Performance analysis of photonic lantern based coherent receivers

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In this paper, we present the simulation results for bit-error-rate improvements of photonic lantern based coherent LIDAR systems. Our results show that using a 19-port photonic lantern, the bit-error-rate can be improved to 0.06 from 0.30 for a range of 100 meters, corresponds to a detection rate improvement from 70% to 94%.

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1. Introduction

3D light detection and ranging (LIDAR) systems have applications in terrain mapping, surveying, meteorology, wind analysis, robotics, and autonomous navigation [1]. These systems have different detection architectures depending on the application range, data acquisition rate and resolution. Between these detection schemes, coherent detection based LIDAR systems have the potential to provide quantum noise limited performance [2]. However, coherent systems suffer from poor free space to fiber collection efficiency due to the single-mode detection characteristics and small size of the optical fiber. In order to overcome this problem, photonic lanterns are introduced to effectively collect the multi-mode beam coming from free space and convert it to a number of single-mode fibers [3]. Using the photonic lanterns, the free space to single-mode coupling efficiency is improved by a factor of 8 dB relative to standard single-mode fibers for near field distances [4]. In the past, a photonic lantern based coherent LIDAR system is demonstrated with an average voltage signal to noise improvement of 2.8 when compared to standard single-mode receivers [5]. Using the same SNRV, the LIDAR system can be configured for longer range or for higher detection rate, however the drawback of such configurations are the lower detection rate. Typically for LIDAR systems, 90% detection ratio is acceptable; the other parameters are configured for this value. In this manuscript, we present numerical results of the bit error rate (BER) improvement of photonic lantern based coherent receivers. Our results show that the BER of the coherent LIDAR system is improved to 0.06 from 0.30 using a photonic lantern which corresponds to a detection rate improvement from 70% to 94%.

2. Photonic lantern

A photonic lantern, Fig. 1, can effectively collect multi-mode light and converts it to a number of single-mode signals and vice verse. The photonic lantern has three parts: the multi-mode fiber part, the section where the multi-mode light is collected, the multi-mode to single-mode transition section and finally the single-mode fibers section. The photonic lantern is introduced to have single-mode filtering ability of multi-mode signals for astronomy applications [3]; however, spatial multiplexed optical communication systems became the biggest application area of photonic lanterns [6]–[8]. In this paper, we analyzed the performance behaviour of a LIDAR system with 19 port photonic lantern, i.e. a photonic lantern with 19 single-mode fibers.

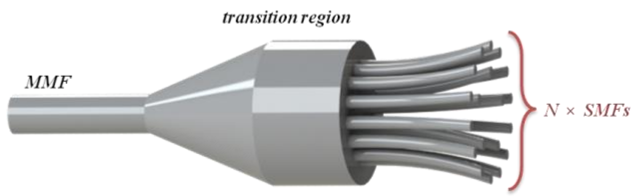


Fig. 1. A photonic lantern

3. Coherent detection modelling

Fig. 2a shows a standard coherent detection setup where the received optical signal is combined with a local oscillator. Fig. 2b shows a coherent detection system using a photonic lantern. Using the photonic lantern, multi-mode optical signal is collected from the free space and distributed to 19 × SMFs. The optical signal at each one of the single-mode fibers are mixed with the photo detector. After passing through a low pass filter, the signal from the 19 channels is combined and after the squaring, averaged.

