Analysis of fiber based coherent detection employing optical preamplifier and time-domain filter

Youming Chen[*a], William Torruellas[a], Brian L. Mark[b], Ralph Burnham[a], Horacio Verdun[a]
[a] Fibertek, Inc., 510 Herndon Pkwy, Herndon, VA 20170
[b] ECE Dept. George Mason University, MS 1G5, Fairfax, VA 22030

ABSTRACT

We report on a novel fiber based coherent detection system employing an optical preamplifier, a spectrum bandpass filter, and a time-domain filter. The time-domain filter, a synchronous time gate, reduces the in-band Amplified Spontaneous Emission (ASE) beat noise, which cannot be achieved by the spectrum bandpass filter alone. In preliminary experiments with a 100 GHz bandpass filter, no degradation is observed from the optically preamplified coherent detection compared to pure coherent detection. With a 10 ns pulse width, 500 kHz repetition rate, and 10 pW input power, 2.78 dB and 1 dB signal-to-noise (SNR) improvement has been achieved, respectively, when 5% and 50% time gating duty cycle is used.

Keywords: coherent detection, optical preamplifier, time-domain filter (TDF), sensitivity, detection.

1. INTRODUCTION

The sensitivity of signal detection is of major interest for optical high speed communication systems and LIght Detection And Ranging (lidar) systems. Sensitive receivers in fiber-optical networks can reduce transmitter power or amplifier amplification requirements and extend link spans. High receiver sensitivity allows links to be established over long distances in deep space satellite communication systems and large atmospheric attenuation to be overcome in terrestrial free space communications. For lidar systems, the sensitivity of signal detection determines how far and how accurately the lidar can detect the remote objects.

Optical receivers employ either coherent or direct detection. In addition to amplitude, coherent detection extracts frequency and phase information from received signals, whereas direct detection extracts the received pulse amplitude only. In theory and previous experiments, coherent detection should yield the higher receiver sensitivity[1,2]. Another possible technique to improve detection sensitivity is to employ a fiber preamplifier. This technique has been successfully demonstrated in direct detection systems[3,4,5], but not in the coherent detection systems. Due to the existence of ASE inside the amplifier, the sensitivity of coherent detection is degraded and varies with the data rate or pulse rate[6,7]. For this reason, fiber based optically preamplified coherent detection is not used in applications as commonly as direct detection.

In this paper, we report on a new architecture for a coherent detection system, which employs an optical preamplifier and a time-domain filter. We provide a characterization of the detection system and a comparison of different detection schemes. In the follow sections, we briefly describe the concepts of the architecture design and noise analysis of the system. Then, we present the experiment results, including results for direct detection, and coherent detection with and without the time-domain filter. Discussions and conclusions are given in the final section.

2. CONCEPT OF THE OPTICAL PREAMPLIFIED COHERENT DETECTION SYSTEM FILTERED BY TDF AND BANDPASS FILTER

[*] ychen@fibertek.com; phone 1 703 471-7671; fax 1703 471-5806; www.fibertek.com

2.1 Principle of the coherent detection system

The schematic diagram of the optical preamplified coherent detection system extended by using time domain and frequency domain filters is shown in Figure 1. The optical signals processed at different stages in the time and spectrum domains are shown in Figures 2 and 3, respectively.

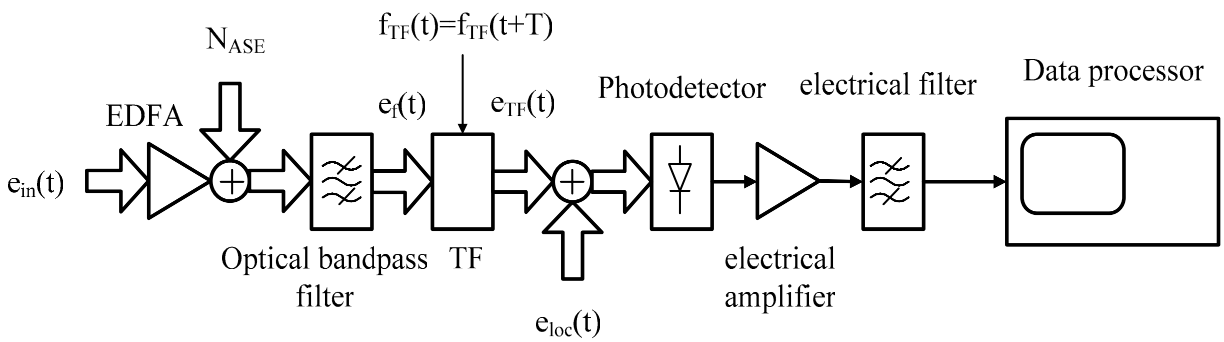


Figure 1. Schematic diagram of optically preamplified coherent detection employing time domain filter.

