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Unrepeatered OTDM Data Transmission over Long Legacy Fiber Span Using Unidirectional Backward Raman Amplification

Mousaab M. Nahas

Electrical and Computer Engineering Department, Faculty of Engineering, University of Jeddah, Jeddah, Saudi Arabia

Email address:
mnahas1@uj.edu.sa

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Abstract: This paper presents experimental results for transmitting 40 Gb/s OTDM signal over in-line long fiber span using unidirectional backward Raman amplification. The investigation uses legacy dispersion-managed SMF-DCF configuration where remote Erbium amplification is used to compensate for the DCF spans losses. It is practically shown that the system performance improves significantly with more Raman pump power if we use an appropriate signal wavelength, Raman pump power and Erbium gain. As a result, successful unrepeatered transmission over 206 km SMF is achieved using 1545 nm signal wavelength, 1.58 W Raman power and unsaturated EDFA gains into the DCF spans. We believe that the results of such investigation can be useful for enhancing systems that still use legacy cables without the need for substantial alteration.

Keywords: Fiber-Optic Communications, OTDM, Raman Amplification

1. Introduction

It is well known in the optical telecommunications arena that Raman amplification is referred to the Stimulated Raman Scattering (SRS) phenomenon where signal amplification is attained via nonlinear power transfer from an intense pump beam propagating simultaneously through the fiber [1]. It is also traditionally recognized that Raman amplification can be applied in either forward or backward direction. In forward Raman pumping, the energy is transferred from the pump beam to the data signal as the two beams co-propagate inside the fiber. In backward Raman, the pump and data signal beams counter-propagate in the fiber, and this type is commonly used in practice due to better amplification results [2]. In reality, most of the long haul optical transmission systems (≥ 200 km) use Raman amplification since the early part of the 20th century [3]. Moreover, plenty of researches have already demonstrated successful transmission using unrepeatered Raman amplification. Many of these researches use multiple 10 Gb/s WDM signals [4-7], while many others use higher bit rates through OTDM as we demonstrate in this research. However, some of these OTDM projects use all-Raman amplification that is split between the SMF and DCF spans, where no EDFA amplification is applied [8]. In other projects, unconventional large effective area fiber (LEAF) is used in which the nonlinear penalty is reduced including SRS, thus high power of Raman pump is required to increase amplification [9-11]. Other unconventional fibers are also used like DSF and NZ-DSF [12-13] that we are not interested in hereby. In later project [14], conventional SMF is used but the authors apply bidirectional Raman pumping scheme. Recently, some projects use conventional SMF in all-distributed Raman configuration [15-16] where multiple Raman modules are distributed around short or medium SMF spans so that transmission over unrepeatered long spans is not demonstrated.

In this paper, we investigate the application of unidirectional backward Raman amplification over unrepeatered long conventional SMF using 40 Gb/s OTDM signal with 2^{31}-1 data length. This signal is being encoded by a simple traditional coding scheme, which is RZ-IMDD, such that the complexity of the transmitter and receiver is minimized. This effectively opens the door for upgrading already installed systems or legacy parts of a network without the need for adding any complexity. However, there have been results of unidirectional Raman over long conventional fibers [17], but since the experiments are too old they use 2^7-1 word length which is much shorter that what we have in this project.

2. Experimental Setup

Fig. 1 shows the experimental setup for our investigation. An RF generator produces 10 GHz electrical signal that is used to drive both a laser source and a pulse pattern generator (PPG). The PPG produces a PRBS data signal with 2^{31}-1 length which is used to modulate the laser signal at a $LiNbO_3$ intensity modulator. The output of this process is basically a 10 Gb/s RZ-IM data signal. This resulting bit rate is experimentally increased to 40 Gb/s through Mach Zehnder optical time division multiplexing (MZ-OTDM) that is shown in Fig. 2, where the output pulses produced by the laser mentioned above are sufficiently narrow. In MZ-OTDM, a 10 Gb/s signal whose pulse time window is 100 ps is split into two channels; one is delayed by 50 ps and then couples back with the other channel. The resultant is 20 Gb/s signal. If this stage is repeated with 25 ps delay, the output signal is then 40 Gb/s. In practice, such delays are insufficient for adequate mixing of bits as they would result in sequential bit repetition within the combined 40 Gb/s random data. Therefore, we use additional 100 ps (one time widow) delay to avoid this effect [18]. Polarization controller is used in one Mach Zehnder arm to equalize the polarization of the two arms. The MZ-OTDM input 10 Gb/s and output 40 Gb/s signals are shown in Fig. 3.

