All-Optical Spectral Magnification of WDM Signals after 50 km of Dispersion Un-Compensated Transmission

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Abstract: We successfully demonstrate an optical time lens system operating on data signals that are not dispersion compensated after fiber transmission. We demonstrate 4x spectral magnification after 50 km of dispersion un-compensated transmission, with BER <1E-9.

1 Introduction

The data usage rises every year and the networks serving the growing need become more sophisticated as well. One of the challenges facing the industry manufacturing these networks is the accompanying growth in energy usage of the infrastructure. All-optical signal processing may reduce energy spending of networks by keeping the signals in the optical domain instead of converting between the electrical and optical domain for signal processing. Time lenses are versatile optical signal processors that allow for coherent, temporal and spectral manipulation of signals without losing any phase [1,2] or amplitude information carried by the data signal. Using time lenses it is possible to construct a spectral telescope that allows for the magnification and compression of wavelength division multiplexed (WDM) channels, enabling e.g. flexible grid manipulation in all-optical networks. When implementing time lenses, the timing of the signal relative to the pump has so far been considered essential; only the signal that fits within the time window of the time lens is manipulated correctly. This has led to the assumption that time lenses would only function properly in conjunction with dispersion compensated links [3]. In this paper, we show that a time lens system also functions properly for dispersion uncompensated links. Using four-wave mixing (FWM) in a large temporal window, the time lens essentially becomes a coherent sampling unit of the data signal, with no loss of information. This means that the input signal may be dispersed, and the information of that accumulated dispersion is maintained in the FWM-samples, and one can then compensate linearly for it after the time lens operation, at the receiver. In this work, for the first time we experimentally implement a spectral magnification time lens unit and demonstrate 4x spectral magnification on 3 WDM channels that have travelled through 50 km uncompensated SCUBA fiber and optically dispersion compensate after the time lens to receive the signals with bit error rate (BER) performances from <1E-9 to 1E-8.

2 Concept and Theory

The theory of temporal and spectral imagining is well studied and have found promising applications in communications [1,4]. The time lens concept is a combination of a parabolic phase shift and dispersion, which can be used to perform time-domain optical Fourier transforms (OFT) of signals, by choosing a matching amount of dispersion and linear chirp from an applied parabolic phase shift. The phase modulation can be achieved using chirped-pump FWM or using e.g. an electro-optical phase modulator [3]. When using chirped pump pulses and FWM to impart the chirp we prepare the pump pulses with half the chirp needed for the time lens, since twice the pump phase is transferred to the idler in the FWM process. The goal of this work is to achieve 4x spectral magnification using a spectral telescope. A spectral telescope requires two time lenses and the frequency shift due to FWM can therefore be compensated by the second time lens. The first time lens Fourier transforms the WDM signal, dispersion is then added and the second time lens transforms the signal back to its original form, though spectrally magnified by a factor of four. To achieve the magnification the second time lens has four times the chirp rate of the first time lens, such that when the signal is converted back it is magnified spectrally. The OFT-based spectral telescope system will have the structure C-D-C, where first we have a chirp stage, then dispersion and then chirp again. The chirp and dispersion have to follow the time lens principle of $C_1 = 1/D_1$ and for the spectral telescope to work $C_2 = 4C_1$.The dispersion, however, is positioned between the two chirp stages and therefore D_1 should be negative while D_2 positive, giving us $D = D_2\text{-}D_1$ and since $D_2\text{=}1/4\ D_1$ we get $D = 3/4\ D_1$. The sign on D_1 changes due to the phase conjugation caused by the FWM in the first chirp stage. In this paper, we apply the spectral magnification to a data signal that has been transmitted through 50 km of SCUBA fiber with no dispersion compensation. With no dispersion compensation the signal pulses will be much broader in time than their original time slots, alleviating the need for temporally aligning the pump and data pulses. Additionally, the pump and data repetition rates are initially the same, yet no clock recovery is needed at the time lenses after transmission, making the system far more practical. As mentioned above, one may compensate for the dispersion accumulated through the transmission link after the time lens unit. In this experiment, we optically dispersion compensate after the spectral magnification, and confirm proper operation of the unit. We previously demonstrated the principle, though with no data characterization [5], which would fully confirm that all the bits are handled properly. Here, we find that we can retrieve spectrally magnified waveforms properly, and confirm that the information bits are transferred to the right time sots by bit error rate measurements.