The input optical pulse trains are amplified when the pulses pass through the active optical preamplifier. In the meantime these amplified optical pulses are also corrupted by ASE. The ASE added to the pulses will degrade the optical SNR of the detection system (Figures 3, 4 b). A spectrum bandpass filter is used to filter out the unnecessary spectrum components outside of the band of the central wavelength (Figure 4 d). Then, the amplified and filtered pulses are fed through the time-domain filter (TDF). The length of the time window can be varied according to the needs of the application. Of course, the window should at least be wider than the coherence time of the transmitted optical pulses. The time-domain filter combined with the narrow band spectrum filter can significantly reduce the negative effects caused by ASE on the coherent detection performance (Figure 3 e).

2.2 Noise analysis

As shown in Figure 1, when an arbitrary, complex, optical field $e_{in}(t)$ is preamplified by a low noise amplifier with small signal gain of G, the preamplified signal will be additionally corrupted by ASE. Since the ASE is treated as an additive Gaussian process $n_{ASE}(t)$, after amplification, the optical field becomes

$$e_G(t) = \sqrt{G}e_{in}(t) + n_{ASE}(t) \tag{1}$$

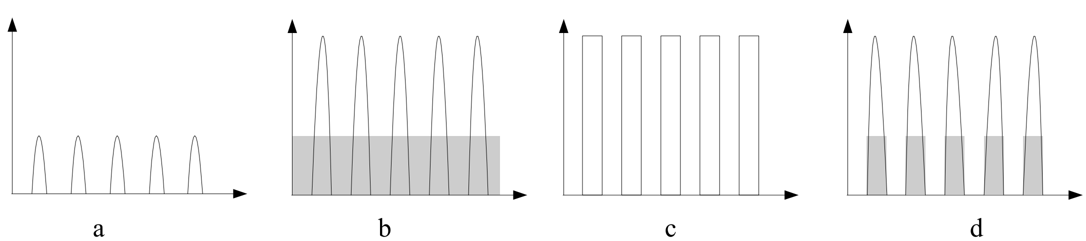
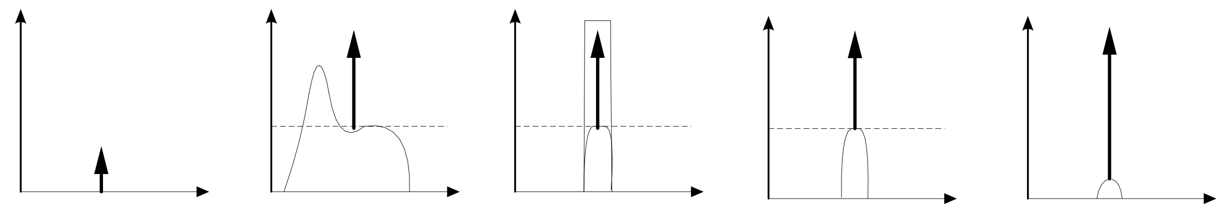


Figure 2. Development of the pulses in the time domain. a. original pulses. b. after the amplifier,with added ASE. c. the time domain filter. d. after the time domain filter.



a. b. c. d. e.

Figure 3. The spectrum properties in the frequency domain with the narrowband filter. a. original signal. b. after the amplifier, with added ASE. c. narrow passband filter. d. after the passband filter. e. after the time doman filter.

The preamplified optical field is spectrally filtered by an optical bandpass filter with impulse response function $h_o(t)$. The filtered optical field $e_f(t)$ becomes

$$e_f(t) = \left[\sqrt{G}e_{in}(t) + n_{ASE}(t)\right] * h_o(t) \tag{2}$$

Then, the optical field is temporally filtered by the TDF with a periodic function $f_{TF}(t) = f_{TF}(t+T)$, where *T* is the period. To simplify the analysis, the TDF function can be written as

$$f_{TF}(t) = \begin{cases} 1 & 0 \le t \le D \\ 0 & D < t \le T \end{cases} \tag{3}$$

where D is the gate width. The TDF filtered field becomes a cycle stationary process $e_{TF}(t) = e_f(t) \cdot f_{TF}(t)$. Upon reaching this point, the optical filed $e_{TF}(t)$ mixes with the local oscillator filed $e_{loc}(t)$ at the photodetector. The optical field can be further written as

$$e_{mix} = \left\{\left[\sqrt{G}e_{in}(t) + n_{ASE}(t)\right] * h_o(t)\right\} \cdot f_{TF}(t) + e_{loc}(t) \tag{4}$$

According to the square law, the detected signal current is given by

$$\langle i(t) \rangle = \eta \left\langle \left|e_{mix}(t)\right|^2 \right\rangle * h_e(t) \tag{5}$$

where η denotes the overall optoelectronic conversion factor of the detection system; $h_e(t)$ is the electrical transfer function of the photodetector, electrical amplifier, and electrical bandpass filter.

