Improving the Sensitivity of LiDARs Using Few-Mode Pre-amplified Receivers

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Abstract: An order of magnitude improvement in the signal-to-noise ratio (SNR) of a 1550 nm LiDAR receiver was achieved using a few-mode optical preamplifier as compared to a multi-mode avalanche photodiode (APD).

OCIS codes: (010.3640) Lidar; (290.5880) Scattering, rough surfaces; (060.2320) Fiber optics amplifiers and oscillators

1. Introduction

Light Detection and Ranging (LiDAR) has received considerable attention in recent years, due in part to its applications in autonomous vehicles [1,2]. The most popular wavelengths for LiDAR in autonomous vehicles are 905 and 1550 nm. LiDARs operating at 905 nm have the advantage of high detection sensitivity and low-cost afforded by silicon avalanche photodiodes (APD) and single-photon avalanche photodiodes (SPADs). However, they are not "eye safe", limiting the maximum allowable transmitter power, and ultimately their range [3]. On the other hand, LiDARs operating at 1550 nm are more eye-safe and can make use of low-cost components in the telecom window, however they cannot use silicon APDs or SPADs [3]. Compound semiconductor APDs or SPADs operating at 1550 nm have much lower sensitivity as compared to their silicon counterparts, driving up the power requirement and the cost of the transmitter laser [4]. Consequently, to date, LiDARs operating at these two wavelength ranges cannot simultaneously provide high performance and low cost, as dictated by the automotive industry. It is well known in telecom that pre-amplified receivers, using Erbium-doped fiber amplifiers (EDFA), have orders-of-magnitude higher sensitivity than APDs [5]. One may wonder then why LiDARs at 1550 nm make use of multi-mode (MM) APDs, rather than pre-amplified receivers. The answer is that in LiDAR, when light reflects off a rough surface, speckle patterns are produced at the receiver [6]. Speckle patterns contain multiple spatial modes. For this reason, single-mode (SM) detectors used in telecom are unsuitable for LiDAR. Recent advances in spatial-division multiplexing have led to the development of few-mode (FM) EDFAs [7]. In this paper, we demonstrate that the signal-to-noise ratio (SNR) (required transmitter laser power) of a LiDAR system can be improved (reduced) by up to an order of magnitude over MM APDs using a FM pre-amplified receiver. As a result, FM pre-amplified receivers may become one of the final pieces of the puzzle to bring large-scale deployment of LiDARs into autonomous vehicles.

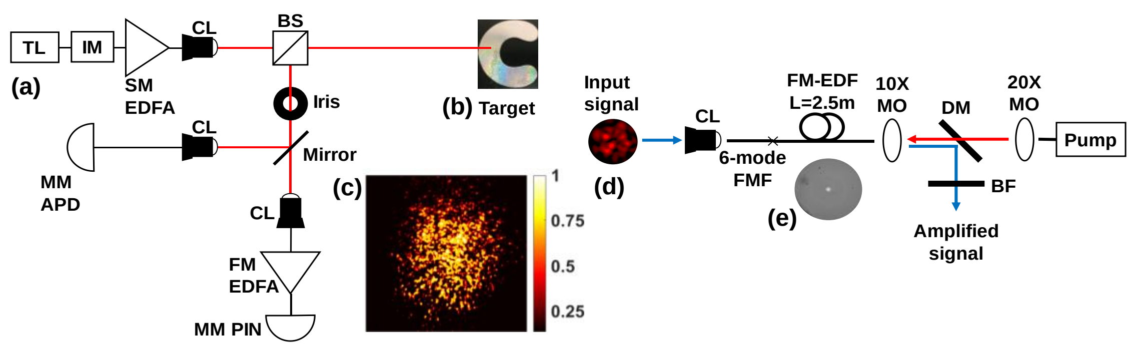

Fig. 1. (a) Experimental set-up, TL: tunable laser, IM: intensity modulator, SM EDFA: single-mode erbium-doped fiber amplifier (EDFA), CL: collimating lens, BS: beam splitter, FM: few-mode, MM APD: multimode (MM) avalanche photodiode, MM PIN: MM PIN photodiode. (b) Target. (c) Speckle pattern reflected from target. (d) FM EDFA schematic; FMF: FM fiber, MO: microscope objective, BF: bandpass filter, DM: dichroic mirror. (e) FM EDF cross-section.

2. Experimental Set-Up

A schematic of the experimental set-up is shown in Fig. 1(a). A 500 ps pulse train was produced by modulating a continuous-wave tunable laser ($\lambda = 1.55\mu m$) with an intensity modulator. The target in this system is shown in Fig. 1(b). The beam reflected from the target contained many modes and formed a speckle pattern, as shown in Fig. 1(c).

