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Reduction of phase-induced intensity noise in a fiber-based coherent Doppler lidar using polarization control

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Abstract: Optimization of signal-to-noise ratio is an important aspect in the design of optical heterodyne detection systems such as a coherent Doppler lidar (CDL). In a CDL, optimal performance is achieved when the noise in the detector signal is dominated by local oscillator shot-noise. Most modern CDL systems are built using rugged and cost-efficient fiber optic components. Unfortunately, leakage signals such as residual reflections inherent within fiber components (e.g. circulator) can introduce phase-induced intensity noise (PIIN) to the Doppler spectrum in a CDL. Such excess noise may be a few orders of magnitude above the shot-noise level within the relevant CDL frequency bandwidth – corrupting the measurement of typically weak backscattered signals. In this study, observation of PIIN in a fiber-based CDL with a master-oscillator power-amplifier tapered semiconductor laser source is reported. Furthermore, we experimentally demonstrate what we believe is a newly proposed method using a simple polarization scheme to reduce PIIN by more than an order of magnitude.

OCIS codes: (010.3640) Lidar; (140.5960) Semiconductor lasers

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1. Introduction

Relying on the coherent superposition of light waves from atmospheric backscatter and a reference beam or local oscillator (LO), coherent Doppler lidars (CDLs) offer an accurate optical means for measuring wind velocity and wind statistics. The development of CDLs began shortly after the invention of the laser. Most wind lidar systems then were based on solid-state and CO_2 lasers and relied on free-space optics [1,2]. At present, commercially sold CDLs [3–5] conventionally employ fiber-lasers (FLs) emitting at eye-safe wavelengths (1540-1575 nm) and benefit from the use of reliable fiber optic components widely used in the telecommunications industry. The emergence of modern CDLs has revived the interest in the use of these systems for wind energy applications. This is expected to increase further as more compact and inexpensive wind lidar systems become available.

Recently, our group has demonstrated the feasibility of using a master-oscillator (tapered) power-amplifier semiconductor laser (MOPA-SL) as a light source for a compact coherent Doppler lidar system [6,7] for remote wind speed measurements. A single-unit MOPA-SL is found to be a good alternative to the commonly employed tandem of a fiber-laser and an erbium-doped fiber amplifier (EDFA) in a CDL system. The advantages gained from an "all-semiconductor solution" by using a MOPA-SL as the light source include compactness, reduced cost, and better wall-plug efficiency. Furthermore, MOPA-SLs do not suffer from the inherently large intensity noise in the low-frequency regime of a few MHz normally present in FL sources. This is due to the fact that the relaxation oscillation frequency of MOPA-SLs is typically a few GHz [8] as opposed to around ~1 MHz in FLs [9]. The peak of the relaxation oscillation in FL can be as high as ~40 dB above shot-noise, which results in significantly elevated noise floor in frequencies extending to a few MHz. As a consequence, FL-based CDL has a reduced sensitivity when measuring low wind speeds, especially during clear atmospheric conditions. To circumvent the unwanted effects of low-frequency (relaxation oscillation) noise, FL-based CDL systems would have to employ additional fiber optic components to separate the path of the LO from the signal beam, and introduce a frequency offset (e.g. using an acousto-optic modulator) between the two signals [10]. Aside from requiring additional components, this solution also entails the use of a faster detector and a signal processor with higher sampling rate to avoid aliasing.

In the intensity noise spectra shown in Fig. 1, one finds that a fiber-coupled MOPA-SL (Model 7115-0000, QPC Lasers) has the attractive characteristic of exhibiting near-shot-noise limited performance over a distributed feedback (DFB) fiber-laser within a typical bandwidth (e.g. 0-25 MHz) relevant for CDL operation. Note that at lower frequencies <10 MHz (which in a CDL corresponds to line-of-sight (LOS) wind speeds <7.8 m/s for wavelength λ = 1550 nm), the noise floor difference can reach a significant amount of 35 dB close to the FL relaxation oscillation frequency of ~0.4 MHz. This can directly translate to several orders of magnitude improvement in signal-to-noise ratio (SNR) when measuring low wind speeds using a MOPA-SL based CDL against its FL-based counterpart. Low LOS speeds also occur when the angle of the CDL transmit beam with respect to the wind direction approaches 90°. The measurement of wind direction – normally performed by scanning the transmit beam such that the CDL takes several LOS measurements at different angles – can gain better accuracy or sensitivity as the CDL's ability to measure low LOS speed is improved using a MOPA-SL.