$$\langle i(t) \rangle = \eta\left[Gp_{ino}(t) * h_e(t)\right] + \eta N_{ASEo}\left[f_{TF}(t)^2 * h_e(t)\right] + \eta\left[p_{loc}(t) * h_e(t)\right] + 2\eta\left[\sqrt{Gp_{ino}(t)p_{loc}(t)} * h_e(t)\right] \tag{6}$$

where $p_{ino}(t) = \left\langle \left| e_{in} * h_o(t) \right|^2 \right\rangle$ stands for the input signal power, $N_{ASEo} = \left\langle \left| n_{ASE} * h_o(t) \right|^2 \right\rangle$ is the average ASE power after filtering with the optical bandwidth B_o, and $p_{loc}(t) = \left\langle \left| e_{loc} \right|^2 \right\rangle$ is the local oscillation power. The variance of the photocurrent is given by

$$\sigma^2(t) = \eta e \left(\left\langle \left| e_{mix}(t) \right|^2 \right\rangle * h_e(t)^2 \right) + \eta^2 \int_{-\infty}^{+\infty}\int \left(\left\langle \left| e_{mix}(\tau) \right|^2 \left| e_{mix}(\tilde{\tau}) \right|^2 \right\rangle - \left\langle \left| e_{mix}(\tau) \right|^2 \right\rangle \left\langle \left| e_{mix}(\tilde{\tau}) \right|^2 \right\rangle \right) h_e(t-\tau) h_e(t-\tilde{\tau}) d\tau d\tilde{\tau} \quad (7)$$

where *e* is the elementary charge. The first term on the right-hand sideis for the variance of the shot noise and the second term is the beat noise. After applying the moment theorem of Gaussian processes and doing some algebra, the variance can be written as

$$\sigma^2(t) = \sigma^2_{s\_shot}(t) + \sigma^2_{loc\_shot}(t) + \sigma^2_{ASE\_shot}(t) + \sigma^2_{ASE\_ASE}(t) + \sigma^2_{s\_ASE}(t) + \sigma^2_{loc\_ASE}(t) \quad (8)$$

The variance of the shot noise caused by the signal, ASE, and local oscillation is given by

$$\sigma^2_{shot}(t) = \eta e \left[G p_{ino}(t) + N_{ASEo} f_{TF}{}^2(t) + p_{loc}(t) \right] * h_e^2(t) \quad (9)$$

The variance of the signal-ASE beating noise is given by

$$\sigma^2_{s\_ASE}(t) = 2\eta^2 G \Re \left\{ \int_{-\infty}^{+\infty}\int \left| f_{TF}(\tau) \right|^2 \left| f_{TF}(\tilde{\tau}) \right|^2 \left(e_{ino}(\tau) e_{ino}{}^*(\tilde{\tau}) \left\langle n_{ASEo}{}^*(t) n_{ASEo}(\tilde{t}) \right\rangle \right) \right\} h_e(t-\tau) h_e(t-\tilde{\tau}) d\tau d\tilde{\tau} \quad (10)$$

The variance of the ASE-ASE beating noise is given by

$$\sigma^2_{ASE\_ASE}(t) = \eta^2 \int_{-\infty}^{+\infty}\int \left| f_{TF}(\tau) \right|^2 \left| f_{TF}(\tilde{\tau}) \right|^2 \left| \left\langle n_{ASEo}{}^*(t) n_{ASEo}(\tilde{t}) \right\rangle \right|^2 h_e(t-\tau) h_e(t-\tilde{\tau}) d\tau d\tilde{\tau} \quad (11)$$

The variance of the local oscillation-ASE beating noise is given by

$$\sigma^2_{loc\_ASE}(t) = 2\eta^2 \Re \left\{ \int_{-\infty}^{+\infty}\int \left| f_{TF}(\tau) \right|^2 \left| f_{TF}(\tilde{\tau}) \right|^2 \left(e_{loc}(\tau) e_{loc}{}^*(\tilde{\tau}) \left\langle n_{ASEo}{}^*(t) n_{ASEo}(\tilde{t}) \right\rangle \right) \right\} h_e(t-\tau) h_e(t-\tilde{\tau}) d\tau d\tilde{\tau} \quad (12)$$

If the bandwidth B_o of the optical filter is much wider than that of the electrical filter, B_e, and the cycle stationary process is taken into account, the equation (9) – (12) can be simplified as follows:

The variance of the shot noise becomes

$$\sigma^2_{shot}(t) = \eta e \left[G p_{in}(t) + N_{ASEo} \left(\frac{D}{T} \right)^2 + p_{loc}(t) \right] * h_e^2(t) \quad (13)$$

The variance of the signal-ASE beating noise becomes

$$\sigma^2{}_{s\_ASE}(t) = 2\eta^2 G N_{ASEo} \left(\frac{D}{T}\right)^2 \left[p_{in}(t) * h_e{}^2(t) \right] \quad (14)$$