Light reflected from the target was split into two paths and was incident on either a MM APD or FM pre-amplified receiver. The MM receiver consisted of a MM APD (Discovery Semiconductors R402APD) and the FM receiver was composed of a MM PIN (Discovery Semiconductors R402) and a backward core-pumped 10-mode EDFA, as shown in Fig. 1(d). The doping concentration ($\mathbf{4*10^{25}/cm^3}$) and the length (~2.5 m) of the Er-doped fiber (EDF) were used to produce a lower noise figure pre-amplification at low input power levels. The core diameter of the EDF is 13 µm and supports 10 spatial modes.

3. System performance

We simulated the SNRs of a MM APD and FM pre-amplified receiver and the results are shown in Fig. 2(a) for an average input power of -40 dBm and a pulse width of 500 ps, corresponding to a depth resolution of 7.5 cm. For this paper, SNR was measured over the pulse width. The sensitivity of the MM APD can be optimized by adjusting the gain and, with k_A = 0.7 for InGaAs, the highest SNR was about 8 dB. For the FM pre-amplified receiver, the dominant noise source is signal-ASE and ASE-ASE beat noise and, as expected, they increase with the number of modes. The number of spatial modes that the FM EDFA should accommodate is given by $Q = 1.314 * M(M+1)$, where $M = (\pi/4)(R \cdot D)/\lambda L$ is the normalized space-bandwidth product of the LiDAR system and R, D, L are the lateral spatial resolution, receiving aperture diameter, and range of the LiDAR, respectively [8]. For $R = 1cm, D = 6cm$ and $L = 200m$, typical for automotive LiDARs, $Q = 5$ per polarization. Due to the orthogonality of spatial modes, the SNR of the preamplified receiver decreases very gently as a function of the number of modes, reaching approximately 19.1 dB with 200 modes from a high of 19.9 dB with one mode. This represents approximately an 11 dB improvement over MM APD.

To characterize the performance of the receivers in a power-limited LiDAR system, SNR was measured for a MM APD and FM pre-amplifier with a PIN photodetector were taken at different input powers. To adjust the power levels, the reflected light was passed through open (D=2.5 cm) and relatively closed (D=6 mm) iris, which also would change the number of modes in the return signal. At low input powers, typical of LIDAR systems where target reflectivity is low, the FM pre-amplified receiver was found to have a higher SNR, as shown in Fig. 3(c). At high input powers, the performance of the FM pre-amplified receiver and MM APD were similar. This is supported by both theory and experimental results.

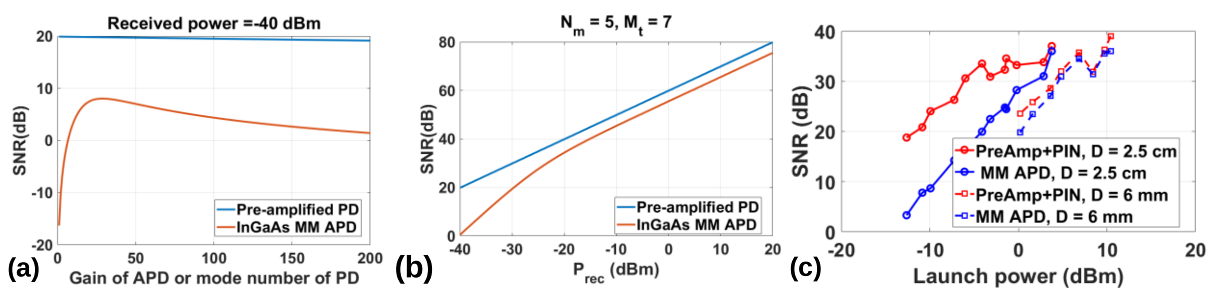

Figure 2. (a) SNR of receivers with pulse length equal 500 ps and received power equal to -40 dBm for MM APD and pre-amplified PIN, (b) SNR of MM APD and pre-amplified PIN for different received powers with the number of modes in the preamplified PD fixed at 5 and the APD gain fixed at 7, (c) Experimental measurement of SNR of MM APD and pre-amplified PIN for different received powers.

5. Conclusion

We take advantage of recent advances in space-division multiplexing to construct a LiDAR receiver with improved sensitivity. By replacing MM APDs with FM preamplified receivers, we increase the receiver SNR up to an order of magnitude. Importantly, an increase in the receiver sensitivity allows for a correspondingly lower transmitted power. Lower transmitted powers would alleviate the high cost of the transmitter laser, currently the major bottleneck in LiDAR systems.

6. Acknowledgements

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7. References

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