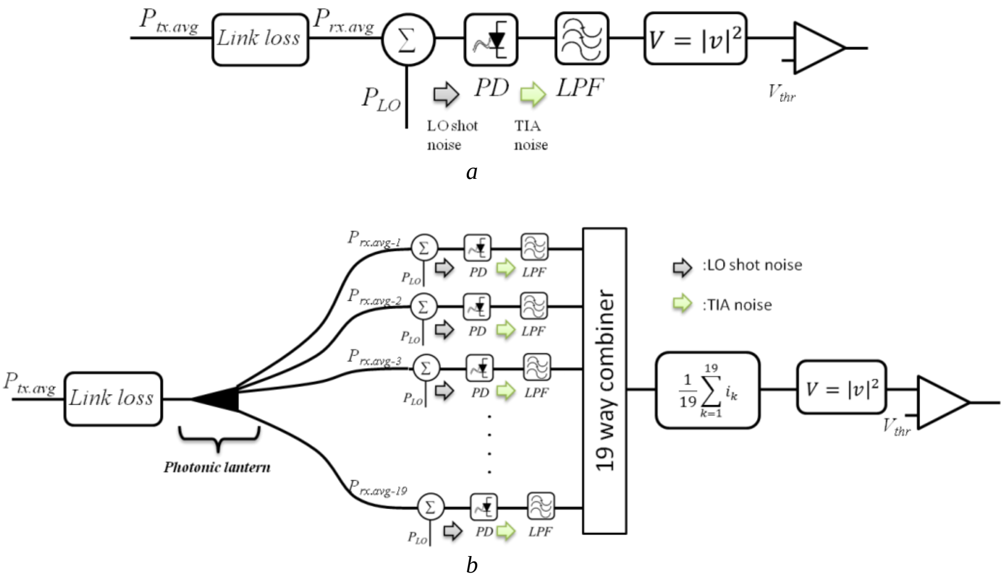


Fig. 2. Model of detection system for single-mode fiber (a), and photonic lantern (b) based coherent systems

The received optical power [9] ($P_{rx.avg}$) is calculated using the single-mode link loss parameters as described in Reference [9]. The received peak pulse power is calculated from the received optical power using,

$$P_{rx.pk} = \frac{P_{rx.avg}}{\Delta t_{pw}/\Delta t_{prt} + ER\,(1-\Delta t_{pw}/\Delta t_{prt})} \qquad (1)$$

where Δt_{pw} is optical pulse width duration, Δt_{prt} is pulse repetition time and ER is the pulse extinction ratio.

The received optical pulse is mixed with the local oscillator (having a power P_{LO}) and sent to the photo detector with a responsivity of R. The detected photocurrent is squared in order to obtain a variable which is proportional to the received optical power ($P_{rx.avg}$) [2].

The transimpedance amplifier (*TIA*) noise [10] has a transimpedance gain equal to G_e (corresponding to absolute temperature, T and photo detector load resistor R_L) and a noise figure is represented by NF_e. Electrical filter of bandwidth is represented with B_e.

The noise is assumed to be a zero-mean Gaussian process. Variances of the TIA and shot noise are given by;

$$\sigma_{TIA}^2 = \langle i_{TIA}(t)\rangle^2 = (4k_B T/R_L) NF_e B_e \qquad (2)$$

and

$$\sigma_{sh}^2 = 2qR_{pd}P_{LO}B_e \qquad (3)$$

where q is the electronic charge, k_B is the Boltzmann constant, R_L is the photo detector load resistor and T is the absolute temperature.

The TIA and shot noise is represented as Gaussian process. Therefore;

$$\sigma_{n0}^2 = \langle i_{n0}(t)\rangle^2 = \sigma_{sh}^2 + \sigma_{TIA}^2 \qquad (4)$$

In the modeling, the optical pulse width and the pulse repetition rate are taken as 10ns and 10kHz respectively. The transmitted pulses have an *ER* value of 20dB and peak power of 400mW. The link loss is calculated using the method given in Reference [9] and found as – 93dB for a distance of 100 meters and for a diffuse target reflectivity of 0.3. The TIA is assumed to have a transimpedance gain of 500Ω, and the TIA noise figure is defined approximately 3dB according to noise statistics and the temperature is assumed to be 333K. The photo detector responsivity is taken as 0.8 and the bandwidth of the photo detected signal is limited to 2GHz. The optical power of the local oscillator is assumed to be 10mW which is typical for fast photo diodes.

