Raman Gain Enhanced FWM 160Gb/s OTDM Demultiplexer with Highly-Nonlinear-Fiber

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Abstract: Error free demultiplexing of 160Gbps data to 10Gbps was demonstrated with less than 2dB power penalty using Raman gain enhanced four-wave-mixing in highly-nonlinear-fiber. A 19dB efficiency increase over FWM without Raman was achieved by using 400mW of Raman pump power.

OCIS codes: (060.2330) Fiber optics communications; (060.4510) Optical communications

1. Introduction

All optical time division multiplexing (OTDM) technology has developed significantly with terabit per second single channel data rates demonstrated recently [1]. All optical demultiplexing is a critical function and one of the more difficult to achieve high performance. Fiber based all optical demultiplexers based on four-wave-mixing (FWM) have a broad operation range and can attain terabit-per-second performance due to the femto-second response time of the fiber nonlinearity [2]. Other approaches include the nonlinear loop mirror (NOLM) [3] and cross-phase-modulation (XPM) induced phase shift in fiber [4]. FWM is transparent to both bit rate and modulation format and therefore techniques to increase the conversion efficiency are desirable. FWM switching is more robust to environmental disturbances compared to the NOLM, since no interferometric process is involved. In the past these fiber demultiplexers have utilized bulk EDFA amplification prior to injecting the signal into the fiber in order to maximize the efficiency and power levels as high as 800mW [4] were used to demultiplex 160Gbps data. At this high power level, it is difficult to control the unwanted nonlinear processes in the fiber, e.g. the self-phase-modulation (SPM) spectral broadening of the switching pulses. Alternatively the Raman amplifier has been studied as a strong candidate for improving optical signal-to-noise ratio and thereby expanding span length in communication systems due to its distributed nature [5]. Recently regenerative Raman gain assisted 80Gbps wavelength conversion using fiber XPM [6] and Raman gain assisted parametric conversion for continuous wave (CW) operation [7] were demonstrated.

In this paper we report what we believe to be the first time demonstration of Raman gain enhanced FWM in optical fiber to achieve 160 Gbps demultiplexing to 10 Gbps. We show that Raman gain assists FWM at 160Gbps data rate by accelerating the energy transfer process from the pump and the probe light to the idler. At a Raman pump power of 400mW, where the small signal peak Raman gain was only around 6dB, the FWM DEMUX efficiency is enhanced by 19dB over that without Raman amplification. To demultiplex 160Gbps data with 450mW of Raman pump power, only 8mW data average power and 3.8mW switching pulse average power were required.

2. Demultiplexing experiment and results

The experimental setup is shown in Figure 1. An actively mode-locked fiber ring laser (FRL) generated 2ps (FWHM) pulse with 10 GHz repetition rate. The higher bit rate data stream was achieved by a passive split, delay and time interleave multiplexer (MUX) after 10Gbps data, PRBS 2^{31}-1, was encoded. The EDFA after the MUX was used to compensate the loss of the MUX and control the power of the data into the fiber. The data was combined with the 10 GHz switching pulse from another FRL using a 50/50 coupler. The pulse width of the switching pulse was 5ps and a polarization controller was used to make sure it had the same polarization state as the data signal. The fiber Raman amplifier and the FWM media consisted of an isolator, 1km of Highly-nonlinear Dispersion shifted fiber (HNLDSF) and a tunable Raman pump laser at 1455nm with a maximum output power of 850mW. A counter propagating pump scheme was used to minimize the effect of pump fluctuation on the amplifier gain [8] and a 0.6nm band pass filter was used to select the FWM component. The HNLDSF has a nonlinear coefficient of 10.5 $km^{-1}W^{-1}$ and a dispersion slope of 0.027ps/nm^2.km with zero dispersion wavelength at 1527nm.

