40 x 10 Gb/s S-band transmission over 600 km of non-zero dispersion fiber

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Abstract: S-band Raman amplifiers are investigated that compensate both dispersion and span loss using distributed and discrete amplification over 1488–1518 nm. Error-free transmission of 40 x 10 Gb/s is demonstrated over 6 x 100 km of Lucent prototype TrueWave® fiber using a recirculating loop.

Introduction: Cost-efficient transmission systems require the bit-rate distance product to be maximised. In WDM systems, the total transmission capacity is determined by the bit-rate of a single wavelength channel and the total number of wavelengths used. To achieve high transmission capacity at a given bit-rate, narrow channel spacing is required. However, dense channel spacing in WDM systems results in fibre nonlinearities due to cross-phase modulation and four wave mixing limiting transmission. One approach to overcome this limitation is the use of additional wavelengths in the low loss region of the optical fiber. Currently, high capacity transmission is restricted to the C and L band only due to the available gain bandwidth of erbium-doped amplifiers. To further expand the bandwidth, novel broad band amplifiers are needed to fully utilize the low-loss spectral window in optical fibers. In the S-band (1480-1530 nm) possibilities include Raman amplifiers [1,2] and gain-shifted Thulium-doped fiber amplifiers (GS-TDFA) [3,4]. Early experiments using GS-TDFAs have demonstrated S-band transmission over dispersion-shifted fiber (10 x 10 Gb/s over 3 x 80 km [5]) and standard singlemode fiber (12 x 10 Gb/s over 125 km [6]). Raman amplification offers a flexible approach: distributed amplification in the transmission span permits system performance not possible using only discrete amplifiers by increasing the optical signal-to-noise ratio (OSNR) [7]. Additional Raman amplification in the inter-span dispersion-compensating fiber (DCF) allows simultaneous compensation of span dispersion and loss. Recently, S-band transmission was demonstrated using discrete Raman amplifiers [8] and [9] using a combination of GS-TDFA and distributed Raman amplification.

In this paper, Raman amplifiers are presented which are designed for S-band transmission from 1488 to 1518 nm. In an all-Raman recirculating loop experiment, 40 channels at 10Gb/s were transmitted over 600 km of a prototype TrueWave® fiber resulting in a bit rate-distance product of 240 (Tb/s)-km [10].

Amplifier designs and performance: Figure 1 shows an overview of the transmission experiment. The inline amplifiers were designed to matched to a prototype TrueWave® fiber. This transmission fiber has a zero dispersion wavelength below commercially available NZDFs (<1400 nm). The dispersion is sufficient in the S-band to allow DWDM transmission without incurring penalties from four-wave mixing (FWM). In addition, the low relative dispersion slope (0.008 nm^{-1} at 1500 nm) would allow slope matching with a DCF specifically designed for the S-band. Figure 2 shows a schematic of the inline amplifier providing up to +18 dBm total output power with ±1.0 dB channel power variation. The span was pumped using a CPFL/CRR fiber laser (cladding-pumped fiber laser + cascaded Raman resonator [11]) to achieve a peak on-off gain approximately 1-dB below transparency at 1505 nm (see Fig. 3). Lucent's High-Slope DCF provided 95% span dispersion compensation and functioned as an efficient Raman gain medium for compensating residual span loss. Two stages with interstage isolation minimized double-Rayleigh scattering [12] and allowed gain flattening using long period fiber Bragg gratings

(LPG). The DCF was pumped using two CPFL/CRRs at 1393 nm (650 mW) and 1427 nm (250 mW). This choice of pump wavelengths reduced the gain variation across the channels so the gain flattening filter (GFF) only needed to provide an additional 2.9 dB attenuation. Figure 3 shows the effective noise figure of the inline amplifier, i.e. the noise figure required for a discrete amplifier to have the same noise performance [13]. It is below the fundamental limit for discrete amplifiers by more than 3 dB which demonstrates the benefit of distributed amplification.