The variance of the ASE-ASE beating noise becomes

$$\sigma^2{}_{ASE\_ASE}(t) = \eta^2 N^2{}_{ASEo} \left(\frac{D}{T}\right)^4 \quad (15)$$

The variance of the local oscillation-ASE beating noise becomes

$$\sigma^2{}_{loc\_ASE}(t) = 2\eta^2 N_{ASEo} \frac{D}{T} \left(P_{loc}(t) * h_e^2(t) \right) \quad (16)$$

The receiver electrical signal to noise ratio can be represented as the ratio of the photocurrent to the photocurrent variance:

$$SNR = \frac{I_s^2}{\sigma_{\det}^2} = \frac{2Gp_{loc}p_{in}}{\sigma_{shot}^2 + \sigma_{s\_ASE}^2 + \sigma_{ASE\_ASE}^2 + \sigma_{loc\_ASE}^2 + \sigma_{th}^2} \quad (17)$$

This is the general equation that can be used for detection evaluation and noise analysis. When *D* equates to *T*, it is the case of optically preamplified coherent detection without the time domain filter. When *D* equates to *T*, N_{ASEo} equates to zero, and *G* equates to one, and the system becomes equivalent to regular coherent detection. From equations (13) to (17), we can see that the ASE power affects all the variances of detection signals of interest; therefore, a narrow optical bandpass filter can effectively improve the detection performance by reducing the ASE power. From the above equations, it is also clear that the smaller the duty cycle $\left(\frac{D}{T}\right)$, the smaller the variances of the detection system.

3. EXPERIMENTS

3.1 Experimental setup and characterization

The optically preamplified coherent detection with time domain fitering is investigated experimentally. The experimental setup is shown in Fig. 4. A 20 mW DFB PM laser diode (JDS Uniphase) is used as the seed source. The linewidth is less than 1 MHz. The wavelength of the seed source is shifted by 500 MHz in the first-order output port of a polarization maintained AO shifter (Biromrose). Two zero-Chirp Intensity Mach-Zehnders made by COVEGA are used in the experiments. One is the Mach-10 TM 004 integrated with a variable optical attenuator. This Mach-Zehnder is used to modulate the shifted laser beam and generate signal pulses. The other Mach-Zehnder Mach-10 056 is used for time domain filtering. An analog Modulator Bias is used to supply the bias voltages on both modulators. The integrated VOA of the Mach-Zehnder of the Mach-10 TM 004 is adjusted by a DC power supplier. Both Mach-Zehnders have a 10 GHz bandwidth. An external in-line PM variable optical attenuator is used to control the signal strength up to 30 dB variations. A 3 dB PM coupler is used to mix signal and local oscillation light. A PIN Photodiode (Discovery Semiconductors, Inc.) is chosen to detect the mixed light. The photodiode has a 10 GHz bandwidth and the optical power linearity range can be up to 25 mW, which ensures that the 25 mW local oscillator optical power is still within the photodiode linear responsive range. An RC circuit is used to filter out the DC component that is mainly contributed by the local oscillator. Two Mini Circuit ZFL-1000LN amplifiers are used to amplify the electrical signal passing through the RC filter. The amplifier has a 1 GHz bandwidth and a 2.9 dB noise figure. A 2.5 GHz Tektronix digital phosphor oscilloscope (TDS7254B) is used to do signal capturing and processing. A special labview program has been developed to control the oscilloscope. The program has been integrated with some special functions such as bandpass filtering, squaring, averaging, summing, and so on.

For weak signal detection, the ASE of the optical preamplifier is a serious issue. Fig. 5 shows the modeling results of the OFS PM fiber (R37pm02) with an input power of 100 pW and a pump power of 300mW, which match the experimental conditions. From the figure, we can see that the input signal at that power level can not saturate the gain of the amplifier and ASE totally dominates the amplification. A 7 m long fiber amplifier is used the experiment with 28.5 dB gain and 3.2 dB noise figure. At 300mW pump power, the forward ASE of the amplifier can be as high as 30 mW, however the signal is amplified to 70 nW, which is 56 dB lower than the ASE in power. The output spectrum of the preamplifier captured in the experiment is shown in the Fig. 6. As discussed before, the strong ASE will cause serious degradation of the detection system. To reduce the negative effects caused by ASE, a 100 GHz bandwidth and 20 dB isolation PM FBG has been specially designed. By using this FBG and combining with a PM circulator, an optical PM bandpass filter with

