Regenerative 80-Gb/s Fiber XPM Wavelength Converter Using a Hybrid Raman/EDFA Gain-Enhanced Configuration

Wei Wang, *Student Member, IEEE*, Henrik N. Poulsen, Lavanya Rau, *Student Member, IEEE*, Hsu-Feng Chou, John E. Bowers, *Fellow, IEEE*, Daniel J. Blumenthal, *Fellow, IEEE*, and Lars Grüner-Nielsen

***Abstract*—Regenerative wavelength conversion at 80 Gb/s using distributed Raman gain and cross-phase modulation (XPM) in 1 km of highly nonlinear dispersion-shifted fiber is demonstrated. Raman gain greatly enhances the fiber nonlinearity by changing the power evolution along the fiber and meanwhile maintains the signal-to-noise ratio of the wavelength converted signal due to the effect of distributed gain on optimizing cross-phase versus self-phase modulation. Bit-error-rate measurements were performed both before and after wavelength conversion, with a negative power penalty of 2 dB at 10^{-9} bit-error rate for return-to-zero formats. The reshaping properties of this wavelength converter were clearly demonstrated in both the frequency and time domain.**

***Index Terms*—Cross-phase modulation (XPM), nonlinear optics, optical fiber communication, Raman effect, wavelength conversion.**

I. 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 a broad conversion range and the potential of attaining terabit-per-second performance due to the femto-second response time of the optical nonlinearity. When the data is combined with the continuous wave (CW) and sent through the fiber, XPM imposes sidebands onto the CW. A bandpass filter is then used to select one of the sidebands and converts phase modulation to intensity modulation, and hence, converts the signal to the new wavelength. In the past, these wavelength converters have utilized bulk erbium-doped fiber amplifier (EDFA) amplification prior to injecting the signal into the fiber in order to maximize the XPM and, hence, the conversion efficiency over the wavelength conversion range of interest [1]. The optical digital regenerative characteristics, namely, impact on optical signal-to-noise (OSNR) and jitter, of wavelength converters is critical for high bit-rate communications over multiple fiber transmission spans and in optical networks. Fiber Raman amplification has been used to manage and optimize the OSNR extending the reach of fiber spans [2], and 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 [6].

It has been shown before that Raman assistance in highly nonlinear fiber promotes parametric amplification and wavelength conversion [4]. Although the principles of the XPM (based on the nonlinear Kerr effect) and four-wave mixing (a parametric process) are very different, the XPM-based wavelength converter can also benefit greatly from Raman gain. In this letter, 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. We obtain a negative 2-dB power penalty for compressed passively multiplexed 80-Gb/s data transmitted over 1 km of fiber and optically demultiplexed using an electroabsorption modulator (EAM). This level of regeneration demonstrates the converter's ability to reshape pulses that have a nonoptimal extinction ratio. We also employ highly nonlinear DSF (HNLDSF) to reduce the required fiber length to 1 km and extend the conversion bandwidth to almost the entire C band. Previous results required 5 km of common DSF fiber due to the relatively low Raman gain coefficient [5]. Conversion using a short fiber length is preferred for minimizing the walkoff effect and improving the stability. Since the Raman amplifier has an amplification bandwidth of more than 30 nm, the probe light was also amplified with an increase in the conversion efficiency as a result. Compared with 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 [6]. It also reduces the amount of spectral crosstalk from the pump light by reducing the amount of self-phase modulation (SPM) of the pump light while maintaining the same conversion efficiency.

II. Experimental Setup

The experimental setup is shown in Fig. 1. An actively mode-locked tunable fiber ring laser was used to generate 4.5-ps pulses at 1559 nm at a 10-GHz repetition rate, which were subsequently compressed to 2 ps using soliton compression and data modulated at 10 Gb/s of pseudorandom binary sequence $2^{31}-1$. An 80-Gb/s data stream was created by passively multiplexing the 10-Gb/s data using a split, delay, and time interleave multiplexer. The 80-Gb/s data was amplified to 10 dBm by an EDFA

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W. Wang, H. N. Poulsen, L. Rau, and D. J. Blumenthal are with the Optical Communications and Photonic Networks Group, Department of Electrical and Computer Engineering, University of California, Santa Barbara, CA 93106 USA (e-mail: wwang@engineering.ucsb.edu).