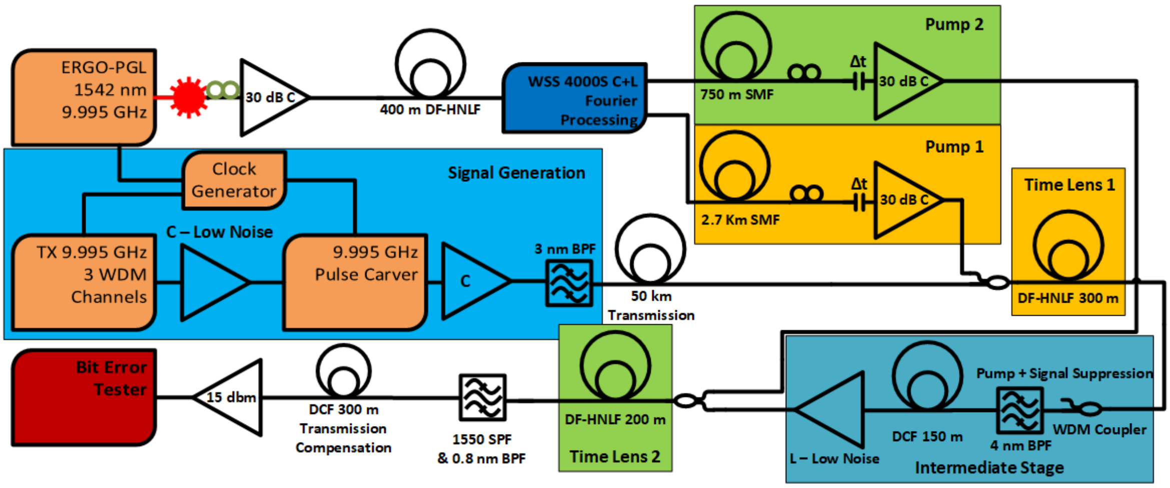


Fig. 1. The experimental setup.

3 Experimental Setup

The experimental setup can be seen in Fig. 1. We generate three 9.995 Gbit/s on-off keying (OOK) WDM signals at the transmitter. The WDM channels are on a 50 GHz grid, which after magnification is converted to a 200 GHz grid. The data channels are subjected to a pulse carver at the transmitter to create 50% duty cycle RZ pulses with on-off keying (OOK) data modulation carrying 2^7-1 pseudo random bit sequences (PRBS). The choice of the RZ format is to more easily see the effect of the spectral magnification on data waveforms. The FWM pumps are generated from an erbium-glass oscillating pulse generating laser (ERGO-PGL) with 9.995 GHz repetition rate and ~2 ps full-width at half maximum (FWHM). The pulses are then amplified to generate a supercontinuum by self-phase-modulation-induced spectral broadening in a highly nonlinear fiber (HNLF). Subsequently, a wavelength selective switch (WSS) is used to carve out two flat-top pump spectra which are diverted to different output ports. Both pumps are centered at 1562 nm with spectral widths of 185 GHz for Pump1 and 740 GHz for Pump2. The Pump1 pulses are broadened in 2.7 km standard single-mode fiber (SMF) whereas the Pump2 pulses are broadened in 750 m SMF, thus achieving approximately linearly chirped flat-top pump pulses with 80 ps FWHM in both cases. Their temporal profiles can be seen in Fig. 2. The high pump duty cycle can lead to overlap between consecutive pulses, although for a dispersion un-compensated link it can be advantageous to reduce the “dead time” of the system by having as broad pumps as possible. Dispersion flattened highly nonlinear fibers (DF-HNLF) are used to facilitate the FWM at the time lenses. We used a delay line on the second of the two pumps to be able to control the timing between the two FWM pulses since it is critical that the idler from the first time lens overlaps in time with the pump in the second time lens. Between the two nonlinear stages dispersion compensating fiber (DCF) is used to add the dispersion needed, fulfilling the time lens principle. The transmission consists of a 50 km spool of SCUBA ultra-low loss fiber with a dispersion parameter of 20 ps/nm/km. We used 5 dBm of WDM signal launch power and the loss in the link is 9.5 dB. Before the spectral telescope the signal is amplified, and the output of the spectral telescope is amplified before the receiver. A WDM-coupler and a filter are used to filter out the pump and original signal after the first time lens. At the output of the spectral telescope a combination of a short-pass filter and a narrow band-pass filter is used to suppress the pump and single out the channel for measurement. Polarization controllers are employed in the time lenses, after transmission and at each pump aligning the polarization of the pumps to the signal to maximize the FWM efficiency. The amount of dispersion compensation needed is reduced by a factor of 16 due to the 4x spectral magnification of the signal after transmission and that the dispersion on the signal is now stretched over a spectrum now 4 times the width. The receiver employs a pre-amplifier, set to a constant output of 15 dBm before detection using a 20-GHz photodiode, the power into the photodiode was kept constant at -3 dBm. The BER performance was evaluated using a commercial 10 GHz BER tester (BERT). Back-to-back measurements were done at the output of the last amplifier in the signal generation stage of the setup, thereby including all the components also present in transmission, save the transmission fiber.

4 Results

In Fig. 2 (right) we show the spectra of the original three channels being transmitted and the spectrally magnified output of the last time lens. The pump spectra for both pumps are shown in the center of Fig. 2 (right) and to the right of this we see the output of the first time lens. The two small peaks on either side of the pump spectrum are due to FWM between the tails of the chirped pump pulses. Fig. 2 (left) shows oscilloscope traces of the pump waveforms, being rectangular shaped with about 80% duty cycle and linearly chirped. We performed bit error-rate measurements (BER) on the central channel of the 3 WDM transmitted channels, and to characterize the crosstalk between the channels we also measured the BER when only transmitting a single channel. The results can be seen in Fig. 3.

