All-Optical 40 Channels Regenerator Based on Four-Wave Mixing

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All-Optical 40 Channels Regenerator Based on Four-Wave Mixing

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Abstract We have proposed a novel multi-channel regeneration scheme for wavelength division multiplexed systems, which is based on four wave mixing in a highly nonlinear fiber. A 40-channel wavelength division multiplexed signal having data rate of 10 *Gbps* per channel is divided into five groups. Each group is composed of eight channels and requires a single pump laser source and two segments of highly nonlinear fibers to regenerate the eight channels. Therefore, our proposed scheme requires four times lesser number of highly nonlinear fibers compared to the previously proposed techniques. The regeneration performance for all the forty channels is presented through bit error rate analysis at low optical signal to noise ratio of 15 *dB*. Simulation results show that an average improvement of 4.246 *dB*, 3.935 *dB*, 3.72 *dB*, 2.71 *dB* and 2.593 *dB* in receiver sensitivities has been observed for all the five groups of channels, respectively.

Keywords Optical regenerators · Four Wave Mixing · Multi-channel regeneration

1 Introduction

Optical fiber technology has revolutionised the concept of information transfer over long distances during the past years. There has been an enormous

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increase in the information carrying capacity of optical fibres from just few kbps to Tbps in just a few decades. These tremendous achievements have not stopped here, as millions of new customers and new devices are being added to the network annually. This evolution is a remarkable achievement for the research community, yet raising the challenge for network operators as advanced technologies such as 5G networks, Ultra high definition (HD) streaming services, and the development of new internet of things (IoT) based devices are putting a huge strain on the network [1]. It is expected that 50 billion devices will be connected to the internet after the availability of 5G technology publicly [2]. To cope with such a huge bandwidth demand, the emphasis is not only on advance network layer protocols but also on advancement in the optical communication devices [3].

Dense Wavelength Division Multiplexing (DWDM) is one of the suitable solutions for the transmission of multiple channels over long distances [4]. However, there are certain challenges due to amplified spontaneous emission (ASE) noise [5] and the use of large number of WDM channels which leads to signal distortion and cross talk [6]. Currently, regeneration is carried out by converting the optical signal into an electrical signal, wherein the regeneration process encompasses re-amplification, re-shaping and re-timing. Thereafter, the signal is again converted back into the optical domain for onward transmission. The whole process is time consuming since it involves multiple conversions and is not scalable to higher modulation schemes and high data rates [7]. The need for efficient, optimized and low-cost optical devices is evident for regeneration of signals. All-optical signal regeneration is the key technology to improve the signal quality by restoring the original shape of the optical signals [8]. All optical regeneration results in reduction of noise in the optical signals for high capacity optical links at a low cost and low power consumption [9]. Based upon their functionality, optical regenerators are generally of two major types that are 2R- and 3R-regenerators. 2R-regenerators have the functionality of re-amplification and re-shaping of the pulse, whereas, 3R-regenerators also add the functionality of re-timing [10], [11].

A 2R-regeneration method is discussed in [12], where the technique is based upon self phase modulation (SPM) and offset filtering using a 2 m long Bismuth Oxide fiber with an ultra-high nonlinearity of $\gamma = 110 \text{ W}^{-1}/\text{Km}$. Similar demonstrations of optical 2R-regeneration achieved by vertical micro-cavity mirror based multiple quantum-well saturable absorber is presented in [13]. The proposed device performs regeneration through a pigtailed saturable absorber chip implemented with eight independent fibers using a cost effective coupling technique. Rochette *et. al.* demonstrated a 3R-regenerator using Cross-Phase Modulation (XPM), where, zeros and ones of the noisy signal are imprinted on to the clock signal after passing through a highly nonlinear fiber (HNLF). Improvement of 4 dB optical signal to noise ratio (OSNR) at $BER = 10^{-10}$ was recorded at a data rate of 40 Gbps. However, the proposed technique is demonstrated for the regeneration of a single channel only [14]. Croussore *et. al.* proposed an all-optical phase regenerator using Symmetric Pump Phase-Sensitive Amplifier (SP-PSA) [15]. SP-PSA is used for phase re-