H.-F. Chou and J. E. Bowers are with the Ultra fast Optoelectronic Group, Department of Electrical and Computer Engineering, University of California, Santa Barbara, CA 93106 USA.

L. Grüner-Nielsen is with the Specialty Photonics Division, OFS Denmark, DK-2605 Brondby, Denmark (e-mail: lgruner@ofsoptics.com).

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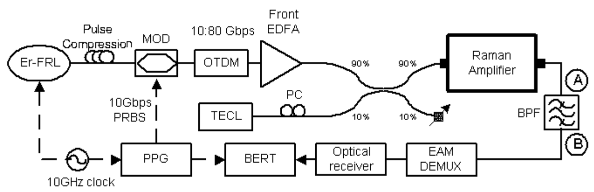


Fig. 1. Experimental setup.

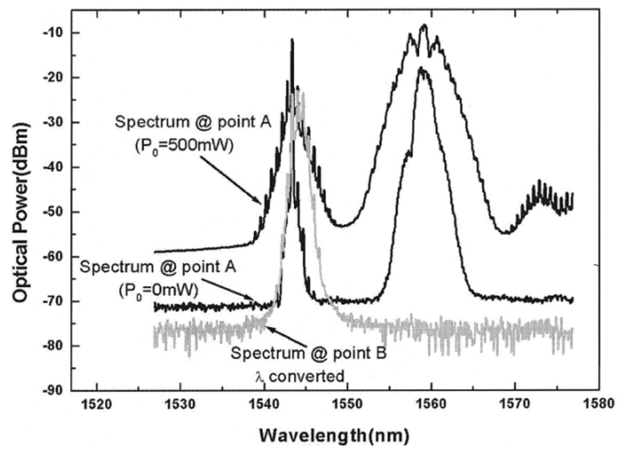
then combined with CW light from a tunable external cavity laser using a 90/10 coupler. The fiber Raman amplifier consisted of an isolator, 1 km of HNLDSF with a zero dispersion wavelength of 1553 nm, and a tunable Raman pump laser with a maximum output power of 850 mW. A counterpropagating pump scheme was used to minimize the effect of pump fluctuation on the amplifier gain [7] and a 1.2-nm bandpass filter was used to suppress the CW light and select the longer wavelength sideband. Demultiplexing the 80-Gb/s signal into a 10-Gb/s signal for bit-error-rate (BER) measurements was achieved using an EAM with a 7.5-ps switching window [8].

III. Results and Discussion

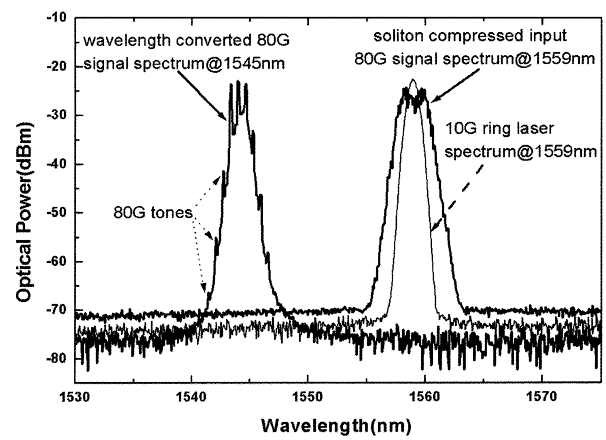
The optical spectrum measured after the HNLF with and without Raman gain is shown in Fig. 2(a). A significant XPM sideband increase was observed with 500 mW Raman pump power. Raman gain enhances XPM by changing the power evolution along the fiber. If we define the nonlinear enhancement factor $E_{\rm RA}$ from Raman gain as the ratio between XPM broadening with and without Raman gain, the expression can be derived under no pump depletion assumption as

$$E_{\rm RA}({\rm dB}) = 10\log\left[\frac{\left(\int_0^L \exp\left[g_R \frac{P}{A_{\rm eff}} \frac{e^{-\alpha_p L}(e^{\alpha_p z}-1)}{\alpha_p} - \alpha_s z\right] dz\right)}{L_{\rm eff}}\right]$$