S-band amplifiers were also required at the transmitter and receiver. We designed a booster amplifier to provide +22 dBm of output power, with less than ±0.35 dB gain ripple, as well as –270 ps/nm of pre-compensation at 1500 nm. The two-stage design used DCF with interstage isolation and gain flattening. The 1.4-km first stage was counter-pumped with 1393 nm (930 mW) and 1427 nm (500 mW); the 2.0-km second stage was counter-pumped with 1410 nm (800 mW). Figure 4(a) shows gain and noise figure performance for +22 dBm output power.

The preamplifier provided more than 20-dB of gain as well as +90 ps/nm of post-compensation. The first stage was 1.6 km of DCF, pumped at 1393 nm (0.9 W) and 1427 nm (0.5 W); the second stage was 15.4 km of SMF, pumped at 1410 nm (1.0 W). The gain and noise figure are shown in Fig. 4(b). In back-to-back tests with a single channel (-10 dBm input power), we obtained a Q-value of 16.0 dB for an OSNR of 17.1 dB (in 0.1 nm RBW).

System demonstration: As shown in Fig. 1, the DFBs and tunable lasers were multiplexed using an arrayed waveguide router (AWG) with a spacing of 100 GHz on the ITU grid from 1488.5 to 1517.9 nm. The channels were polarization aligned and modulated using a Mach-Zehnder modulator with 10 Gb/s NRZ data having $2^{31}-1$ PRBS length. The booster amplifier increased the power launched into the span to +16 dBm (0 dBm per channel) and provided –270 ps/nm of precompensation to decorrelate the channel bit patterns. In the three-span recirculating loop the output power of the third inline amplifier was increased to partially compensate for loop loss. An additional GFF inside the loop flattened the output spectrum to ±1.3 dB after 600 km.

Figure 5 shows the accumulated dispersion for center and edge channels. The residual dispersion varied by 220 ps/nm across the 30-nm band after transmission. The transmitted channels were selected using an optical bandpass filter (BPF) and amplified before detection. Figure 6 shows the OSNR for each channel at the input of the first span, after 300 km and 600 km. A variation of 3dB across the channels after 600 km is due in part to the wavelength dependence of the effective noise figure of the inline amplifiers. The Q-values for each channel, obtained by measuring bit error rate versus decision threshold [14], are shown in Fig. 7, (worst-case value = 16.0 dB, best-case = 18.3 dB) demonstrating error-free transmission. Figure 8 shows the output spectrum with channel 21 turned off. Even for the worst-case of initially aligned channel polarizations, no significant FWM is present after 600 km of propagation in the prototype TrueWave® fiber. In a modified setup, channel 20 was modulated with a separate modulator at 10Gb/s to investigate the impact of XPM on the transmission penalty. The detected channel was modulated whilst the interfering channels were either modulated or in CW mode. This technique allowed to estimate the XPM penalty of the center channel to be approximately 0.5 dB after 300km transmission. This value is close to the accuracy of the experimental Q-factor measurements and therefore negligible.