To characterize the demultiplexer, the experiment was first carried out at 80Gbps. Figure 2 shows the spectrum at various points of the demultiplexer. The wavelength of the 80Gbps data was set at 1546nm and the wavelength of the 10GHz switching pulse was at 1554nm. The FWM component filtered out for the demultiplexed 10G signal was at 1562nm. A significant FWM component increase as much as 13.3dB was observed with only 300mW of Raman pump power. Additional measurements were performed with the Raman pump power varied from 200mW to 400mW to further study the influence of Raman gain on the DEMUX efficiency. With a Raman pump power of 400mW, a DEMUX efficiency enhancement of 19dB was achieved. Compared to the enhancement of 13.3dB with a pump power of 300mW, the total enhancement increase was close to 6dB, while the small signal gain increase was only 2dB. Figure 3 shows the BER for demultiplexing 80Gbps data at 1546nm to 8 10Gbps channels at 1562nm and the eye patterns of the 80Gbps signal and one of the demultiplexed channels. The Raman pump power was set at 300mW for the measurement. The BER was measured for each of the demultiplexed 10Gbps channels from the 80 Gbps stream. An average power penalty of less than 1.5dB at BER=1E-9 for all eight channels compared to back to back measurement was measured. The difference among all eight channels was within 1dB, which was due to the non perfect multiplexing process.

160Gbps demultiplexing was next achieved by using a 1:16 passive multiplexer. To show the wide-band operation of this demultiplexer, the wavelength of the 160Gbps data was set at 1554nm and the 10G switching pulse was set at 1547nm. The FWM component filtered out for the demultiplexed 10G signal was at 1540nm. Although the switching window for the demultiplexer was only determined by the switching pulse width and 5ps was enough for 160Gbps, the switching pulses were found to be broadened due to accumulated dispersion and were only marginally applicable for 160Gbps demultiplexer. For this reason the switching pulses were compressed to 4ps by using a soliton compressor before injection into the fiber. The average power of the 160Gbps data was measured to be 8mW into the fiber and the power of the 10G switching pulse was only 3.8mW. Figure 4 shows the BER for demultiplexing 160Gbps data at 1554nm to 16 10Gbps channels at 1540nm and the eye patterns of all 16 demultiplexed channels. The Raman pump power was set at 450mW for the measurement. Full BER measurements for all 16 channels were performed and Figure 4(a) shows four of the bit error rate curves and the receiver sensitivities for all the 16 channels. It is evident from this figure that no indication of an error floor was observed. It is noted that the slope of the demultiplexed curve was almost the same as that of the back-to-back curve. The power penalty of the 16 channels was quite low and varied from 1.2dB to 1.9dB at BER=1E-9. Again the difference among the 16 channels was attributed to the imperfection of the optical multiplexer. A similar measurement to calibrate the Raman enhancement for the FWM DEMUX efficiency was done for the 160Gbps demultiplexer. Figure 5 shows the efficiency enhancement measurement results for both the 80Gbps demultiplexing experiment at 1546nm and the 160Gbps experiment at 1554 nm together with the small signal peak Raman gain at 1552nm. When comparing these two curves, a similar trend could be observed and it was very clear that Raman gain greatly enhanced the FWM process. The absolute value difference between these two curves was attributed to the non flat shape of the Raman gain for this Raman amplifier. The inset of Figure 5 shows the measured small signal Raman gain with a Raman pump power of 850mW. The Raman gain at 1542nm for the 160Gbps experiment was 2dB lower than the gain at 1560nm for the 80Gbps experiment. With a proper designed flat gain Raman amplifier, we would be able to get equal enhancement for all wavelengths.

3. Conclusion

We have demonstrated a low input power 160 Gbps all-optical fiber FWM demultiplexer by using distributed Raman gain to enhance the FWM process. The power level of the 160Gbps data was only 8mW with a 10GHz switching pulse power level of 3.8mW into the fiber. The total FWM DEMUX efficiency enhancement was 19dB with only 400mW of Raman pump power. Furthermore, the demultiplexer has the potential to operate over a wide wavelength range due to the wide bandwidth of FWM in HNLF and meanwhile the distributed Raman gain can offer improved OSNR. Bit-error-rate measurements demonstrated less than 2.0dB penalty for 160Gbps RZ data. At this low input power level, Raman enhanced FWM shows great promise to increase the demultiplexing efficiency while at the same time managing the unwanted nonlinear effects, such as the SPM spectral broadening of the switching pulses.