where P is the pump power, $L_{\rm eff}$ is the effective length of the fiber, α_p is the pump wavelength loss, and α_s is the signal wavelength loss. Using the fiber parameters we have for this experiment, the enhancement factor is calculated to be 5 dB with a pump power of 500 mW. The converted signal at 1545 nm has an OSNR of more than 50 dB (resolution bandwidth (BW) of the spectrum analyzer 0.1 nm). Fig. 3(a) shows the BER for wavelength conversion from 1559 to 1545 nm and Fig. 3(b) shows the eye patterns of the original and the wavelength-converted 80-Gb/s signals. At the receiver, an EAM was used to gate 10-Gb/s data to a 10-Gb/s photodector and the BER was measured for each of the demultiplexed 10-Gb/s channels from the 80-Gb/s converted stream by tuning the receiver to the appropriate time slot. A negative 2-dB power penalty at ${\rm BER} = 1E-9$ was measured for all eight channels compared with back-to-back measurements of the 80-Gb/s solition compressed pulses. Fig. 3(c) shows the eye diagrams of all the eight demultiplexed 10-Gb/s channels. Eye diagrams were measured with a 50-GHz digital sampling scope and a 40-GHz photodetector. The tuning characteristic of the wavelength converter was measured by varying the CW light from 1535 to 1555 nm in 2-nm steps. Open eye diagrams of the converted 80-Gb/s signal were obtained for all wavelengths. Since the EAM used to demultiplex in this experiment had different switching windows within this wide wavelength range, the converted pulsewidth was measured at 10 Gb/s using an autocorrelator. The converted pulsewidth and eye diagrams of the converted wavelength are shown in Fig. 4 and were measured to be 3.75 ps with less than 25% variation over the output wavelength range. The received pulses were slightly broadened due to the converter output filter bandwidth, but maintained values less than 6 ps minimizing the intersymbol interference (ISI) at 80 Gb/s.



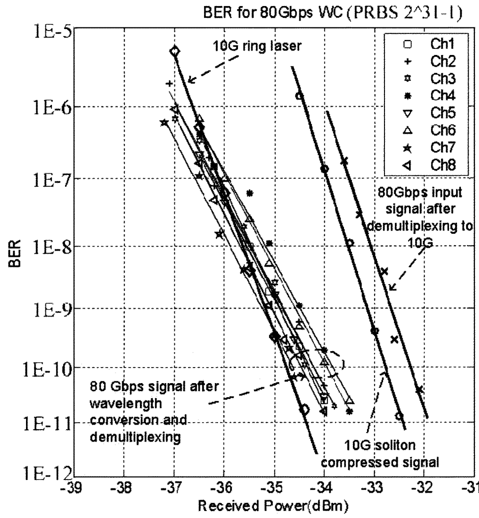
(a)



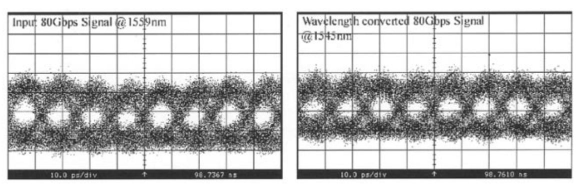
(b)

Fig. 2. (a) Spectrum at Point A (with Raman pump ON–OFF) and B of the wavelength converter in Fig. 1. (b) Optical spectrum of the original and the wavelength converted signal (resolution BW: 0.1 nm).