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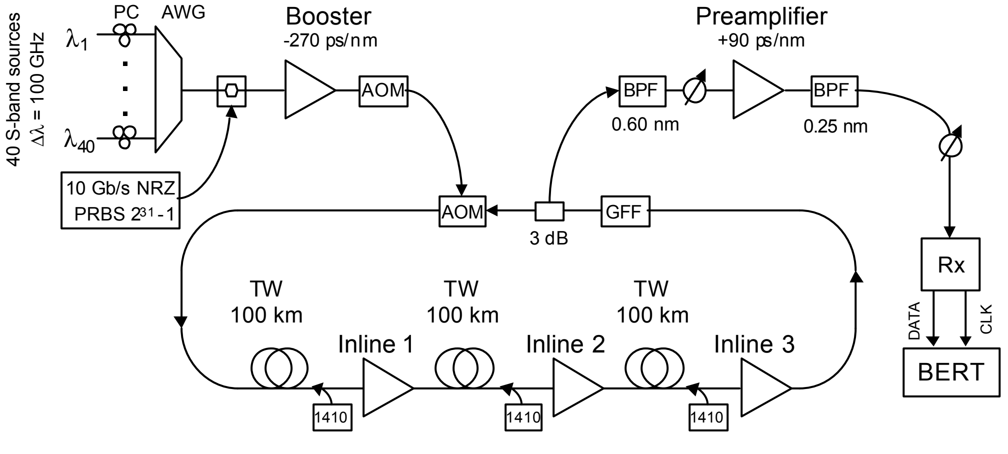
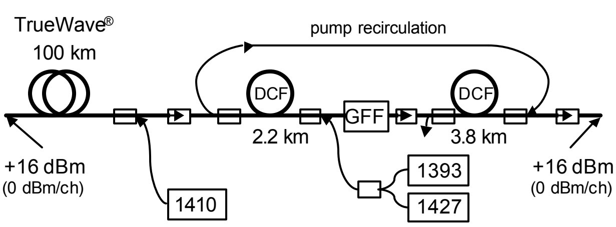


Fig 1: Experimental setup for S-band all-Raman WDM transmission.



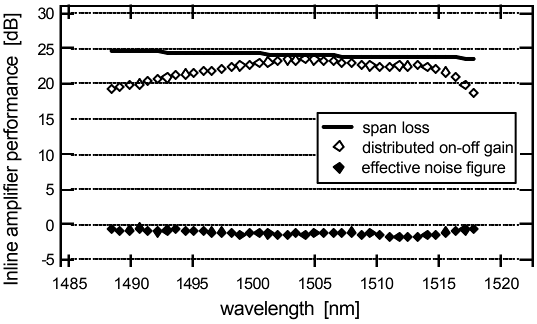


Fig 2: Inline amplifier configuration showing distributed amplifier (100-km span) and two-stage discrete amplifier

Fig 3: Span loss, distributed on-off gain produced by the 1410-nm pump, and effective noise figure [10]

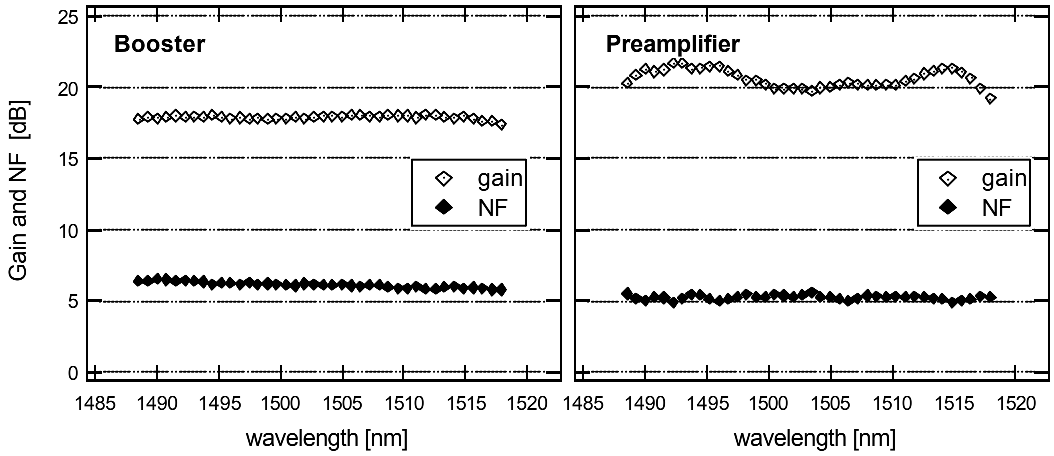


Fig. 4: Gain and noise figure performance measured for the Raman S-band booster and preamplifier