generation of a phase-noise degraded non-return-to-zero differential phase-shift keying (DPSK) signal using bismuth oxide highly nonlinear fiber (Bi-HNLF). Recently, four channel phase regeneration of quadrature phase shift keying (QPSK) signals using phase sensitive amplification is demonstrated in [16], [17]. The technique uses Four wave mixing (FWM) in a HNLF to generate the corresponding three harmonic conjugates that are optically combined to realize phase regeneration by coherent addition. Experimental results showed that the OSNR can be improved up to 3 dB. Contestabile *et. al.* experimentally investigated all-optical regeneration of constant envelope alternate modulation format signals at 40 Gbps using hard limiting amplification in a saturated semiconductor optical amplifier (SOA). This technique is efficient when Polarization Shift Keying and Frequency Shift Keying signal formats are used, whereas, the improvement of OSNR is limited for Non-Return-to-Zero (NRZ) DPSK signal format [18]. Sixteen channels are regenerated using a Group-delay-managed (GDM) medium that is made by concatenation of ' N ' number of fibers and periodic group-delay device (PGDD) unit cells [19]. The proposed design has a complex structure that is implemented in different stages.

Most of the techniques discussed above regenerate a single optical channel. The techniques proposed for multiple channels are generally complex and require specialized equipment. Therefore, there is a need for a multi-channel regeneration technique that uses off-the-shelf components and simple optical signal processing. In this study, we have proposed such a technique by employing FWM in a HNLF. Our proposed technique requires a single span of dispersion shifted HNLF to simultaneously regenerate four optical channels. We have divided the incoming WDM signal into groups of eight channels. Each group requires a single continuous wave (CW) pump source and two spans of HNLFs. The center frequency of the pump laser source in each group is chosen such that the multiple sidebands generated as a result of FWM do not overlap with each other at the output of the HNLF. Our proposed technique is suitable for WDM signals having large number of channels such as a forty channel system. For example, for a forty channel WDM system, the total number of pump sources and HNLF segments required for regeneration based on our technique are five and ten, respectively, compared to forty pump sources and forty HNLF segments required for previously proposed techniques. Therefore, the proposed technique is cost-efficient, employs off-the-shelf components and is simple to implement. Section-2 of the paper discusses the working principle of the proposed technique while Section-3 presents the simulation setup that is designed using the commercial tool OptiSystem 17. Section-4 of the paper presents the performance analysis while Section-5 discusses the conclusions.

2 Working Principle

The working principle of the proposed regeneration scheme is based on FWM in a HNLF. A pulsed optical signal is coupled with a CW high power pump, as illustrated in Fig. 1. The combined optical signal whose field envelope is

Fig. 1 A CW pump and a pulsed signal are passed through a dispersion shifted HNLF to generate multiple sidebands by employing FWM.

denoted as $E(z, t)$ is transmitted through the HNLF where its propagation may be represented by the following expression [20]:

$$i \frac{\partial E}{\partial z} = -i\alpha E - \gamma |E|^2 E + \frac{1}{2} \beta^{(2)} \frac{\partial^2 E}{\partial t^2} + \frac{i}{6} \beta^{(3)} \frac{\partial^3 E}{\partial t^3} \quad (1)$$

The constants $\beta^{(2)}$ and $\beta^{(3)}$ represent the dispersion and dispersion slope of the HNLF. The pulsed optical signal can be treated as a CW signal since the time duration of Kerr nonlinearity in the HNLF is much shorter than the intensity fluctuations induced over the signal by the optical link. Therefore, the input field can be represented in terms of the complex amplitude $A_j(z)$ of the pump and signal as:

$$E(z=0, t) = \sum_{j=1}^2 A_j(z=0) e^{-i\omega_j t} \quad (2)$$

Here, ω_j is the frequency offset of the signal from the pump. The number of sidebands generated at the output of the HNLF are dependent upon the power of the CW pump signal. In our scheme, the pump is operated in the depletion regime while its power is chosen such that the sidebands generated beyond f_1 and f_{-1} , as shown in Fig. 1, have almost negligible powers at the output of the HNLF. It has been shown in [20] that for the sideband centered at f_1 , the output power on ones saturates for high input powers and scales as square of the input power for low input power values. As a result, we get reduced fluctuations on ones of the input pulsed signal while any power appearing over the zeros is strongly attenuated. To take advantage of the regenerative properties of the signal centered at f_1 , it is filtered out using a bandpass filter at the output of the HNLF. If we neglect the sidebands beyond f_1 and f_{-1} , the evolution of the remaining four waves along the HNLF may be represented by the following four coupled ordinary differential equations [20]:

$$i \frac{dA_j}{dz} = -i\alpha A_j - \beta_j A_j - \gamma \sum_{l,m,n=1}^4 A_l^* A_m A_n \delta(\omega_m + \omega_n - \omega_l - \omega_i) \quad (3)$$