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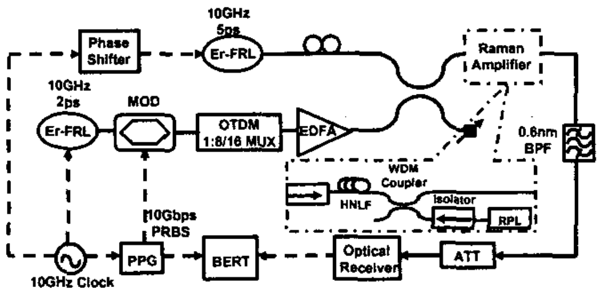

Fig.1: Experimental Setup

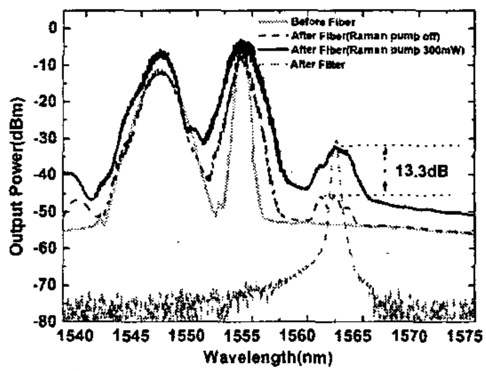

Fig. 2: Optical spectrum at various points of the DEMUX

BER for 80Gbps DEMUX(2^31-1)

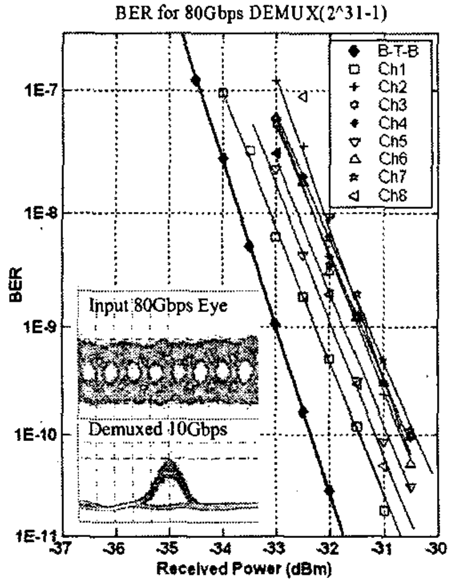

Fig. 3: Optical BER measurements for demultiplexing 80Gbps signal at 1546nm to 8 10Gbps channels

BER for 160Gbps DEMUX(2^31-1)

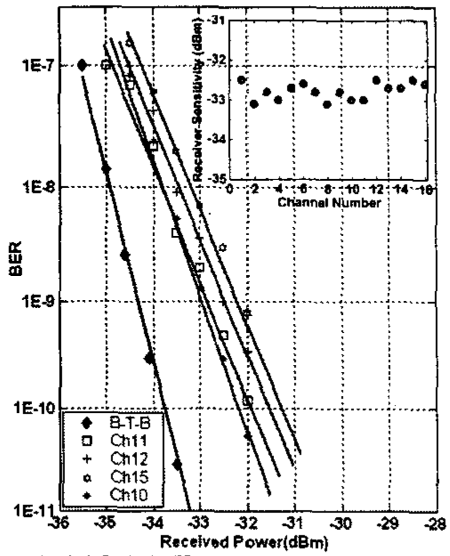

Fig. 4(a) Optical BER measurements for demultiplexing 160Gbps signal at 1554nm to 16 10Gbps channels

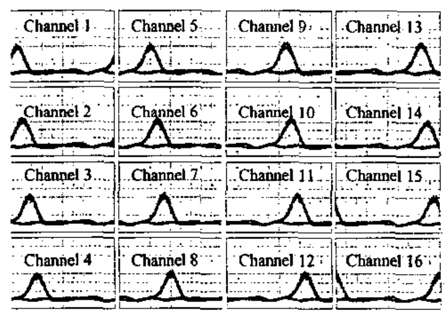

Fig. 4(b) Eye diagrams of 16 demultiplexed channels (Time 10ps/div)

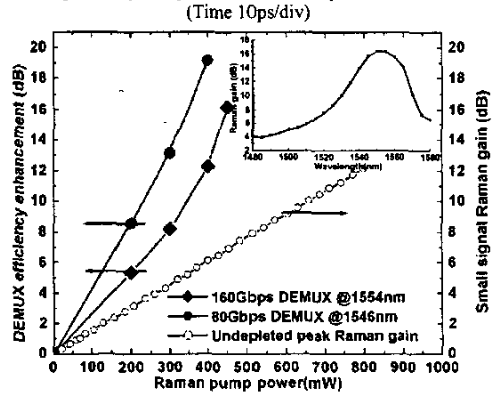

Fig. 5 FWM DEMUX efficiency enhancement measured at peak FWM component versus Raman pump power