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**TuH2 2:30 PM**

## 80-Gb/s Regenerative Wavelength Conversion Using a Hybrid Raman/EDFA Gain-Enhanced XPM Converter with Highly-Nonlinear-Fiber

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Regenerative Wavelength conversion at 80 Gbps with a negative power penalty of 2dB at $10^{-9}$ BER is demonstrated using Cross Phase Modulation (XPM) enhanced by Raman gain in 1Km of highly-nonlinear-dispersion-shifted fiber.

### 1. Introduction

All optical wavelength conversion is a key technology for improving the flexibility and increasing the capacity of photonics networks. Wavelength conversion using cross-phase-modulation (XPM) in a dispersion-shifted-fiber (DSF) has the potential of attaining terabit-per-second performance due to femto-second response time of the optical nonlinearity and broad conversion range. In the past these wavelength converters have utilized bulk EDFA amplification prior to injecting the signal into the fiber in order to maximize the XPM over the wavelength conversion range of interest [1]. Alternatively the Raman amplifier has been studied as a strong candidate for improving optical signal-to-noise ratio and expanding span length in communication systems due to its distributed nature and superior noise performance [2]. Recent studies show that timing jitter is reduced by up to a factor of two when lumped amplification is replaced by complete or partial distributed amplification [3].

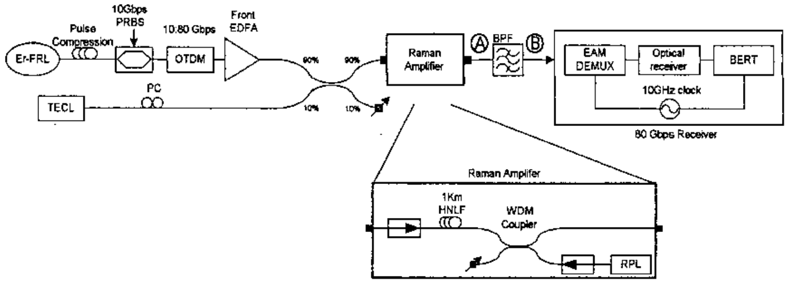

Fig. 1. Experimental setup

|  | Length of fiber(Km) | Fiber Parameter<br>$\gamma$ (1/W.Km)/$A_{eff}$($\mu$ m$^2$)/$g_R$(*$10^{-14}$m/W)/D'(ps/nm$^2$.Km) | $G_A$(dB)<br>$P_0$=500mW |
|---|---|---|---|
| DSF WC | 5 | 3.5/50/2.08/0.27 | 3.9 |
| HNLDSF WC | 1 | 10.9/11.8/5.03/0.0167 | 8.5 |

Table 1. Standard DSF and HNLF wavelength converter parameters

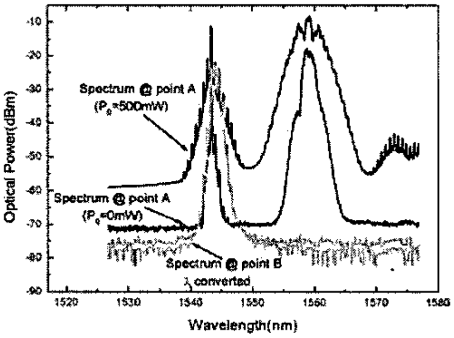

Fig.2. (a) Spectrum at point A (with Raman pump on/off) and B of the wavelength converter in figure 1

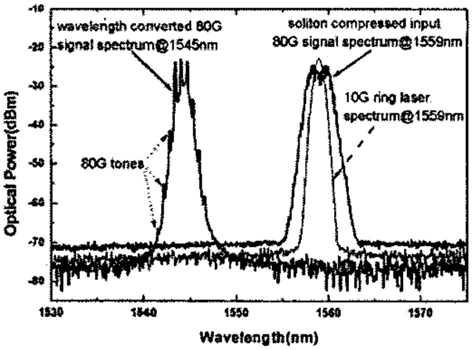

Fig. 2. (b) Optical Spectrum of the original and the wavelength converted signal (Resolution BW: 0.1nm)

In this work we demonstrate that by combining distributed Raman amplification with bulk-EDFA amplification, the OSNR and extinction ratio of fiber XPM wavelength conversion can be optimized. With the help of highly-nonlinear-dispersion-shifted-fiber (HNLDSF), we have successfully shortened the fiber length to 1Km and extended the conversion bandwidth to almost entire C band at 80 Gbps rate. Previous results required 5Km of common DSF fiber due to the relatively low Raman gain coefficient [4]. Shorter fiber is preferred for XPM based wavelength converter in order to minimize the walk off effect and improve stability. Since the Raman amplifier has a broad amplification bandwidth of more than 30nm, the probe light was also amplified with an increase in the conversion efficiency. Compared to lumped amplification using erbium-doped fibers, this scheme significantly improves the signal-spontaneous beat noise performance at the receiver by amplifying the signal channels while they are in the transmission fiber [5]. It also reduces the amount of crosstalk from the pump light by reducing the amount of Self-Phase-Modulation (SPM) of the pump light while maintaining the same conversion efficiency.