Here, δ represents the Kronecker delta and is either 1 or 0, depending upon the values of the frequencies ω , and β_j represents the propagation constants that may be expressed as:

$$\beta_j = \left(\frac{\beta^{(2)}}{2}\right)\omega_j^2 + \left(\frac{\beta^{(3)}}{6}\right)\omega_j^3 \quad (4)$$

It may be observed from Eq. 3 that FWM between the pump and the signal results in the generation of multiple sidebands at the output of the HNLF. These sidebands are spaced at frequencies that are equal to the frequency difference between the pump and the signal. For single channel regeneration, a simple bandpass filter centered at f_1 may be used to filter out the regenerated signal. However, the situation becomes complex when we have more than one optical channel at the input of the HNLF. In this scenario, the equally spaced optical sidebands of different channels will overlap in frequency and will result in channel distortion. Therefore, to the best of our knowledge, FWM based regeneration for multiple channels has not been demonstrated until now. To cope with this issue, we have proposed a novel scheme that regenerates four optical channels simultaneously by employing a single dispersion shifted HNLF and a CW pump. The center frequency of the CW pump is chosen such that each channel is spaced at a different frequency from the CW pump before FWM is performed. Therefore, the multiple sidebands generated due to FWM would be centered at different frequencies and can be easily filtered. Furthermore, the power of the CW pump is chosen such that it is almost depleted while generating the sidebands f_1 and f_{-1} .

3 System Architecture

Fig. 2 shows the simulation setup of our proposed scheme. Forty optical channels, each having a data rate of 10 *Gbps* are generated at the transmitter. The frequency range of the channels span from 192.1 *THz* to 196.0 *THz* with a channel spacing of 100 *GHz* in order to reduce cross-talk among the channels. On-Off keying (OOK) modulation is used where the pulse width of each channel is 15 *ps*. Broadband ASE noise is added to the 40-channel WDM signal to reduce the OSNR of each channel, as shown in Fig. 2. The 40-channel WDM signal is transmitted over a 40 *km* standard single mode fiber (SMF) to introduce dispersion over the optical signals. After inducing noise as well as dispersion over the WDM signal, we now implement our proposed multi-channel regeneration scheme. The WDM signal received at the regeneration block is demultiplexed by employing a 1x40 demultiplexer having a channel spacing of 100 *GHz* and channel bandwidth of 25 *GHz*. The forty optical channels received at the output of the demultiplexer are divided into five groups, where each group has eight channels. The first group called Group 1 has eight optical channels having center frequencies between 192.1 *THz* to 192.8 *THz* with a frequency spacing of 100 *GHz*. Therefore, we have a total of five groups whose range of frequencies are mentioned in Table. 1.

Fig. 2 Simulation setup for the proposed all-optical 40 channel regeneration scheme. OC: Optical coupler, SMF: Single mode fiber, DEMUX: Demultiplexer, MUX: Multiplexer, EDFA: Erbium doped fiber amplifier, OS: Optical splitter, HNLF: Highly nonlinear fiber, BPF: Bandpass filter.