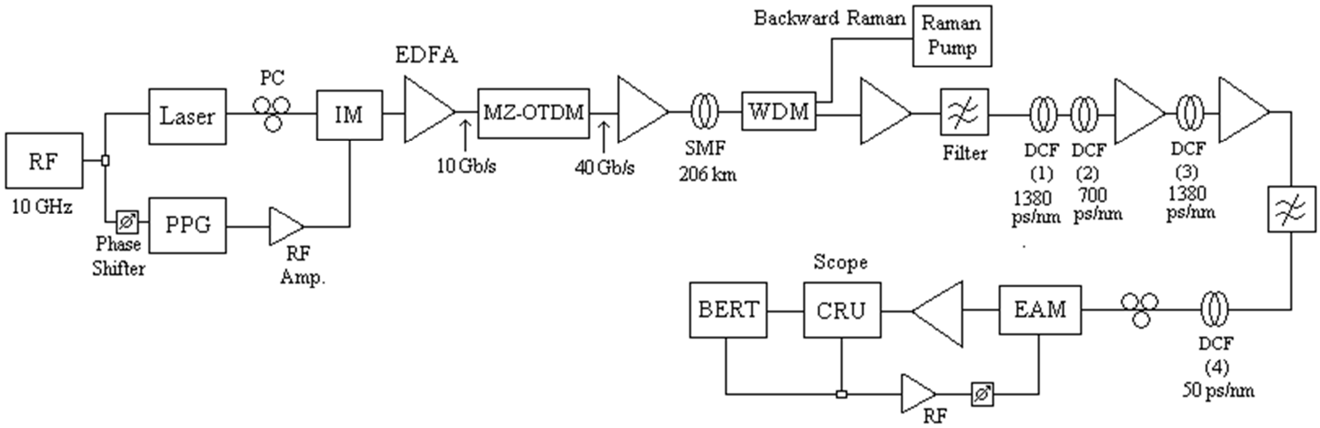


Figure 1. *Experimental setup.*

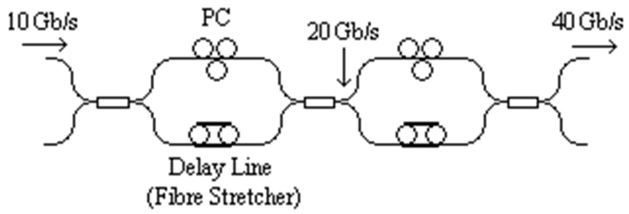
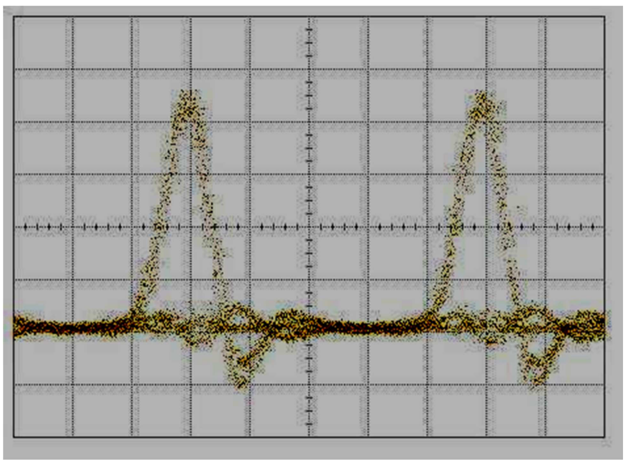
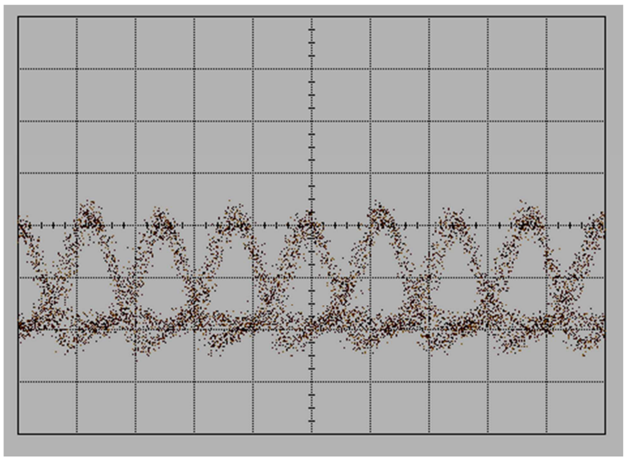