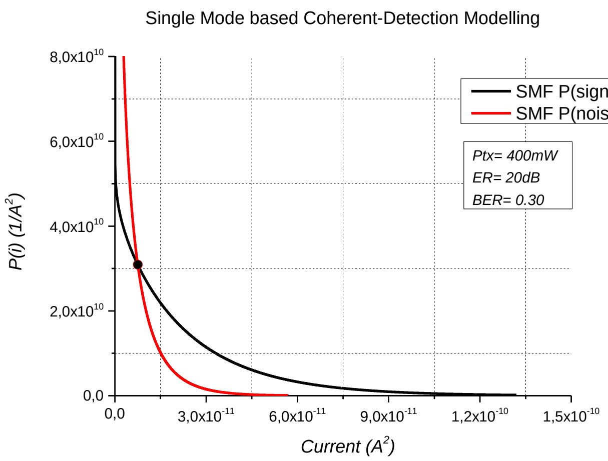
It was shown previously that the optical signal distribution of the 19 single-mode fibers of the photonic lantern are random [4]. In the simulation, we used the power distribution that is reported in Reference [4]. The SNR improvement occurs from the fact that 19 all electrical signals of 19 × SMF collected in phase coherency and so amplitude of output signal will increase, but noise will be self-suppress because it has Gaussian random distribution. This SNR improvement has also affected to BER performance positively.

The BER is calculated using the following equation,

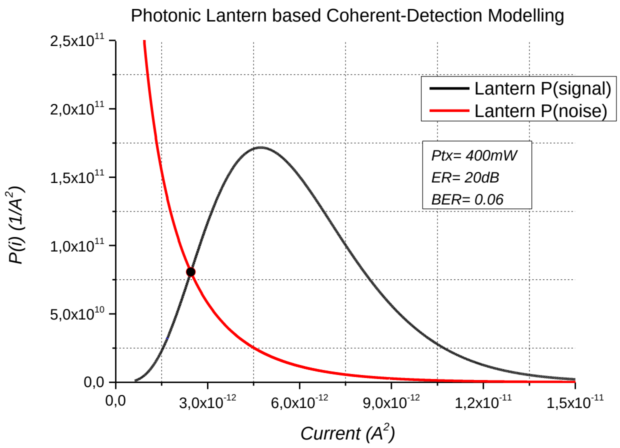
$$BER = p(signal)P(noise \mid signal) + p(noise)P(signal \mid noise) \qquad (5)$$

where *p(x)* is the probability of transmitting an *x* (signal or noise) and *P(x | y)* is the probability of detecting *x* given that *y* is sent. The point of decision is taken as the intersection point of the noise and signal plots.

Fig. 3 shows the probability density functions of single-mode fiber based coherent detection (Fig. 3a) and photonic lantern based coherent detection (Fig. 3b). The noise and the signal are separated significantly in the photonic lantern case whereas the single-mode fiber based system there is no clear separation. As a result, the BER is improved to 0.06 from 0.30 which corresponds to a detection ratio improvement from 70% to 94% using the photonic lantern based coherent receivers.



a



b

Fig. 3. Probability density functions for (a) single-mode based receiver (b) photonic lantern based receiver

The threshold current level dependency of bit error rate is also analyzed and the results are shown in Fig. 4. The optimum current threshold level is found to be $4.18\times10^{-13}A^2$ at which the BER is 10^{-4}. The optimum threshold value is very small due to the fact that the duty cycle is very low 0.0002, which means 99.98% of the time the receiver will get noise and only 0.02% of the time it will get the signal.

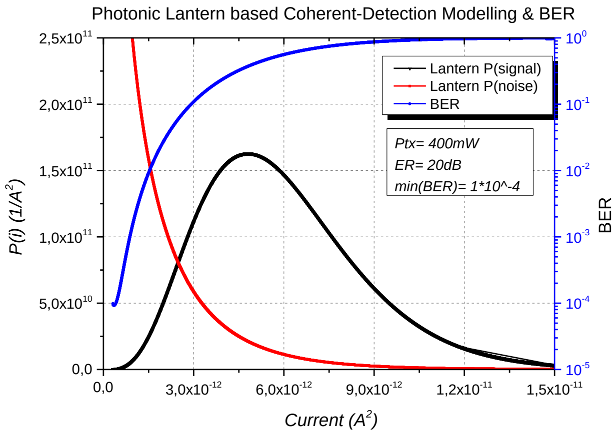


Fig. 4. Minimum BER calculation

4. Conclusion

In this work, bit-error rate improvement of photonic lantern-based coherent receivers over single-mode fiber based coherent receivers is analyzed. Our results show that using a 19-port photonic lantern, the bit-error-rate can be improved to 0.06 from 0.30 for a range of 100 meters, which corresponds to a detection rate improvement from 70% to 94%.

Acknowledgments

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