Each group of channels is further divided into two sub-groups, as shown in Fig. 2. For Group 1, the first sub-group is composed of channels having frequency span of 192.1 THz to 192.4 THz , while the second sub-group has a frequency span of 192.5 THz to 192.8 THz . Similarly, each group that is composed of a total of eight channels is divided into two sub-groups, each having four optical channels. The wavelengths of each sub-group are combined using an optical combiner, as shown in Fig. 2. The combined optical channels are amplified, coupled with a CW pump source and given to the input of a HNLF. It may be observed from Fig. 2 that for each group, a single CW pump source is amplified, split in two paths and coupled with the channels of the two sub-groups. The center frequencies of the pump laser sources employed for Group 1 to Group 5 are 192.45 THz , 193.25 THz , 194.05 THz , 194.85 THz and 195.65 THz , respectively. As discussed earlier, the frequencies of the pump laser sources are chosen such that each channel that is coupled with the pump source has a different frequency spacing from the pump. Consequently, there is no overlap among the optical sidebands generated at the output of the HNLF due to FWM. The HNLF has a length of 1 km , an attenuation of 0.22 dB/km , dispersion slope of $0.07 \text{ ps.nm}^{-2}.\text{km}^{-1}$ and nonlinearity coefficient of $10.61 \text{ W}^{-1}\text{km}^{-1}$. For each group, the zero dispersion frequency of the HNLF is kept the same as the frequency of the CW pump laser for that particular group. For example, the zero dispersion frequency of the HNLF employed for Group 1 is 192.45 THz , that is the same as the center frequency of the

Fig. 3 Spectral plots of the first sub-group of Group 1 that has a frequency range of 192.1 THz to 192.4 THz (a) Before addition of broadband noise, (b) After addition of broadband noise and transmission over 40 km SMF, (c) At the output of the HNLF after FWM.

pump signal used for Group 1. While propagating through the HNLF, the optical channels and the pump signal interact nonlinearly to generate multiple sidebands due to FWM. Fig. 3 shows the spectral plots at different points of the link for the four channels of the first sub-group of Group 1 that has a frequency range of 192.1 THz to 192.4 THz. Fig. 3(a) shows the four channels before the addition of noise and transmission over the 40 km SMF. Fig. 3(b) shows the four channels after noise is added and the channels are transmitted over the SMF. Fig. 3(c) shows the spectral plot of the signal at the output of the HNLF. It may be observed from Fig. 3(c) that the spectral plot is composed of multiple sidebands that are generated due to FWM between the four channels and the CW pump. These sidebands are not overlapping due to the choice of a suitable frequency for the pump source.

As discussed earlier, the optical sidebands generated as a result of FWM have lesser noise power compared to the actual signal when the pump is completely depleted. Therefore, we use optical bandpass filters at the output of the HNLF to extract the optical channels at frequencies that are offset from their original values. For the Group 1, the channels centered at frequencies of 192.1 THz to 192.8 THz are filtered at frequencies of 192.8 THz to 192.1 THz, respectively by using optical bandpass filters each having a bandwidth of 25 GHz. Similarly, the data modulated sidebands generated at the output of the HNLFs for the channels of the remaining groups are also filtered using bandpass filters that are centered at offset frequencies. Table 1 shows the center frequencies of the channels before and after regeneration for Group 1 to Group 5, respectively. Fig. 4 shows the eye diagrams for Channel 1 before and

Fig. 4 Eye diagram of Channel 1 at (a) the input of the regenerator, (b) output of the regenerator.

after regeneration. Fig. 4(a) shows the signal before regeneration where it may be observed that the eye opening is narrow due to the addition of ASE noise to the signal. Fig. 4(b) shows the eye diagram of the regenerated signal where it may be seen that the eye opening is wide due to lower amplitude fluctuations. These eye diagrams are used to calculate the bit error rate (BER) performance of the link, as discussed in the next section.

4 Performance Analysis

This section discusses the performance of our proposed regeneration scheme. As mentioned earlier, we transmitted 40 WDM channels, each having a data rate of 10 Gbps. To consider the degradation of OSNR of the optical channels due to multiple optical amplifiers in a long haul optical link, we add broadband ASE noise through an external source. The power of the ASE noise source is chosen such that it results in a low OSNR of around 15 dB for all the channels received at the regenerator. Furthermore, to induce the effect of fiber dispersion, the noisy WDM channels are passed through a 40 km SMF without dispersion compensation. BER analysis was performed for all the channels. The received optical power required to obtain a BER of 10^{-9} is considered to observe the improvement in power penalty of all the channels due to the introduction of the regeneration scheme. Since we have a large number of channels, the improvement in their sensitivity due to regeneration have been shown in the form of a table denoted as Table 1. Table 1 also shows the center frequency of each channel before and after regeneration. For each channel, the sideband centered at frequency f_1 shown in Fig. 1, has been filtered out. Therefore, the frequency of the regenerated channel is shifted from that of the input channel. It may be observed from Table 1 that on average, the sensitivity of the regenerated signals has improved by a value of 4 dB compared to the noisy signal at the input of the regenerator.