Figure 2. *MZ-OTDM.*



(a)



(b)

Figure 3. *(a) MZ-OTDM input 10 Gb/s signal; (b) MZ-OTDM output 40 Gb/s signal.*

The resulting 40 Gb/s signal is boosted by an EDFA and then transmitted over a 206 km SMF span. The average fiber attenuation is measured to be 0.2 dB/km at 1550 nm, while the total dispersion is measured to be 3510 ps/nm. This dispersion is compensated by the DCF modules shown in the setup. The loss of the SMF span is to be compensated by backward Raman as seen, while the cascaded EDFAs are used to compensate for losses in the DCF spans and in other components such as filters. The filters are used to eliminate the accumulative ASE noise along the system.

At the receiver, the individual 10 Gb/s signal must be extracted from the 40 Gb/s OTDM bit stream for measurements. Since each pulse occupies a 25 ps window in the 40 Gb/s signal, it is required to create a 25 ps switching window every 100 ps to extract a 10 Gb/s channel. To achieve this, an electro-absorption modulator (EAM) is used to absorb the unwanted three channels and leave only one channel in the time window. The EAM is initially driven by a 10 GHz electrical signal generated by clock recovery unit (CRU) to enable modulation of the first arrived bits, and then it is driven through feedback clock recovery for the next coming bits. The phase of the 10 GHz signal can be adjusted using a phase shifter which enables sliding the switching window in the time domain, giving the ability to select which of the four OTDM channels to be detected. The output 10 Gb/s signal is isolated and pre-amplified before being detected and analyzed.

3. Results and Discussion

Fig. 4 shows the back-to-back demultiplexed RZ data signal obtained from the above setup (without transmission) using -1 dBm EAM input power. It is obvious that the receiver demonstrated above can successfully extract a single 10 Gb/s channel out of the entire OTDM signal, where the original pluses are recovered properly and no errors are counted at the BERT.

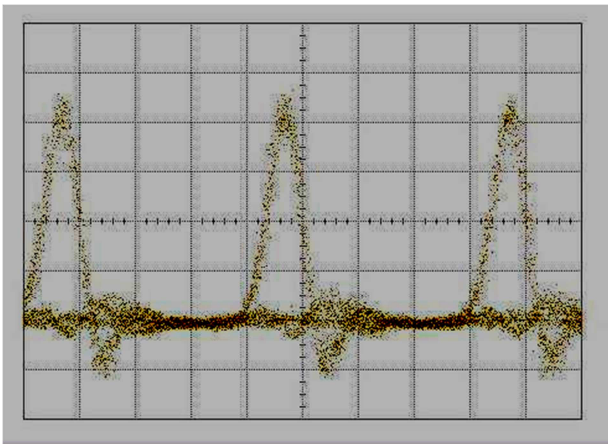


Figure 4. *Back-to-back 10 Gb/s signal.*

In transmission over 206 km, it is initially observed that the signal performance is varying with the wavelength, which is common with most laser sources that produce narrow pulses due to chirp variation. Therefore, it is significant to identify the best operating wavelength for this system before applying Raman amplification. Fig. 5 shows the signal BER as a function of wavelength using high launched power (17 dBm) and EDFA amplification only. As a result, the best performance is found to be around 1545 nm, thus this is the operating wavelength for our data signal from now on. Obviously, the BER is not aimed to be optimized at this stage as it is used here just for comparison purpose.