The intensity noise measurements in Fig. 1 are taken for ~1 mW output power from each of the two lasers. This is the typical LO power used in a CDL to achieve optimal SNR [11]. The data in Fig. 1 suggest that the need for a frequency offset between the LO and the signal

#122841 - $15.00 USD Received 15 Jan 2010; revised 25 Feb 2010; accepted 25 Feb 2010; published 26 Feb 2010

beam may be avoided in a CDL with MOPA-SL as source. Due to the low and relatively flat noise floor, high SNR even when sensing low wind speeds are possible. Thus, previously observed inaccuracies (when compared with conventional anemometers) of FL-EDFA-tandem based CDLs without a frequency offset for measuring low wind speeds [12] can be potentially circumvented by replacing the light source with a MOPA-SL.

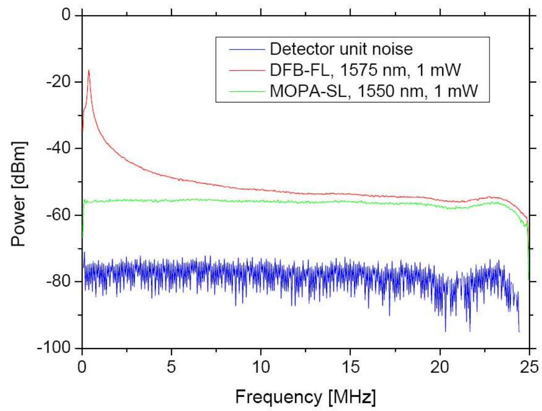

Fig. 1. Comparison of intensity noise spectra. The lowest (blue curve) is the noise spectrum of the detection unit; Model HCA-S preamplified InGaAs photoreceiver, Femto GmbH (i.e. no laser light incident on the photodetector). The middle (green curve) is obtained when ~1 mW of optical power from the MOPA-SL is incident onto the detector. The topmost (red curve) is for the case when ~1 mW beam from a fiber-laser (common lidar source) is detected. The cutoff frequencies for the high-pass and low-pass filters of the detection unit are ~100 kHz and ~25 MHz, respectively.

2. Characteristics of a fiber-coupled MOPA-SL

We also assessed the performance of the fiber-coupled MOPA-SL by measuring the cw power from the output end of its ~1-m long single mode fiber (SMF) pigtail as a function of drive currents. The monolithically integrated master oscillator (MO) and tapered amplifier (TA) sections of the laser are independently driven by current controllers (PRO8000-4, Thorlabs, Inc., which also includes temperature controllers). At 20 °C, the laser can be driven by a maximum of 700 mA MO current, I_{MO}, and a maximum of 4.0 A amplifier current, I_{TA}.

Figure 2 shows the characteristic L-I (i.e. optical power versus I_{TA}) curves of the SMF-pigtailed MOPA-SL for three different I_{MO} values. The plot shows that a high output power reaching ~650 mW can typically be achieved for the TEM_{00} output of the laser.