Fig. 5 shows the complete set of BER values at different received optical powers for the ten subgroups mentioned previously. For each subgroup, the BER curves of the four channels before and after regeneration have been

Fig. 5 BER versus received optical power plots with and without regeneration for signals of the ten sub groups.

Table 1 Receiver sensitivity values of the 40 channels before and after regeneration.

Group	Before Regeneration		After Regeneration	
	Frequency (THz)	Sensitivity (dBm)	Frequency (THz)	Sensitivity (dBm)
1	192.1	-14.268	192.8	-19.874
1	192.2	-16.832	192.7	-19.713
1	192.3	-15.954	192.6	-19.371
1	192.4	-15.287	192.5	-19.845
1	192.5	-14.671	192.4	-19.859
1	192.6	-14.514	192.3	-19.459
1	192.7	-17.797	192.2	-20.145
1	192.8	-14.621	192.1	-19.138
2	192.9	-17.994	193.6	-20.136
2	193.0	-16.169	193.5	-20.083
2	193.1	-15.45	193.4	-20.557
2	193.2	-14.796	193.3	-18.216
2	193.3	-15.005	193.2	-19.636
2	193.4	-16.337	193.1	-20.127
2	193.5	-16.769	193.0	-20.088
2	193.6	-14.873	192.9	-20.04
3	193.7	-16.332	194.4	-20.663
3	193.8	-17.335	194.3	-20.007
3	193.9	-16.63	194.2	-19.611
3	194.0	-15.229	194.1	-19.398
3	194.1	-18.334	194.0	-20.431
3	194.2	-16.832	193.9	-20.579
3	194.3	-16.769	193.8	-20.492
3	194.4	-14.793	192.7	-20.898
4	194.5	-16.325	195.2	-20.604
4	194.6	-16.335	195.1	-20.316
4	194.7	-17.791	195.0	-19.613
4	194.8	-16.663	194.9	-19.998
4	194.9	-18.004	194.8	-19.213
4	195.0	-17.589	193.7	-20.112
4	195.1	-18.013	193.6	-20.111
4	195.2	-17.874	192.5	-20.289
5	195.3	-18.001	196.0	-20.817
5	195.4	-17.502	195.9	-20.273
5	195.5	-17.257	195.28	-20.663
5	195.6	-15.96	195.7	-19.151
5	195.7	-18.004	195.6	-19.74
5	195.8	-18.588	195.5	-20.376
5	195.9	-18.43	195.4	-20.58
5	196.0	-18.278	195.3	-20.165

shown. It may be observed from the BER plots that the proposed regeneration scheme significantly improves the BER of the 40 channel WDM signal. It is worth mentioning here that the BERs were obtained by choosing a suitable optical power for each sub-group that is input to the regenerator. As discussed in [20], for low input signal powers, the power of the sidebands at the output of the HNLF remains very low. Therefore, the intensity of noise appearing on the zeros in the data stream is strongly compressed at the output of the

regenerator. After crossing a certain value of input power, the output power suddenly increases and reaches a maximum point. This behaviour is similar to that of a nonlinear switch. After the output power reaches a maximum point, further increasing the input power does not result in a significant increase in the output power of a particular sideband. At this point, maximum compression of intensity fluctuations on ones in the data stream is obtained. Based on this behaviour of the generated sidebands, we have chosen a suitable operating point for each sub-group by adjusting the gain of the amplifier placed after the 4x1 multiplexer in Fig. 2. This operating point is close to the point of maximum output power and results in the lowest BER.

