Photonic-lantern-based coherent LIDAR system

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Abstract: In this work, a photonic–lantern-based coherent LIDAR system is experimentally demonstrated and the voltage signal-to-noise ratio improvement is analyzed. A voltage signal-to-noise ratio (SNR_V) improvement of 2.8 is demonstrated experimentally for photonic-lantern-based coherent receivers relative to single-mode coherent receivers. The voltage signal-to-noise ratio improvement is obtained when other parameters are kept constant. We have also analyzed the effect of random optical power distribution among the single-mode fibers. We found that the distribution does not significantly impact the SNR_V improvement. The mean value of voltage signal-to-noise ratio improvement is found to be ~ 2.4.

OCIS codes: (280.3640) Lidar; (120.0280) Remote sensing and sensors; (060.4005) Microstructured fibers.

References and links

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1. Introduction

Free-space coherent optical systems suffer from target or channel-induced speckle, reduced collection efficiency, and multimode effects that degrade the mode matching of the local oscillator (LO) and the signal during signal detection. To overcome the mode matching penalty for free-space coherent optical systems, single-mode fibers are often used at the collection optic in place of free-space detection because the LO is also a single-mode and the mixing efficiency is nearly perfect [1–4]. However, a drawback of single-mode detection is the poor free-space-to-fiber collection efficiency due to the single-mode design of the fiber and smaller core size when compared to a larger diameter multi-mode fiber. The photonic

#228898 - $15.00 USD Received 3 Dec 2014; revised 29 Jan 2015; accepted 30 Jan 2015; published 20 Feb 2015

lantern has been introduced recently to effectively collect light in a large-core multimode fiber and convert to an ensemble of single-mode fibers [5–8]. Because of its mode transforming properties, the photonic lantern can be anticipated to benefit coherent free-space optical detection systems, such as light detection and ranging (LIDAR) or free-space optical communication (FSOC). Previously, the single-mode collection efficiency enhancement for free-space optical systems using a photonic lantern to collect scattered light at near-field distances was investigated, and a single-mode collection efficiency improvement of:8 dB was demonstrated relative to standard single-mode fiber [9]. This manuscript is a continuation of our previous work [9] and demonstrates the voltage signal-to-noise ratio ($\mathrm{SNR_V}$) improvements of a photonic-lantern-based free-space coherent detection system. The photonic lantern-based coherent LIDAR system presented in this manuscript has 2.8 times higher $\mathrm{SNR_V}$ compared to a single-mode fiber-based system. We have also analyzed the effect of random optical power distribution among the single-mode fibers (see Fig. 2 in Reference [9]). We found that the distribution does not significantly impact the $\mathrm{SNR_V}$ improvement.

2. Experimental setup

The elements of our coherent LIDAR system setup are shown in Fig. 1. A narrow line width (1 kHz) CW laser at 1550 nm and 100 mW output power is used for the source. In the upper path of Fig. 1, the optical frequency is shifted by 4 GHz using a DQPSK modulator, which is driven at single-side band suppressed-carrier mode. An acousto-optic modulator can also be used to shift the optical frequency. The following intensity modulator (LiNbO3) is driven by a pattern generator outputting 2 ns digital pulses at a 1 MHz repetition rate. Two EDFAs (erbium doped fiber amplifiers) are used to overcome the optical losses in the optical frequency shifter and the intensity modulator. The transmitted optical power is ~10 mW. The transmitter and receiver lenses are used to send and collect the modulated optical signal, respectively. In order to test the photonic lantern-based coherent detection system, the modulated optical signal is directly sent to the coherent detection system after passing through an attenuator, which emulates the free-space link loss for near-field distances. We did not use a diffuse target in this experiment in order to eliminate the optical power fluctuations due to the speckle pattern during the measurement.

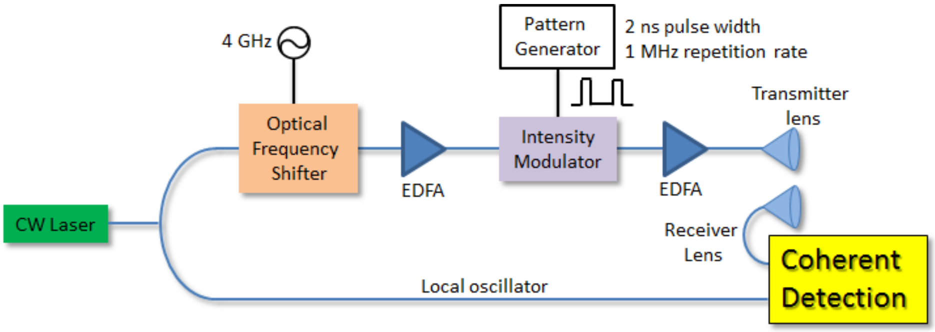

Fig. 1. The coherent light detection and ranging system (LIDAR) setup used in the experiment