#122841 - $15.00 USD Received 15 Jan 2010; revised 25 Feb 2010; accepted 25 Feb 2010; published 26 Feb 2010

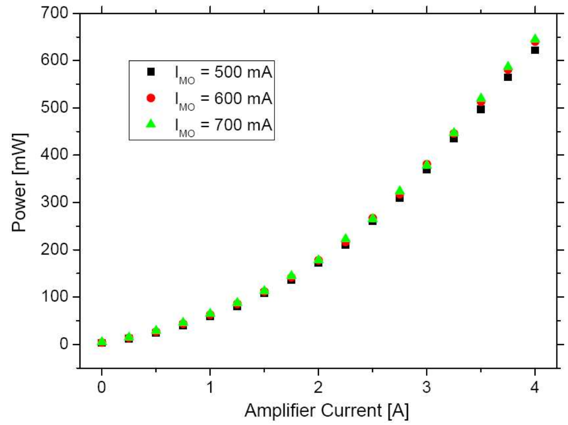

Fig. 2. L-I curves of a fiber-coupled MOPA-SL, which compares the output power of the beam emitted from the output end of the fiber pigtail as a function of amplifier current I_{TA} for master oscillator currents I_{MO} = 500 mA (black squares), I_{MO} = 600 mA (red circles), and I_{MO} = 700 mA (green triangles). The laser set temperature was kept at 20 °C.

A non-linear dependence of power with I_{TA} is also evident, which indicates that the fixed optics (inside the laser package) that couples the originally astigmatic beam from the MOPA laser emitter to the SMF has been optimally aligned to achieve high coupling efficiency at maximum operating drive currents. The degree of astigmatism of laser emitters with tapered geometry, such as the MOPA-SL used here, is known to depend on the laser drive currents [13]. Thus a decrease in I_{TA} effectively results in a nonlinear decrease in output power at the fiber end due to reduction in both beam power from the emitter and fiber coupling efficiency.

Although it can supply ample beam power for a CDL, high-power SLs with tapered or flared geometry possess spectral characteristics characterized by regimes of single-frequency operation, dynamic instabilities and multimode operation [8,14]. The MOPA-SL we used in this work is no exception as these various types of spectral behavior were experimentally observed here. Nevertheless, we found several pockets of stability wherein single longitudinal mode is maintained even at high output powers for a continuous laser operation of several days [7]. For CDL applications, it is important that a stable single-frequency operation is achieved to obtain the lowest possible relative intensity noise (RIN) such as the shot-noise-limited performance of the MOPA-SL shown in Fig. 1 (green curve) over the entire CDL measurement bandwidth. In our experiments, we observed that laser drive current settings corresponding to multimode operation and dynamic instabilities result in increased and unstable RIN levels that degrade the SNR and overall performance of the CDL.

3. Fiber-based CDL with a MOPA-SL as a light source

Using the fiber-coupled MOPA-SL described above, we constructed a simple fiber-based CDL setup from a relatively few off-the-shelf components as shown in Fig. 3. The laser is set to provide a cw output power of 520 mW at λ = 1550 nm (drive currents I_{MO} = 0.7 A and I_{TA} = 3.54 A; TEC set temperature T = 20 °C). At this particular setting, the laser operates in a stable single-frequency operation. It is easily connected to the input port-1 of a standard three-port fiber optic circulator (6015-3-APC; Thorlabs, Inc.) through FC/APC connectors. Most of the laser power takes the route from port-1 to port-2 while a tiny fraction of light from port-1 leaks into port-3 (>50 dB directivity according to specification or a few microwatts of leakage). Approximately 0.34 mW of LO power reaches the detector due to the light reflected from the fiber-to-air interface of the antireflection (AR) -coated (<0.25%) FC/PC connector of port-2 and travelled in *reverse* (i.e. from port-2 to port-3). This LO reaches the active-area of the photodetector (HCA-S InGaAs PIN photodiode with pre-amplifier, Femto GmbH) connected to circulator port-3 and should ideally possess the noise spectrum obtained in Fig. 1 (green curve), apart from a scaling factor (Note: measurements in

Fig. 1 are for ~1.0 mW of power delivered in the *forward* direction to the detector when the MOPA-SL and the detector are connected through a series of fiber attenuators and a fiber optic isolator). However, the detector at port-3 that should only receive the reflection-tapped LO and the backreflected signal from the probed volume (i.e. a rotating disk is used in our experiment), also receives some unwanted signals such as the inherent leakage from circulator port-1 to port-3 (Fig. 3).