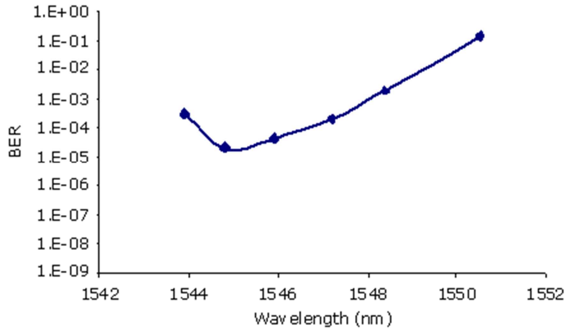
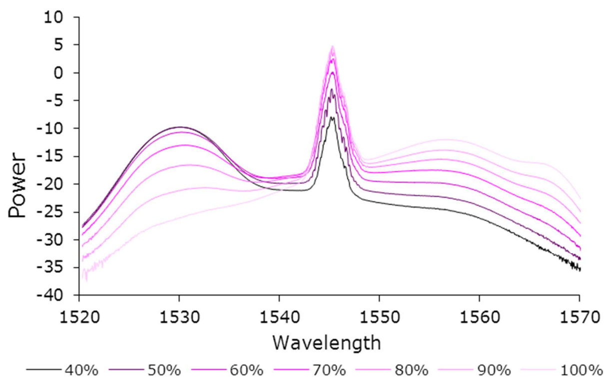
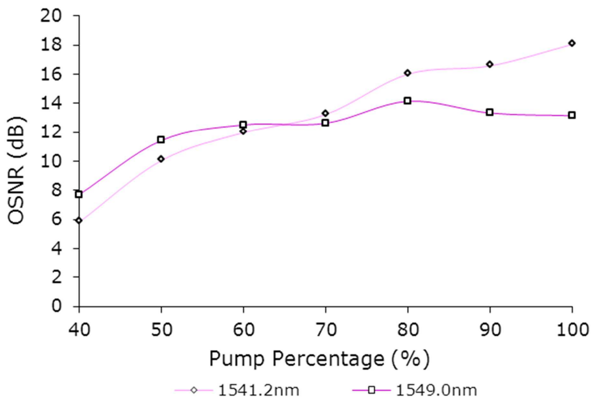


Figure 5. *BER vs operating wavelength.*

To apply Raman amplification, the Erbium gains are set to mainly compensate for the DCF losses which are ~0.5 dB/km in all DCF spans. This Erbium gain should also cover the filters losses as stated before. However, the signal launched power used at this stage is chosen to be 13 dBm, and this is based on the existing EDFAs saturation levels. This would imply that all Erbium amplifiers are allowed to work near saturation. By applying backward Raman pump signal at 1455 nm to the 206 km SMF span, the received signal counts considerable number of errors and is significantly distorted. This can be understood from Fig.6 (a) that shows the output spectra from the first amplifier, i.e. after the SMF span, using different pump powers in the range 40-100% according to the existing pump module. The corresponding values of the percentages mentioned above (and seen in the figure) are 0.06, 0.353, 0.624, 0.894, 1.13, 1.37 and 1.58 W, respectively. In (b), the OSNR measurements at the same point are presented versus Raman pump for higher and lower wavelengths. It is clear from both (a) and (b) that, the lower the Raman pump, the higher the ASE peak at 1530 nm, while the higher the pump, the higher the ASE noise around 1555 nm. However, the received BER against Raman pump is shown in Fig. 7. It is noticeable that the Raman pump increases the signal BER so far. Fig. 8 shows the eye closure due to increased Raman pump, where the worst eye is observed at 100% pump power. Practically, this degradation is mainly caused due to the interaction between Raman signal and the ASE noise signal caused by the lumped Erbium amplification, where this interaction is wavelength dependent.