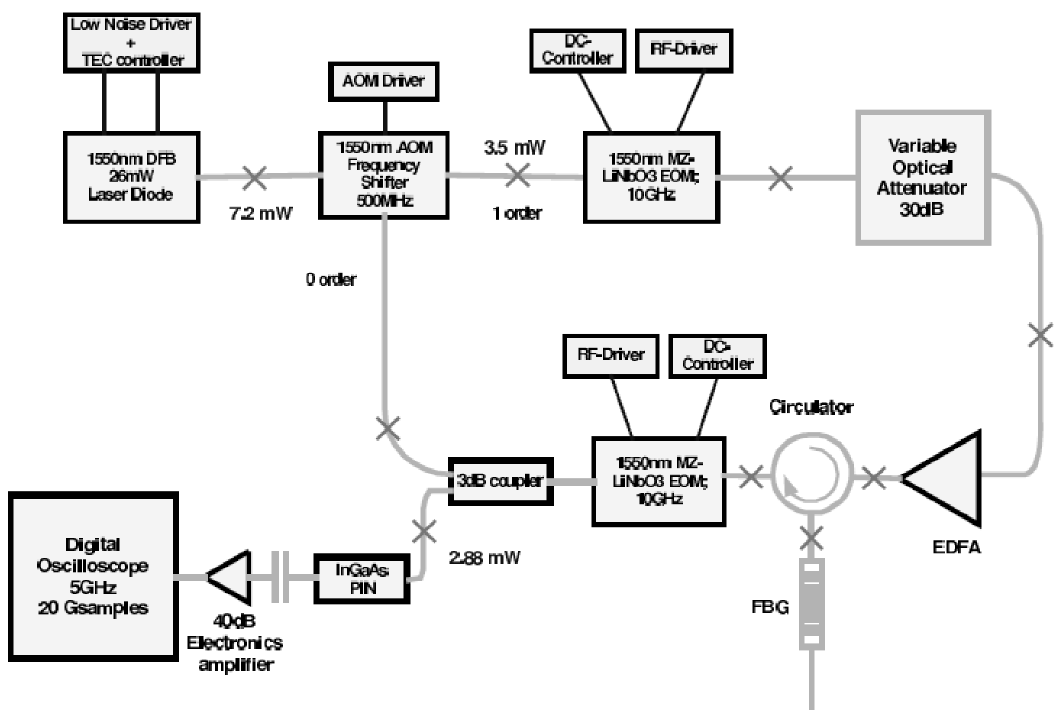


Figure 4. Schematic diagram of an optically preamplified coherent detection system by time domain filtering.

bandwidth of 100 GHz and isolation of 20 dB has been successfully constructed. By using the optical bandpass filter, the experiment successfully demonstrates that the filtered signal and in-band ASE is 20 dB higher than the peak of any other wavelengths of the ASE (see Fig. 6.). To achieve the maximum signal power, the input signal wavelength is tuned to the central wavelength of the FBG by changing the temperature of seed laser diode. The picture on the upper right corner of Fig. 6 shows the signal wavelength location referred to the spectrum window of the FBG.

Although most of the ASE can be successfully removed by the optical bandpass filter, the residual in-band ASE still exists. To reduce this ASE, the second MZM is used as a time domain filter that is modulated by a Philips pulse generator synchronized with the first MZM. Fig. 7 shows the experimental results without and with the time-domain filter filter, for which the open time slot is 100 ns, corresponding to a 5% duty cycle for a 500 kHz repetition rate. The experimental results show that the in-band ASE can be reduced by about 70% using the time-domain filter. Since the figure is captured by an Optical Spectrum Analyzer (OSA), it shows that the time-domain filter is very efficient in improving direct detection.

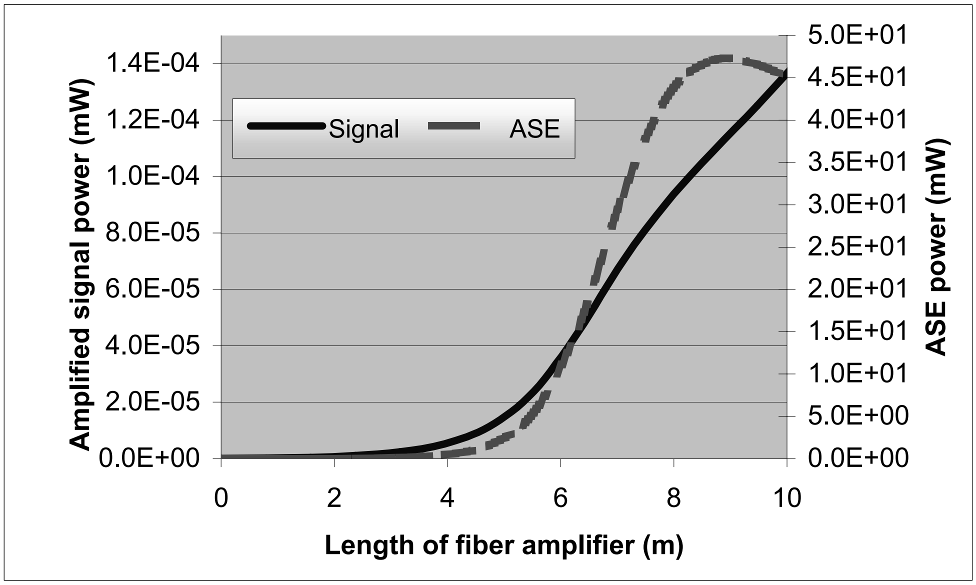


Figure 5. Simulation results of the preamplifier. The blue curve is the amplified signal power on left Y-axis and the pink curve is the ASE power on the right Y-axis.