### 2. Experimental Setup

The experimental setup is shown in Figure 1. An actively mode-locked fiber ring laser generated 4.5ps pulses at 1559nm with 10 GHz repetition rate. The pulses were compressed to 2ps using soliton compression before 10Gbps data, PRBS $2^{31}$-1, was encoded. An 80Gbps data stream was achieved by a passive 10 to 80 Gbps split, delay and time interleave multiplexer. The 80Gbps data was amplified to 10dBm and then combined with CW light from a tunable external cavity laser using a 90/10 coupler. The fiber Raman amplifier consisted of an isolator, 1Km of HNLDSF with a zero dispersion wavelength of 1553nm and a tunable Raman pump laser 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 [6] and a 1.2nm band pass filter was used to select the longer wavelength sideband. Demultiplexing 80Gbps signal into a 10Gbps signal for Bit-Error-Rate (BER) measurements was achieved using an electroabsorption modulator (EAM) with a 7.5-ps switching window.

Table 1 shows the comparison between common DSF and HNLDSF based wavelength converter in terms of nonlinear coefficient, dispersion and Raman gain. Raman pump on-off gain can be approximately described by $G_A=\exp(g_R P_0 L_{eff}/A_{eff})$, where $g_R$=Raman Gain Coefficient, $P_0$=pump power, $L_{eff}$=effective length, $A_{eff}$=effective area. Due to the larger Raman gain coefficient and smaller mode area, 16dB small signal gain can be achieved within only 1Km of HNLF.

## 3. Results and Discussion

The optical spectrum measured after the HNLF with and without Raman gain is shown in Figure 2(a). It is seen that a significant XPM sideband increase was observed with 500mW Raman pump power. The converted signal at 1545nm has an OSNR of more than 50dB. Figure 3 shows the BER for wavelength conversion from 1559 to 1545 nm and the eye patterns of the original and wavelength converted 80Gbps signal. The BER was measured for each of the demultiplexed 10Gbps channels from the 80 Gbps converted stream. It showed a negative power penalty of 2dB at BER=1E-9 for all eight channels compared with back to back measurement. Tuning characteristic of the wavelength converter was measured by tuning the CW light from 1535 to 1555nm in 2nm steps. The converted pulse width was measured to be 3.75ps with less than 25% variation over the considered wavelength range. The converted pulses were broadened due to limited filter bandwidth, which were maintained less than the intersignal-interferece limit for 80Gbps signal 6ps.

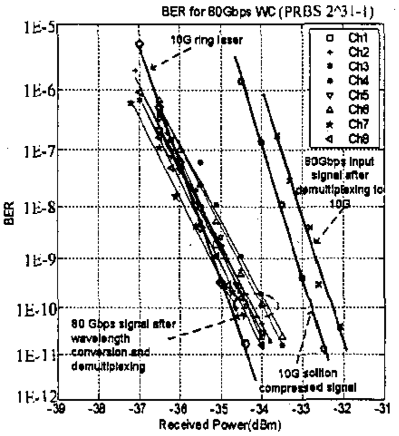

Fig. 3. (a) BER measurements for wavelength conversion of 80 Gbps data from 1559 nm to 1545nm

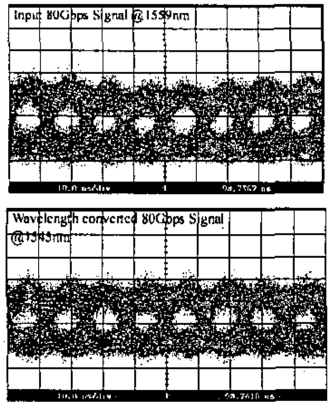

Fig. 3. (b) Eye diagrams of input and wavelength converted signal @80G (Time 10ps/div)

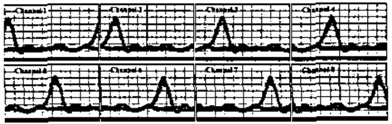

Fig. 3. (c) Eye diagrams of converted 80Gbps signal demultplexed to 8·10Gbps channels (Time 10ps/div)

The negative power penalty exhibited by the wavelength converter can be explained by the nonlinear transfer function of the wavelength converter, and clearly demonstrates the reshaping properties in both the frequency and the time domain. Figure 2(b) shows the optical spectrum of the original and the wavelength converted signal at 80G. After soliton compression, the spectrum of the original signal was broadened, which showed a large amount of chirp. By comparing the original and the wavelength converted signals, the spectral reshaping effect is clearly seen. The reshaping effect is also observed from eye diagrams, with the converted signal having more uniform eyes.