The coherent detection system shown in Fig. 1 has two different detection configurations. The first configuration uses a single-mode fiber to collect the reflected modulated optical signal collected by the receiver lens. The modulated signal is mixed with a local oscillator, which is also single-mode, and sent to a balanced photo detector (Fig. 2(a)). This configuration represents a typical coherent LIDAR system. The second coherent detection configuration uses the photonic lantern for collection, as shown in Fig. 2(b). The multi-mode section of the photonic lantern is placed behind the receiver lens to collect the reflected

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modulated optical signal. A 19 port photonic lantern with a 50 µm multimode core diameter is used in the experiment, which is the same as the one used in Reference [9]. Each single-mode fiber of the photonic lantern is combined with single-mode local oscillator using an optical coupler and sent to a balanced photo detector. This process is repeated for each single-mode section independently, and the results are averaged. During the process, the multi-mode section of the photonic lantern is kept stationary to prevent optical power fluctuations due to randomized coupling into the 19 single mode fibers.

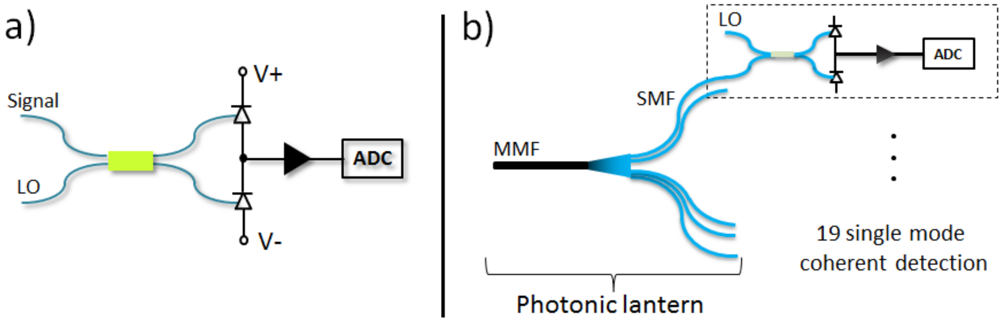

Fig. 2. (a) Single-mode fiber-based coherent detection system with balanced photo detector. (b) Proposed photonic-lantern-based coherent detection with 19 single-mode receivers.

3. Results

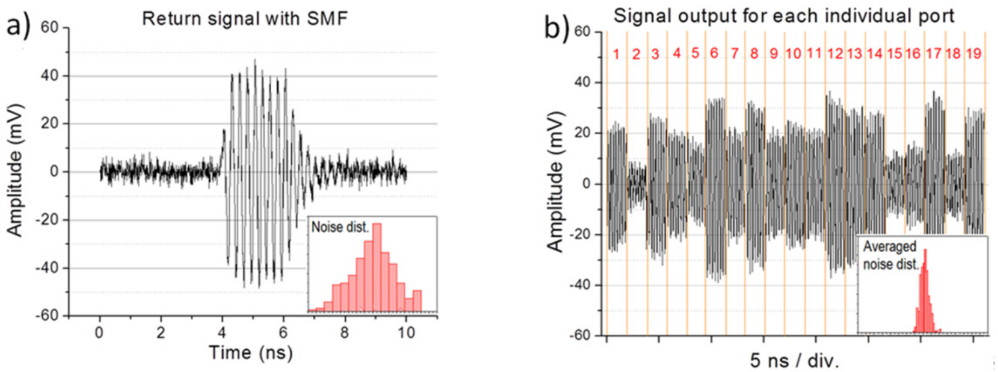

Fig. 3. (a) The detected signal with the single mode fiber based coherent detection and the noise histogram (inset). (b) The signal output for each single mode fiber of the photonic lantern is shown in the figure. The inset noise histogram is the averaged noise distribution of the 19 single mode coherent detections. The inset noise distributions in (a) and (b) have the same horizontal scale.

The return signal from the single-mode fiber-based coherent detection is shown in Fig. 3(a). The 2 ns pulse and the 4 GHz carrier frequency can be seen in the figure along with the noise distribution histogram as an inset. The signal amplitude is 41.8 mV, and the standard deviation of the noise is 2.64 mV, which results in a SNR_V of 15.8. In the photonic lantern-based coherent detection configuration, 8 dB higher modulated optical signal is collected by the photonic lantern as the free-space-to-fiber collection efficiency is 8 dB higher [3]. The plot in Fig. 3(b) is divided into 19 sections, each having a time span of 2 ns. The number at each section indicates the single-mode fiber from which the signal is obtained. The difference in detected signal amplitudes is a result of the unequal output power distribution across the 19 single mode fibers, which is due to the varying optical power distribution inside the multi-mode fiber and single-mode core position. Treating each signal independently, the averaged

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signal and noise amplitude of the 19 single mode coherent detections are 23.7 mV and 0.53mV respectively, which results in a SNR_V of 44.7. The noise reduction after averaging the outputs of 19 single mode fibers is apparent from the noise histogram inset in Fig. 3(b). In the averaging process the phases of the photo detected signals are aligned manually. In the automated case, the phases can be matched using an adaptive phase alignment system.

