel power variation was within 4dB.

After 6000km transmission, the received OSNRs for the 90 channels ranged from 17.4 to 21.1dB (in 0.1nm), with average of 19.3dB (Fig 7a). The OSNRs had approximately 2dB of slope across the channels due to stimulated Raman scattering, which causes power transfer from the shorter wavelength channels to the longer wavelength channels. However, the co-pumping at 1425 and 1455nm mitigates the OSNR degradation of the short wavelengths. The average BER is 2.0×10^{-3} (as shown in Fig. 7b), and all 90 channels have BERs less than 5×10^{-3}, which is well below the threshold of 2.4×10^{-2} BER for 20% soft-decision forward error correction using quasi-cyclic low-density-parity-check code [11]. Figure 8a plots BER versus OSNR for the center channel (1563.05nm) for back-to-back and after 6000km transmission with addition of amplified spontaneous emission at the receiver (as shown in Fig. 1). Based on the least-squares fits, the OSNR penalty at 2.0×10^{-2} BER was 1.9dB. This penalty is quite close to the 1.76dB optimum nonlinear penalty derived in [12] from closed-form expressions for performance prediction of WDM PM-QPSK long-haul uncompensated transmission, thus indicating that the launch power was close to optimum. For this particular channel, the OSNR margin was nearly 7dB, and for channels with the lowest OSNR, the margin still would be more than 3.0dB.

Finally, to evaluate the possibility of 50GHz channel spacing, ten additional 100GHz-spaced channels were multiplexed with the channel-under-test before the PM-QPSK modulator

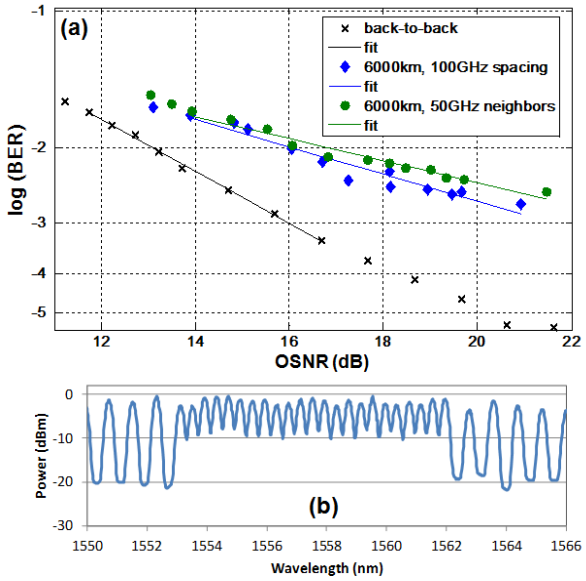

Fig. 8. (a) Comparison of BER vs OSNR performance of back-to-back, 1563.05nm channel with 100GHz channel spacing after 6000km, and 1557.77nm channel with 50GHz neighbors after 6000km. (b) Optical spectrum showing the 50GHz-spaced channels.

to create twenty-three 50GHz-spaced channels near the center of the band (which carried 100 channels in total). The per-channel power of the twenty-three 50GHz-spaced channels was set to be the same as the other 100GHz-spaced channels, so the nominal per-channel power was −2.0dBm (and close to the −1.5dBm per-channel power in the experiments with 90 channels at 100GHz spacing). The BER versus OSNR curve for the center 50GHz-spaced channel (at 1557.77nm, see Fig. 8b) was measured and is also plotted in Fig. 8a. Compared to the BER curve with 100GHz channel spacing, there is less than 1dB of additional OSNR penalty at 2.0×10^{-2} BER. Thus, we conclude that for these 100Gb/s PM-QPSK signals, due to the large A_{eff} and large dispersion of the ULA fiber, intra-channel nonlinearities are dominant over inter-channel nonlinearities, and the tighter channel spacing causes little additional nonlinear impairment. Given the more than 3dB margin for 100GHz spacing, and assuming that sufficiently powerful pumps would be available to provide inline discrete DRA and distributed Raman amplification supporting total launch powers of up to 21 dBm, transmission with 50GHz channel spacing (i.e. 18Tb/s) in a seamless 73nm band appears feasible over similar distances.

IV. Conclusion

In summary, we have demonstrated 6000km transmission of ninety 128Gb/s, 100GHz-spaced PM-QPSK signals in a seamless 73nm band. The result was enabled by all-Raman amplification in 100km spans of ultra-large-area fiber and by low-noise-figure, single-stage discrete Raman amplifiers. Equalization of the spectrum was achieved using liquid-crystal-on-silicon optical processors capable of seamlessly covering the entire 73nm band. To our best knowledge, 60×100km is the longest transmission distance demonstrated for a >70nm seamless band of 100G channels. In addition, the OSNR margin of more than 3dB, coupled with less than 1dB additional OSNR penalty observed in tests with 50GHz-spaced neighbors compared to 100GHz spacing, indicate the potential for practical long-haul WDM systems carrying 100Gb/s channels on the 50GHz grid in a single seamless C+L band over distances of several thousand kilometers.

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