## 4. Conclusion

We have demonstrated an 80 Gbps all-optical fiber XPM wavelength converter using distributed Raman gain to enhance the process. By utilizing the distributed nature of the fiber Raman Amplifier, the balance between SPM and XPM become easier to manage leading to an improved extinction ratio. Furthermore, the converter has the potential to operate over a wide wavelength range due to the HNLF and meanwhile the distributed Raman gain offers improved OSNR. This approach may therefore have advantages over approaches which use lumped optical gain at the input when scaling to higher bit-rates. Bit-error-rate measurements demonstrated 2.0dB negative penalty for 80Gbps RZ data.

## 5. Acknowledgments

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**TuH3** **2:45 PM**

## Experimental Demonstration of A Fiber-based Optical 2R Regenerator in Front of an 80Gbit/s Receiver

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We demonstrate, for the first time to our knowledge, an 80 Gbit/s optical 2R regenerator based on self phase modulation in fiber. The potential improvement in receiver sensitivity and tolerance to degraded optical signal-to-noise ratio is investigated.

### Introduction

To satisfy the demand for more transmission bandwidth, fiber capacity is expanded by increasing the number of wavelength channels (WDM) and/or the time-multiplexed bit rate (TDM) per wavelength channel. TDM beyond 40Gbit/s is an attractive approach because it decreases the channel counts of WDM systems, and therefore reduces the effort of the channel management. For transmission at such high bit rates, degradation due to fiber nonlinearities, noise accumulation, and dispersion are more difficult to overcome; therefore it will require signals with high optical signal-to-noise ratio (OSNR) and receivers with high sensitivity. Alternately, a regenerator that performs 2R (re-amplification and reshaping) or 3R (re-timing) regeneration can help to alleviate degradation caused by these limitations. Re-timing in a 3R regenerator, which includes clock recovery and an optical pulse source in some cases, may be very costly. A simple 2R regenerator, which does not require clock recovery, can provide significant improvements in system performance at a fraction of the cost of a 3R regenerator.

As electronic signal processing is not available at bit rates higher than 40 Gbit/s, all optical regeneration is the only means to regenerate data at such high bit rates. An all-optical fiber-based 2R regenerator (O2R) has recently been demonstrated to enable improved receiver sensitivity , 50 GHz-channel-spaced WDM transmission over 2500 km, and single-channel pseudo-linear transmission over one million kilometers. This O2R utilizes a filter to discriminate marks and spaces based on the difference in self-phase-modulation (SPM) induced spectral broadening in an optical fiber with nearly zero normal dispersion. As the spectrum is broadened, the pulse width increases due to group velocity dispersion (GVD). Longer pulses reduce the extent of spectral broadening, and the adjacent pulses start to interfere with each other as the pulse width becomes even longer. Both degrade the performance of O2R, and therefore its applicability to bit rates above 40 Gbit/s is still an open question. In this paper, we demonstrate, for the first time to our knowledge, a SPM-based O2R regenerator operating at 80 Gbit/s. We show that the O2R can improve the receiver sensitivity for OSNR greater than 17 dB (measured in 1 nm bandwidth).

### Experiment setup

Figure 1(a) shows the schematic of the experimental setup. The light source is a 10 GHz mode-locked fiber ring laser, generating sech-like 3-ps pulse at 1552.5 nm. The pulses are optically multiplexed to 40 GHz using *polarization-maintaining* fiber delay lines, followed by a dual-arm driven Lithium Niobate data modulator. The 40 Gbit/s NRZ data is derived from electrically multiplexing four $2^{31}$-1 PRBS signals with proper delays. The single-polarized 80 Gbit/s signal is realized by optical multiplexing of two 40 Gbit/s RZ signals by another optical delay lines. The fiber lengths of the delaying branches in the multiplexers are several meters long, which assure data and phase decorrelation of adjacent time channels. The receiver is configured to resemble a real WDM 80 Gbit/s system and thus a 300 GHz arrayed waveguide-grating router (AWG), whose 3dB bandwidth is around 1.5 nm, is used at the input to represent the demultiplexer in a WDM system. The resulting 80-Gbit/s RZ signals has an OSNR > 35 dB as measured in 1 nm resolution bandwidth (RBW) on the optical spectrum analyzer. A representative 80Gbit/s eye diagram is shown in Fig. 1(b), taken with a 45 GHz photodiode and a 50 GHz sampling scope. Alternatively, the OSNR of the signal can be reduced by attenuating the power at the input to the Erbium doped fiber amplifier (EDFA) in front of the AWG router.

The O2R consists of a high power EDFA, a highly nonlinear fiber (HNLF), and an optical bandpass filter. The HNLF has a nonlinear coefficient around 8.4 $W^{-1}$ $km^{-1}$, a loss of approximately 0.6 dB/km, and a dispersion of -0.5 ps/nm-km at signal's wavelength. The optical bandpass filter is another 300-GHz AWG router with a 3dB bandwidth of 1.5 nm, and can be slightly temperature-tuned within less than 1 nm. The optimum launch power into the HNLF is around 350 mW and the filter offset is around 2.8 nm. We also monitored the backscattered light due to stimulated Brillouin scattering (SBS) in the HNLF with a RF spectrum analyzer. Over the range of power used in this experiment, we did not