(a)



(b)

Figure 6. *(a) SMF output spectra for different Raman pumps. (b) SMF output OSNR vs Raman pump.*

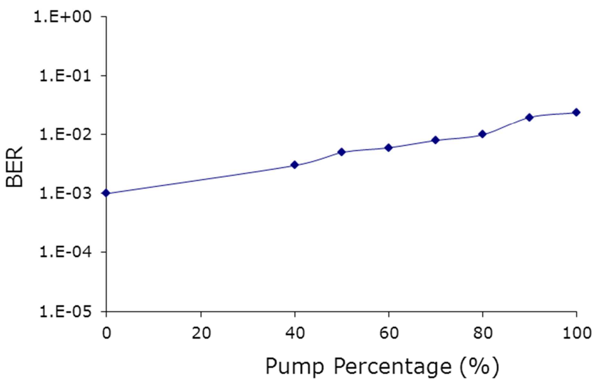
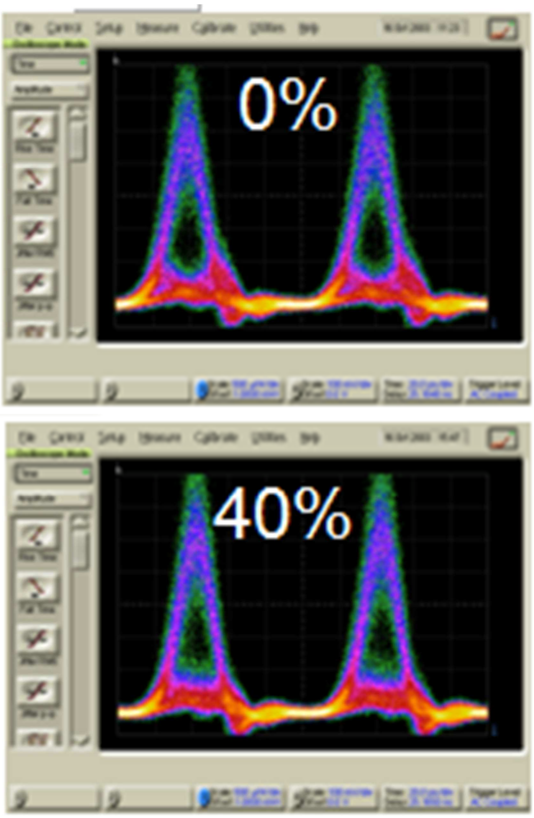