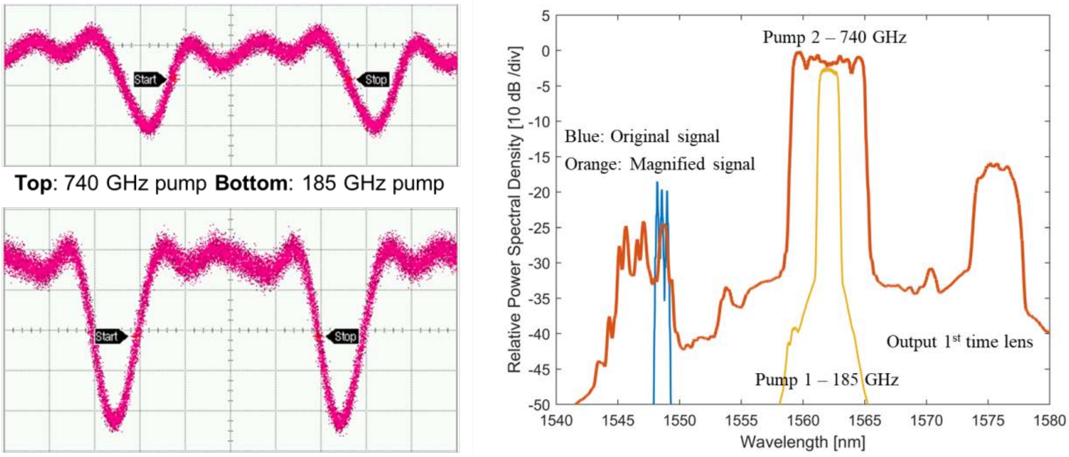
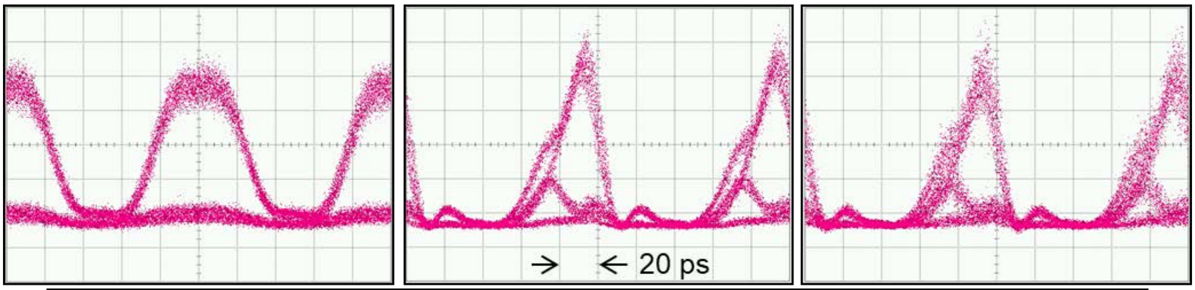


Fig. 2. Left: The temporal profiles of the pumps, 20 ps per division. Right: The spectra of the original channels and the magnified output.

It can be seen from the eye-diagrams of the 1-channel transmission (Fig. 3 (middle)) and the 3-channel transmission (Fig. 3 (right)) that the data pulses are compressed, as we would expect from the spectral magnification. The pulses are so narrow that they give rise to some ringing in the oscilloscope traces also we observe some aliasing effects seen as double traces present. We expect these distortions in the eye-diagrams to be due to small frequency shifts stemming from the sampling process of the time lens window itself, as well as overlapping of consecutive data pulses with the pump pulses giving rise to offset FWM frequencies not properly matched in the final dispersion compensation. The spectrum of the signal is modulated periodically by the pumps so the spectral shape that we attempt to dispersion compensate at the receiver is therefore not only broadened by the spectral telescope but also shaped by the spectral shape and the temporal shape of the FWM pumps. These effects make it very challenging to recover the exact pulse shape at the receiver however we believe this can be better compensated with digital signal processing. Beneath the eye diagrams we state the corresponding BER values obtained for this particular eye. We see that it is indeed possible to recover the data for this concept, thus demonstrating that the time lens does function properly for a dispersion uncompensated link. When transmitting 3 WDM channels the BER increased from <1E-9 to 6.2E-8 for the same received power of -8 dBm, at the receiver-side amplifier, owing to increased interchannel crosstalk.



Back-to-Back	**1 Channel**	**3 Channels**
BER < 1E-9	**BER** < 1E-9	**BER** = 6.2E-8

Fig. 3. From left to right: Back-to-back 1 channel, 50 km transmission of 1 channel and 50 km transmission of 3 channels. All figures have 20 ps per division, showing two full time slots.

5 Conclusion

We demonstrate for the first time a time lens based spectral telescope operating successfully on data signals transmitted through dispersion uncompensated links. We demonstrate the concept by transmitting a 10 Gbit/s OOK signal through 50 km SCUBA fiber followed by 4x spectral magnification. We obtain BERs below 1E-9 revealing proper operation of the system. This result demonstrates improved prospects for practical applications of time lenses in communication systems. Thanks to OFS for the SCUBA fiber and to the SPOC center of excellence (ref. DNRF123).

6 References

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