The negative power penalty exhibited by the wavelength converter can be explained by the nonlinear transfer function of the wavelength converter. The conversion process relies solely on an intensity change in the time domain, i.e., an intensity change at one wavelength translates to a phase change at another wavelength. The transfer function is nonlinear, resembling that of a sinusoidal when measuring the output power versus input power. This will minimize the fluctuations in the top and bottom level of the signal due to the flatter characteristics of the transfer function at these power levels. For the same reason, any chirp contained in the input signal will not be transferred during the conversion and the output pulse will, therefore, be very close to transform limited, having spectral distinctiveness corresponding to the converted pulse without chirp. However, the reshaping capability is not only observed in the time domain, but also in the spectral domain. This behavior is clearly



(a)



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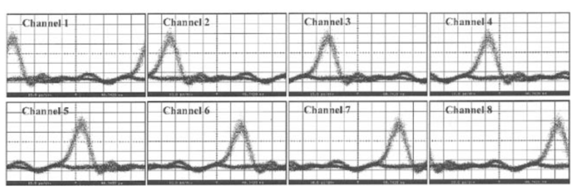

(c)

Fig. 3 BER measurements for wavelength conversion of 80-Gb/s data from 1559 to 1545 nm. (b) Eye diagrams of input and wavelength converted signal at 80 G (time: 10 ps/div). (c) Eye diagrams of converted 80-Gb/s signal demultiplexed to eight 10-Gb/s channels (time: 10 ps/div).

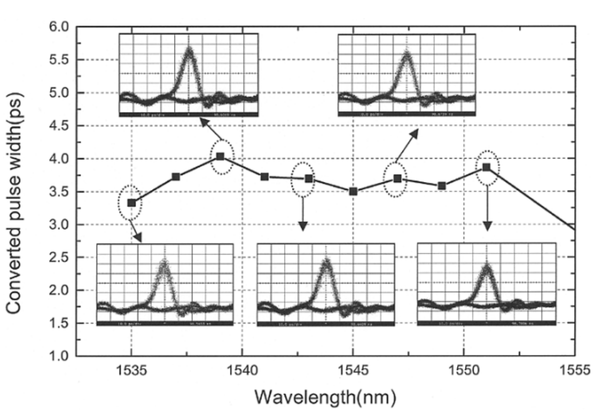

Fig. 4. Tuning characteristics of the wavelength converter.

seen from Fig. 2(b) showing the optical spectrum of the original and the wavelength-converted signal at 80 G. The mode-locked fiber-ring laser used in this experiment was a versatile high-quality pulse source, which gave short transform limited pulses and had high output power. The BER measurement showed the receiver sensitivity of -35.18 dBm at $\mathrm{BER} = 1E - 9$, but due to limited filter bandwidth, the shortest output pulsewidth at 1559 nm is more than 5 ps, which is not suitable for 80-Gb/s signal generation by optical multiplexing. Soliton pulse compression was, therefore, used to compress the pulsewidth down to 2 ps. The compressor contained an EDFA with a saturated output power of $+14$ dBm and 5 km of DSF. After soliton compression, the spectrum of the original signal was significantly broadened, displaying a large amount of chirp. As a result, the receiver sensitivity was degraded by 2 dB to -33.15 dBm at $\mathrm{BER} = 1E - 9$. After passively multiplexing the compressed pulse to 80 Gb/s, the input signal at 1559 nm was first directly demultiplexed to 10 Gb/s and the BER was measured for one of the eight demultiplexed channels. It showed a receiver sensitivity of -32.67 dBm. The 0.5-dB power penalty compared with the 10-Gb/s compressed pulse is mainly brought by the loss through the EAM and ISI induced by the 10- to 80-Gb/s multiplexer. The regenerative function of the wavelength converter is shown by the BER curves of the demultiplexed wavelength-converted signal, lying closely to the original ring laser BER curve position, with an averaged receiver sensitivity of -34.9 dBm.

IV. Conclusion

An 80-Gb/s all-optical fiber XPM wavelength conversion using distributed Raman gain to enhance the nonlinear interaction has been demonstrated. BER measurements showed a negative power penalty of 2 dB for 80-Gb/s return-to-zero data. The regenerative property of the wavelength converter is clearly seen when comparing the spectrum of the original and the wavelength converted signals. It can also be observed from the eye diagrams measured before and after conversion, with the converted signal having more uniform eyes. This regenerative effect is partly ascribed to the use of Raman amplification, which allows the balance between SPM and XPM to be managed, thereby obtaining an improved extinction ratio and OSNR. Furthermore, the use of HNLDSF also allows wavelength conversion over a wide wavelength range. When scaling to higher bit rates, this approach could prove advantageous compared with the approaches only with lumped optical gain at the input.

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