Figure 7. *BER vs Raman pump.*



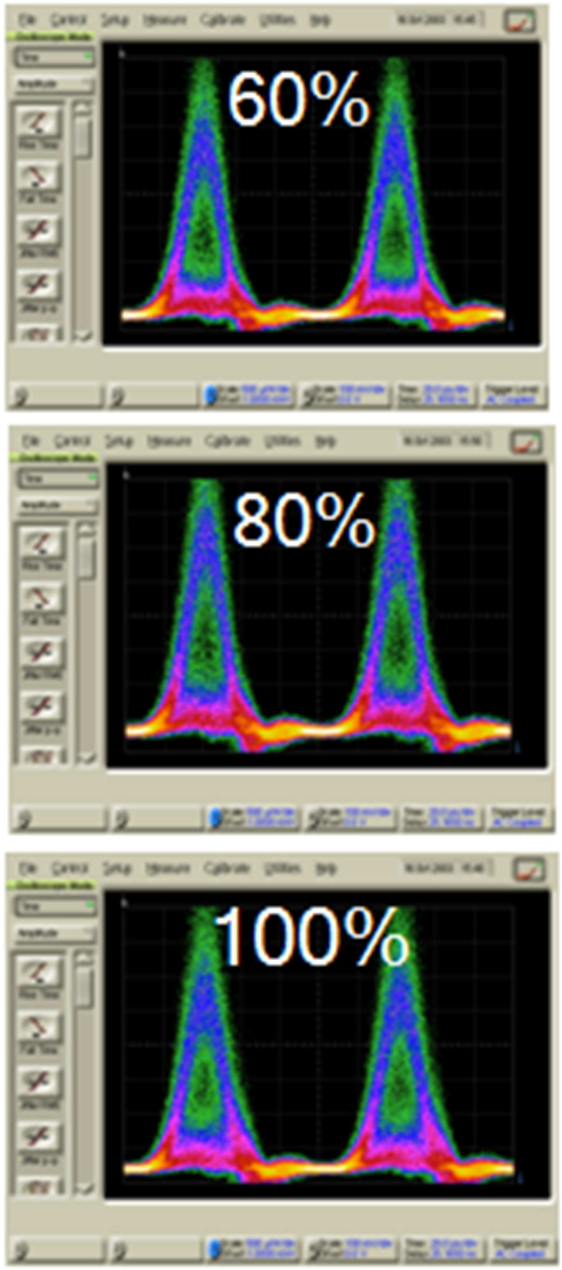


Figure 8. *Received eye diagrams with different Raman pumps.*

To solve the above problem, the lumped EDFA gains are empirically reduced such that the accumulated ASE noise is improved and the entire spectrum is nearly flattened. By doing this, all EDFA gains in our system (excluding the booster and pre-amplifier) are dropped by about 2 dB and no longer operate at saturation. This essential adjustment allows using higher Raman powers comfortably where it is noticed that the signal performance is now improved with Raman rather than degraded as before. In this case, the Raman amplification effectively compensates for the drops in the Erbium gain thus the data signal power throughout the system is balanced on average. As a result, successful transmission of the 40 Gb/s data is achieved where the best signal is obtained by using the highest Raman percentage (100%) which is corresponding to 1.58 W. The eye diagram of the received 10 Gb/s signal is presented in Fig. 9 where it measures ~10^{-9} BER. We believe that this result is satisfactory for backward Raman amplification, and there is no need to afford higher Raman power as long as the intended OTDM data signal is successfully transmitted and received via our system.

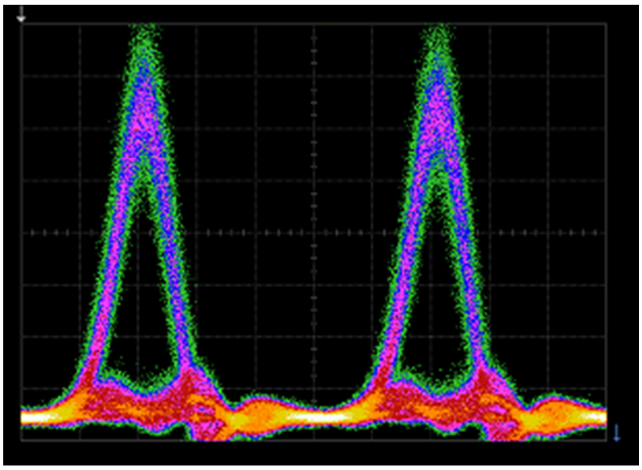


Figure 9. *Received signal obtained by 1.58 W Raman pump and reduced Erbium gain.*

In fact, this kind of results can encourage upgrading systems that use traditional fiber types/configurations where the above study can be expanded over larger systems such as long and ultra-long haul transmission systems, whether having real or recirculating-loop-based setup [19-20]. These large systems are composed of multiple unrepeatered fiber spans that are typically << 200 km and are conventionally amplified by EDFAs. To make use of the above results without major alteration on the basic configuration, it is possible to insert multiple Raman pumps where each one can serve single unrepeatered 200 km SMF span. In this case, each section of the entire system can be simulated by our single in-line long fiber span presented in this paper. The main purpose in such large systems would be reducing the required lumped Erbium gain (hence ASE noise) such that the total number of EDFAs can be reduced significantly while the overall performance is improved. Additional work can also be done where the investigation can be extended to be applied with complex modulation formats such as QPSK, DPSK, etc.

4. Conclusions

In this paper, we demonstrate unrepeatered 40 Gb/s OTDM data transmission over 206 km conventional SMF span using backward Raman amplification. The experiment uses dispersion-managed SMF-DCF configuration so that Raman amplification is applied to compensate for the SMF span loss while remote EDFAs are used for the DCF spans. The system is optimized with respect to the operating wavelength, Erbium gains/spectra and Raman pump power. As a result, successful transmission of the intended OTDM signal is attained using 1545 nm signal wavelength, 1.58 W Raman power and unsaturated gains in the cascaded EDFAs.

Acknowledgments

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