5 Conclusion

We reported an all-optical multi-channel regeneration scheme for WDM systems. A forty channel WDM signal was generated and passed through a standard SMF to induce dispersion and nonlinear effects over the channels. To reduce the OSNRs of the channels to 15 dB at the regenerator, broadband noise source was coupled with the WDM signal before transmission over the SMF. The forty channels were divided into five groups, each composed of eight channels. A single CW pump laser source and two segments of HNLFs were used to regenerate all the eight channels in a single group. The proposed scheme is very useful for implementation in current WDM systems that are using a single regenerator for a single channel. The introduction of our proposed regeneration scheme to such WDM systems would result in significant reduction in component count and therefore, an increase in cost efficiency. An average improvement in receiver sensitivity of 4.246 dB, 3.935 dB, 3.72 dB, 2.71 dB and 2.593 dB was observed for the first, second, third, fourth and fifth group, respectively. The proposed scheme is scalable to higher data rates since it is based upon ultra-fast nonlinear interaction inside HNLFs.

6 Declarations

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Not Applicable

Conflicts of interest/Competing interests

On behalf of all authors, the corresponding author states that there is no conflict of interest.

Availability of data and material

Available on request.

Code Availability

Available on request.

References

1. Samael Sarmiento, Jose A. Altabas, Salvatore Spadaro, Jose A. Lazaro, "Experimental assessment of 10 Gbps 5G multicarrier waveforms for high-layer split U-DWDM-PON-based fronthaul," *Journal of Lightwave Technol.*, vol. 37, no. 10, pp. 2344–2351, May 2019, doi: 10.1109/JLT.2019.2904114.
2. Alsulami, Mashael and Akkari, "The role of 5G wireless networks in the internet-of-things (IoT)," *International Conference on Computer Applications & Information Security (ICCAIS)*, pp. 1–8, Dec. 2018, doi: 10.14419/ijet.v7i1.5.9155.
3. Matteo Fiorani, Paolo Monti, Bjorn Skubic, Jonas Martensson, Luca Valcarengghi, Piero Castoldi, Lena Wosinska, "Challenges for 5G transport networks," *IEEE International Conference on Advanced Networks and Telecommunications Systems (ANTS)*, pp. 1-6, Dec. 2014, doi: 10.1109/ants.2014.7057286.
4. Peter Ohlen, Bjorn Skubic, Zere Ghebretensae, Wolfgang John, Meral Shirazipour, "Software-defined networking in a multi-purpose DWDM-centric metro/aggregation network," *IEEE Globecom Workshops*, pp. 1233-1238, Dec. 2013, doi: 10.1109/glo-comw.2013.6825162.
5. A. D. Ellis, M. E. McCarthy, M. A. Z. Al-Khateeb, and S. Sygletos, "Capacity limits of systems employing multiple optical phase conjugators," *Opt. express*, vol. 23, no. 16, pp. 20381–20393, Aug. 2015, doi: 10.1364/oe.23.020381.
6. E. Ciaramella, F. Curti and S. Trillo, "All-optical signal reshaping by means of four-wave mixing in optical fibers," in *IEEE Photonics Technol.*, vol. 13, no. 2, pp. 142-144, Feb. 2001, doi: 10.1109/68.910515.
7. Francesca Parmigiani, Lionel Provost, Periklis Petropoulos, David J. Richardson, Wolfgang Freude, Juerg Leuthold, Andrew D. Ellis, Ioannis Tomkos, "Progress in Multi-channel All-Optical Regeneration Based on Fiber Technology," *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 18, no. 2, pp. 689-700, Mar. 2012, doi: 10.1109/jstqe.2011.2126040.
8. B. Guo, F. Wen, B. Wu, F. Sun and K. Qiu, "All-Optical Multilevel Amplitude Regeneration Based on Polarization-Orthogonal Continuous-Wave-Light-Assisted Nonlinear-Optical Loop Mirror (PC-NOLM) Subsystem," in *IEEE Access*, vol. 7, pp. 149666-149671, Oct. 2019, doi: 10.1109/access.2019.2947303.
9. Sygletos, Frascella, Gunning, F.C.G. and Ellis, "Multi-wavelength regeneration of phase encoded signals based on phase sensitive amplifiers," *ICTON*, pp. 1–4, Jul. 2012, doi: 10.1109/icton.2012.6253868.
10. Leclerc, Olivier, "Optical vs. Electronic in-line Signal Processing in Optical Communication Systems: An exciting challenge for Optical Devices," *Signal*, vol. 1, pp. 0, Jan. 2003.
11. Jeyran Amirloo, Mohsen Razavi, A. Hamed Majedi, "Quantum key distribution over probabilistic quantum repeaters," *Physical Review A*, vol. 82, no. 3, pp. 032304, Sep. 2010, doi: 10.1103/physreva.82.032304.
12. Francesca Parmigiani, Symeon Asimakis, Naoki Sugimoto, Fumihito Koizumi, Periklis Petropoulos, and David J. Richardson, "2R regenerator based on a 2-m-long highly nonlinear bismuth oxide fiber," *Optics express*, vol. 14, no.12, pp. 5038–5044, 2006, doi: 10.1364/oe.14.005038.
13. Laurent Bramerie, Quang Trung Le, Mathilde Gay, Arthur OHare, Sebastien Lobo, Michel Joindot, Jean-Claude Simon, Hoang-Trung Nguyen, Jean-Louis Oudar, "All-optical 2R regeneration with a vertical microcavity-based saturable absorber," *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 18, no. 2, pp. 870–883, Mar. 2012, doi: 10.1109/jstqe.2011.2125779.
14. Martin Rochette, Justin L. Blows, and Benjamin J. Eggleton, "3R optical regeneration: An all-optical solution with BER improvement," *Opt. Express*, vol. 14, no. 14, pp. 6414–6427, June 2006, doi: 10.1364/oe.14.006414.