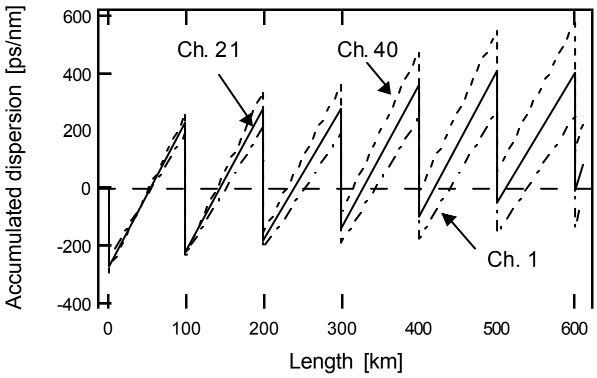


Fig. 5: Dispersion map for 600km showing pre-compensation in the booster, 95% span compensation in the inline amplifiers and post-compensation in the preamplifier. The residual dispersion after 600 km across the band is 220 ps/nm

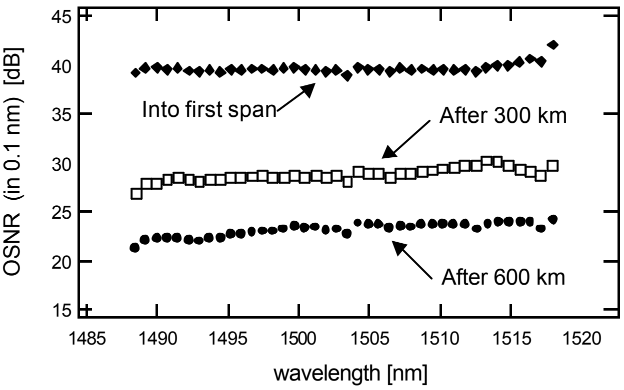


Fig. 6: Optical signal-to-noise ratio (in 0.1 nm RBW) launched into first span, after 300 km, and after 600 km.

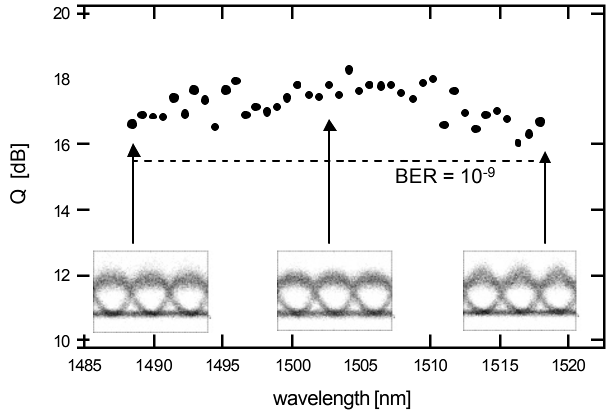


Fig. 7: Q-values and received eye diagrams after 600-km transmission..

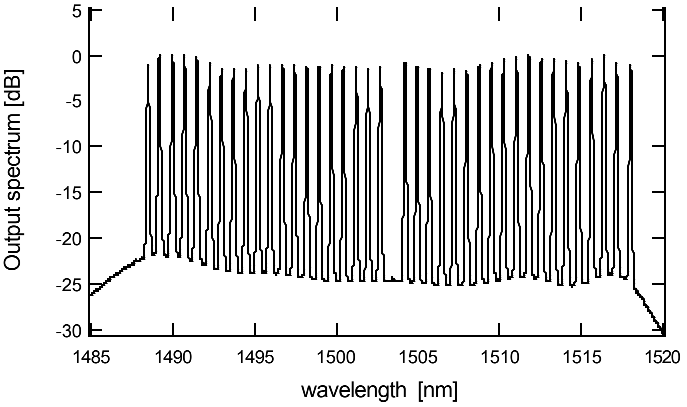


Fig. 8: Output spectrum after 600 km with channel 21 turned off to show absence of four-wave mixing