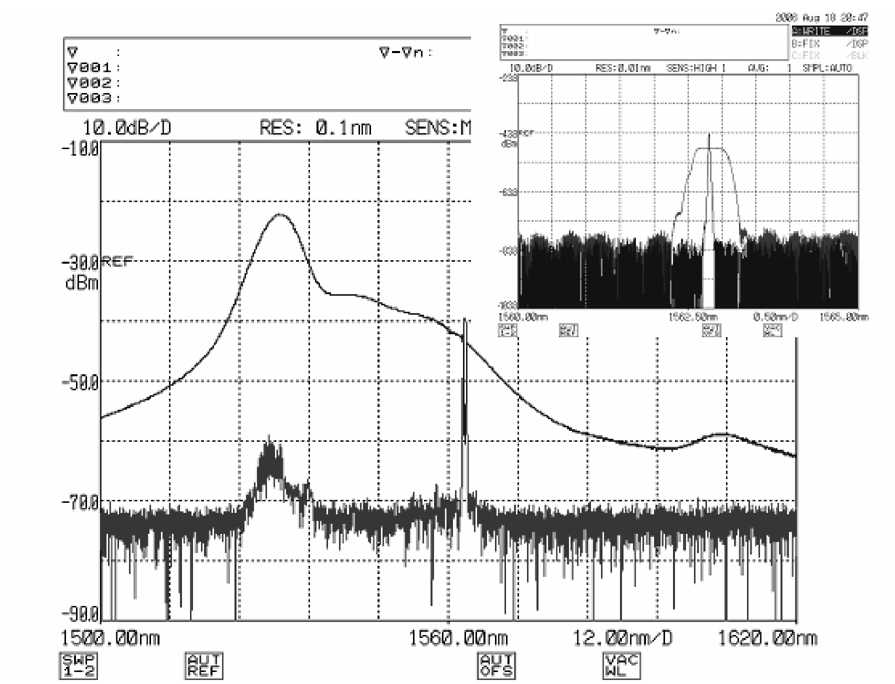


Figure 6. Output spectrum of the optical preamplifier with 100 pW input signal. The blue curve is the forward ASE and the red curve is filtered signal and in-band ASE. The top right corner shows the seed spectrum and spectrum window of the filter in expanded scale.

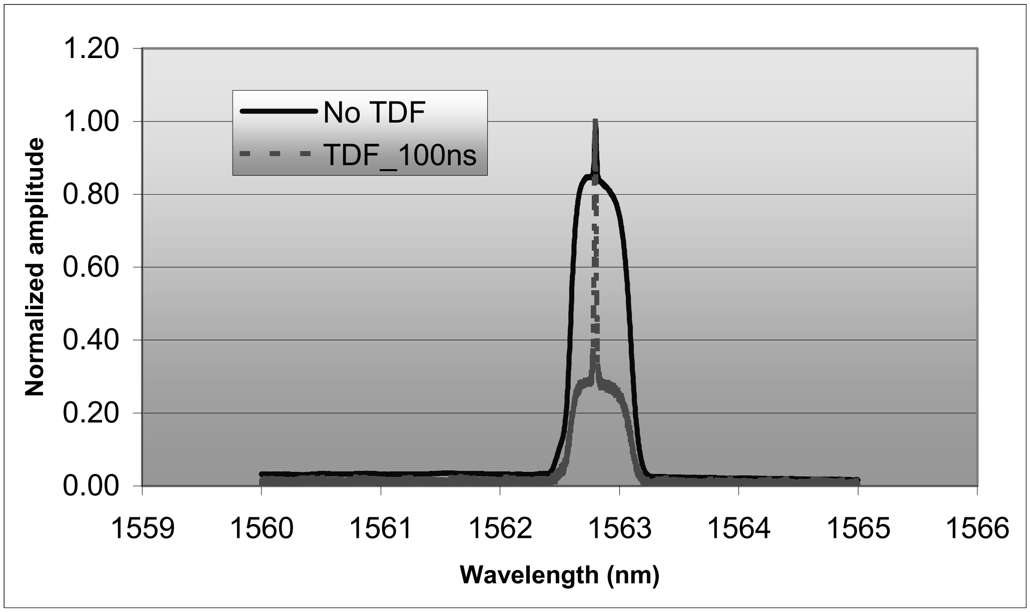


Figure 7. The spectra of the signal and in-band ASE. The blue curve is the spectrum without the time-domain filter and the pink is the one with the time-domain filter.