15. Kevin Croussore and Guifang Li, "Phase regeneration of NRZ-DPSK signals based on symmetric-pump phase-sensitive amplification," *IEEE Photonics Technol. Letters*, vol. 19, no. 11, pp. 864–866, June 2007, doi: 10.1109/lpt.2007.897501.
16. Hongxiang Wang, Tiantian Luo, and Yuefeng Ji, "Multi-channel phase regeneration of QPSK signals based on phase sensitive amplification," *Frontiers of Optoelectronics*, vol. 12, no. 1, pp. 24–30, Mar. 2019, doi: 10.1007/s12200-018-0754-8.
17. Ju Wang, Hua Ji, Hao Hu, Jinlong Yu, Hans Christian Hansen Mulvad, Michael Galili, Palle Jeppesen, and Leif Katsuo Oxenlowe, "4× 160-Gbit/s multi-channel regeneration in a single fibre," *Optics express*, vol. 22, no. 10, pp. 11456–11464, May 2014, doi: 10.1364/oe.22.011456.
18. Giampiero Contestabile, Marco Presi, Ernesto Ciaramella, "All-optical regeneration of 40 Gb/s constant envelope alternative modulation formats," *IEEE journal of quantum electronics*, vol. 46, no. 3, pp. 340–346, Mar. 2010, doi: 10.1109/jqe.2009.2033017.
19. Lu Li, Pallavi G. Patki, Young B. Kwon, Veronika Stelmakh, Brandon D. Campbell, Muthiah Annamalai, Taras I. Lakoba and Michael Vasilyev, "All-optical regenerator of multi-channel signals," *Nature commun.*, vol. 8, no. 1, pp. 1–11, Dec. 2017, doi: 10.1038/s41467-017-00874-0.
20. E. Ciaramella and S. Trillo, "All-optical signal reshaping via four-wave mixing in optical fibers," in *IEEE Photonics Technology Letters*, vol. 12, no. 7, pp. 849–851, July 2000, doi: 10.1109/68.853523.

Figures

Figure 1

A CW pump and a pulsed signal are passed through a dispersion shifted HNLF to generate multiple sidebands by employing FWM.

Figure 2

Simulation setup for the proposed all-optical 40 channel regeneration scheme. OC: Optical coupler, SMF: Single mode fiber, DEMUX: Demultiplexer, MUX: Multiplexer, EDFA: Erbium doped fiber amplifier, OS: Optical splitter, HNLF: Highly nonlinear fiber, BPF: Bandpass filter.

Figure 3

Spectral plots of the first sub-group of Group 1 that has a frequency range of 192.1 T Hz to 192.4 T Hz (a) Before addition of broadband noise, (b) After addition of broadband noise and transmission over 40 km SMF, (c) At the output of the HNLF after FWM.

Figure 4

Eye diagram of Channel 1 at (a) the input of the regenerator, (b) output of the regenerator.

Figure 5

BER versus received optical power plots with and without regeneration for signals of the ten sub groups