4. Discussion

In [9], Ozdur et al showed that the photonic lantern distributes the received optical power to the 19 single mode fibers randomly. The power distribution can fluctuate due to the input mode profile change or any temperature and pressure variations on the multi-mode fiber section of the photonic lantern. We previously demonstrated the ability to collect 8 dB (6.3 times) higher total received power with a 19-fiber photonic lantern compared to a single-mode fiber, which can be expressed as $P_{Total} = 6.3P_{SMF} = \sum_{i=1}^{19} P$, where P_{SMF} is the received optical power with a single-mode fiber and P_i is the amount of optical power coupled to the *i*th fiber of the photonic lantern. One can also write the P_i as $P_i = a_i P_{SMF}$ where a_i is the power coupling coefficient of the *i*th fiber and $\sum_{i=1}^{19} a_i = 6.3$. As the input mode profile inside the photonic lantern changes, the power coupling coefficients of the single mode fibers also changes.

In coherent detection systems, the amplitude of the electrical signal (A_{sig}) is proportional to the *square root* of the received optical power. If A_i is the signal amplitude of the *i*th fiber then $A_i \propto \sqrt{P_i}$ or $A_i \propto \sqrt{a_i}$. The average signal amplitude of the 19 single-mode fibers is proportional to $\sum_{i=1}^{19} \sqrt{a_i}/19$. In this case, the amplitude of the averaged signal (A_{ave}) depends on the random distribution of the optical power among the 19 single mode fibers. For example if all the optical power is divided equally among the single mode fibers ($a_i = 6.3/19$) the SNR_V improvement reaches to a maximum value of 2.5 (In the experiment, we obtained an improvement factor of 2.8, and we believe the difference is due to experimental measurement errors). The worst case condition occurs when the received optical power is coupled into only one of the single mode fibers (ie. $a_1 = 6.3, a_{i>1} = 0$). If all the received power were to be coupled in only one of the fibers, which is very unlikely, the SNR_V would *drop* by a factor of ~2. Hence it is critical to understand the statistical behavior of the photonic-lantern-based coherent receiver system. In order evaluate these statistics, we have numerically analyzed the variation in SNR_V as the power coupling coefficient factor to each single mode fibers is randomly assigned while keeping the overall optical power constant.

The probability density function of the SNR_V improvement from this analysis is shown in Fig. 4. The maximum value of the SNR_V improvement factor is 2.5, and the probability goes to nearly zero values for SNR_V values less than 2.1.The probability of having an SNR_V improvement factor higher than 2.1 is 99.996%.

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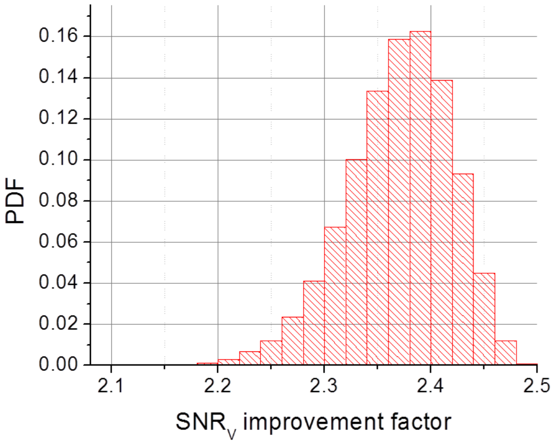

Fig. 4. The histogram of SNRV improvement factor.

4. Conclusion

In this work, the voltage signal-to-noise ratio improvement of a photonic lantern-based coherent receiver over a single-mode fiber-based coherent receiver is demonstrated. An improvement is achieved without increasing the lens size or transmitted optical power. We have also analyzed the effect of random optical power distribution among the single-mode fibers of the photonic lantern. We found that the distribution does not significantly impact the SNR_V improvement. The probability of having an SNR_V improvement factor of higher than 2.1 is 99.996%.

This paper describes one approach to enhance the SNR_V using photonic lantern and other methods remain under study. Photonic-lantern-based coherent detection systems can increase the system performance of LIDAR and FSOC systems for demanding applications, and the performance improvement can also be traded with lower size, weight, and power (SWaP) systems for SWaP-constrained platforms.

Acknowledgment

We are pleased to acknowledge Dr. D. Noordegraaf of NKT Photonics for the loan of the photonic lantern device used in the experiments. The experimental work of this manuscript is supported by the internal funding of Applied Communication Sciences and the numerical calculations are supported by The Scientific and Technological Research Council Of Turkey (TUBITAK) Project no 114E402.

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