3.2 Coherent detection experiment

With the above experimental setup, the preliminary experiment has successfully demonstrated fiber-based heterodyne detection. The signal pulses are generated by the first MZM with pulse duration of 10 ns and a 500 kHz repetition rate. With the same detection system, we also evaluate the direct detection performance and find that the sensitivity of the direct detection is over 20 dB less than that of the coherent detection, even though the direct optical detection of on-off keyed signals is better, in principle, than that of heterodyne detection of these same signals. However, in practice, the thermal noise, excess noise, and electronics background radiation seriously degrade the direct detection sensitivities.

From equation (17), we can see that the received signal can be amplified by the local oscillation after two beam mixing. If the local oscillation is strong enough, the shot noise caused by the local oscillation will dominates the noise field. In this experiment, the local oscillator should be higher than 1 mW to overcome the Johnson noise. The highest sensitivity of coherent detection achieved in the experiment is 0.7 pW, corresponding to 10.9 photons within the 10 ns pulse width. This sensitivity is observed in pure coherent detection and optically preamplified coherent detection. To achieve this sensitivity, whatever the methods are to be used, averaging multiple traces of multiple traces has to be applied to smooth out the random noise. For the single trace capturing, at 1 pW average input power, the undetectable probability of the optically preamplified coherent detection varies from 20% to 60% by adjusting the bandwidth of the digital bandpass filter integrated in the Labview program from 50 MHz to 400 MHz.

The experimental results of the detection performance with the different time-domain filtering windows are shown in Fig. 8. The results shown with red, blue and yellow markers are taken with 200 MHz bandwidth of the digital bandpass filter, which is centralized at IF, i.e., 500MHz. As expected, the detection performances improve when the time-domain filter window narrows down. Compared with an open window, 100 ns or 5% duty cycle and 50% duty cycle time windows show 2.78 dB and 1 dB improvement, respectively, for a single shot process at 10 pW input power level. The shot noise limits in the theoretical analysis for the bandwidths of 200 MHz and 1 GHz are also given in the figure in colors of blue and pink, respectively. Both experimental and analytical results show that the redudant digital bandpass filter is very helpful in improving the detection performance. In Figure 8, the best experimental results that are close to the shot noise are taken in the 5% duty cycle time window at 200 MHz. However, there is not a big change when the time window is changed from 20% to 50% duty cycle at 1 GHz digital bandwidth. A wider bandwidth of the digital bandpass filter results in stronger shot noise. In this case, the ASE induced noises are limited, because only a small portion of the ASE passes through the narrow and strong optical bandpass filer. Only half of this ASE has the same polarization as the signal and local oscillation. Even among the half part of ASE, there is a small portion that has coherent relations with the signal and local oscillation. The typical squared temporal pulse profile is shown in the Fig. 9, which shows the signal captured at 10 pW received power with 100 ns or 5% duty cycle window size.

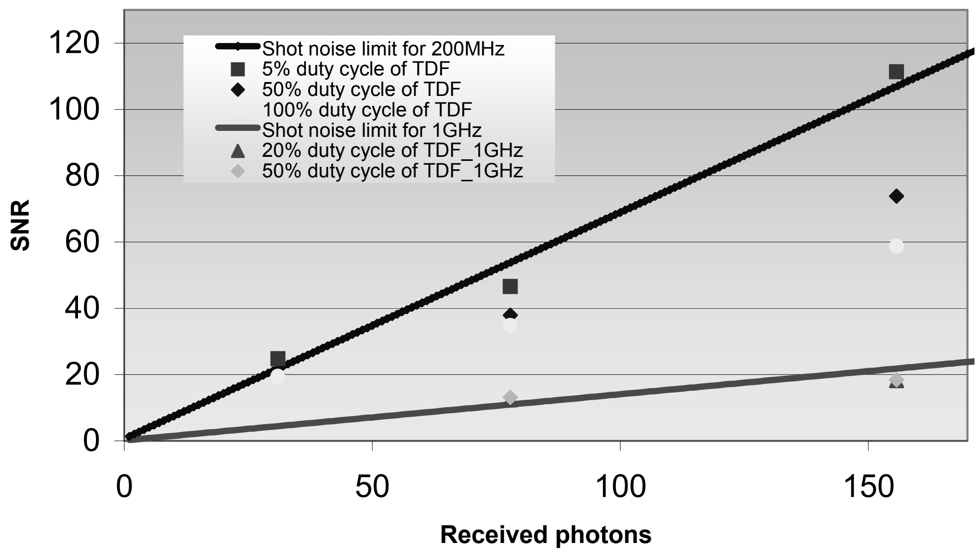


Figure 8. Signal to noise ratio versus number of received photons with different detection conditions. The blue line is the shot noise with a digital bandpass filter of 200 MHz and the pink one is for 1 GHz bandwidth. The red, blue, and yellow markers are the single trace captured results of the duty cycle windows with 5%, 50% and 100% for 200 MHz digital bandwidth, respectively. The green and brown markers show results for 20% and 50% duty cycles for the 1 GHz digital bandwidth.

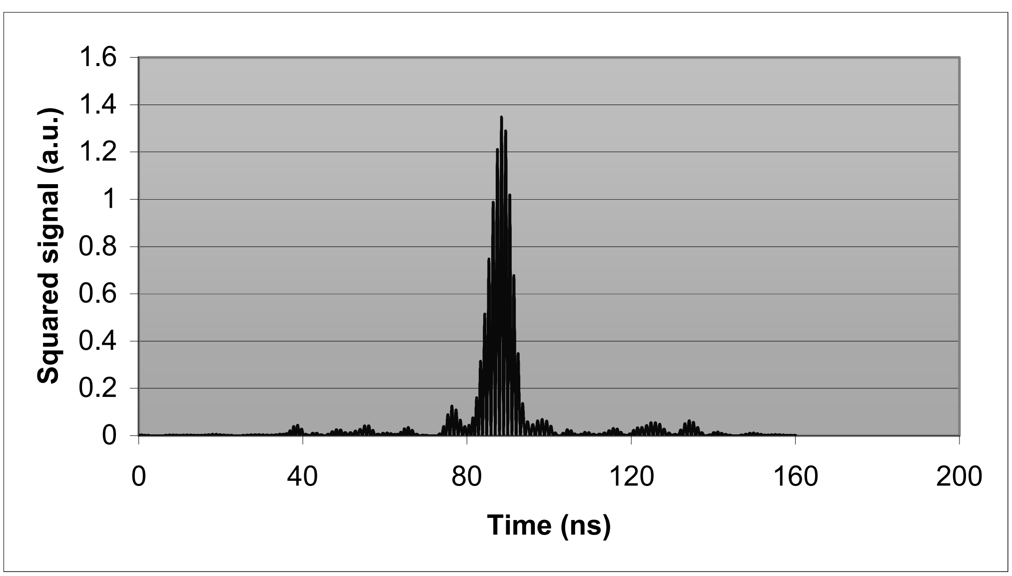


Figure 9. The squared temporal pulse profile is shown in the Fig. 9, which is the signal captured from the optically preamplified coherent detection at 10pW received power with 100 ns or 5% duty cycle window size.

4. CONCLUSIONS

We demonstrated a novel fiber based coherent detection system that uses an optically preamplifier, a spectrum bandpass filter and a time-domain filter to strengthen the received signal and reduce ASE effects. We described the basic concept and principle and derived related equations for this detection architecture. With a 100 GHz optical bandpass filter, we conducted experiments with different window sizes for the time-domain filter. We successfully demonstrated 2.78 dB, 1 dB SNR improvements with respect to open windows, i.e., 100% duty cycle with 100 ns and 1000 ns window size or 5% duty cycle and 50% duty cycle, respectively, at 200 MHz bandwidth of a digital bandpass filter. We also demonstrated that for a shot noise-dominated optically preamplified coherent system, the time domain filter could not improve the detection significantly. When the ASE-induced noise is comparable to the shot noise, the time-domain filter is very helpful in improving the performance of coherent detection.

REFERENCES

1. Max Ming-Kang Liu, *Principles and Applications of Optical Communications* The McGraw-Hill Companies, Inc., 1996.
2. U. Timor, et al., *A Comparison of Sensitivity Degradations for Optical Homodyne versus Direct Detection of On-Off Keyed Signals*, J. of Lightwave Tech., Vol. 6, No. 11, 1782, 1988.
3. O. Tonguz, et al., *Equivalence Between Preamplified Direct Detection Heterodyne Receivers,* IEEE Phot. Tech. Lett., Vol. 3, No. 9, 1991.
4. P. Humblet, et al., *On the bit error rate of lightwave systems with optical amplifiers*, J. Lightwave Tech. Vol. 9, No. 11, 1991.
5. H. Sanjoh, et al. *Time-domain filtering to reduce signal-spontaneous beat noise for a pulse type multiwavelength light source*, IEEE Phot. Tech. Lett., Vol.15, No. 5, 757, 2003.
6. B. Glance, et al., *Sensitivity of an Optical Heterodyne Receiver in Presence of an Optical Preamplifier*, Elect. Lett., Vol. 24, No. 19, p. 1229, 1988.
7. S. Ryu, et al., *Use of an Optical Amplifier in a Coherent Receiver*, IEEE Phot. Tech. Lett., Vol. l3, No. 7, p. 663, 1991.
8. L. Mandel and E. Wolf, *Optical Coherent and Quantum Optics,* Cambridge University Press, 1995.