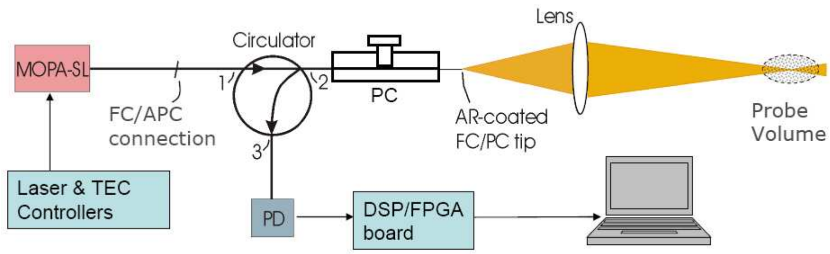

Fig. 3. Experimental setup. The fiber-based lidar consists of the fiber-coupled MOPA-SL, a circulator, an inline polarization controller (PC), and a preamplified InGaAs PIN photodetector (PD). The FC/PC tip of the circulator's port-2 is AR-coated (<0.25%). The PD current is converted to a proportional voltage signal, which is sent to a digital signal processor (DSP) – Field Programmable Gate Array (FPGA) unit that calculates the signal power spectrum. Each fiber segment of the circulator is about 1 m in length. Normally focused to a probe volume in air during CDL operation, the beam collected by a lens (diameter = 75 mm; focal length = 200 mm) is focused ~8 m away to a diffusely reflecting disk rotating at a constant angular speed.

The effect of the interferometric beating of such stray signals with the dominant LO introduces excess intensity noise resulting in an overall noise floor much greater than the intrinsic LO shot-noise level. One way of physically interpreting this increase in noise level is to consider that an "effective LO" has been formed by the phasor sum of the "raw LO" and the leakage signal(s) [15]. The instantaneous magnitude of the "effective LO" fluctuates about a mean value due to the inherent fluctuations in phase (i.e. laser phase noise). The corresponding "effective intensity fluctuation" increases the total noise level above the shot-noise of the solitary raw LO. In the literature, this type of excess noise has been referred to as phase-induced intensity noise (PIIN) (also known as beat or interference noise).

4. Polarization-based suppression of phase-induced intensity noise

One way of achieving a significant reduction in the cost of building a CDL system is the use of inexpensive and compact semiconductor lasers. However, there are some technical challenges, which make such approach not as trivial as a simple replacement of the typically used FL-EDFA combination with an SL. A previous attempt reports a fiber-based CDL that employed a multi-sectioned DFB semiconductor laser whose output beam was still externally amplified by an EDFA [15]. In the previous work, a DFB-SL was used with a measured linewidth of ~400 kHz. A CDL was constructed using a similar circulator-based design shown in Fig. 3 except that the source was a more bulky unit combining a DFB-SL and an EDFA. The authors of Ref. 15 observed that a considerable amount of excess noise was present in the SL-based CDL. Such excess noise (or PIIN) originates from the phase noise of the laser that is converted to intensity noise through the beating or interference of stray light with the relevant signals (i.e. LO and probe volume backreflected light) that arrive at the detector plane.

Power spectral analysis of the signal received by the detector at port-3 in our system revealed that a considerable level of PIIN is also present in a MOPA-SL based CDL. A comparison of the Doppler spectra (whose baselines represent the overall noise levels) for two contrasting situations is shown in Fig. 4. A 15-second video clip (Media 1) associated with Fig. 4 is also provided to compare the temporally varying nature of the noise levels for two different cases of polarization control (PC) settings. Changes in noise levels are due to temperature dependence of relative optical path delays of the signals in the fiber.

#122841 - $15.00 USD Received 15 Jan 2010; revised 25 Feb 2010; accepted 25 Feb 2010; published 26 Feb 2010

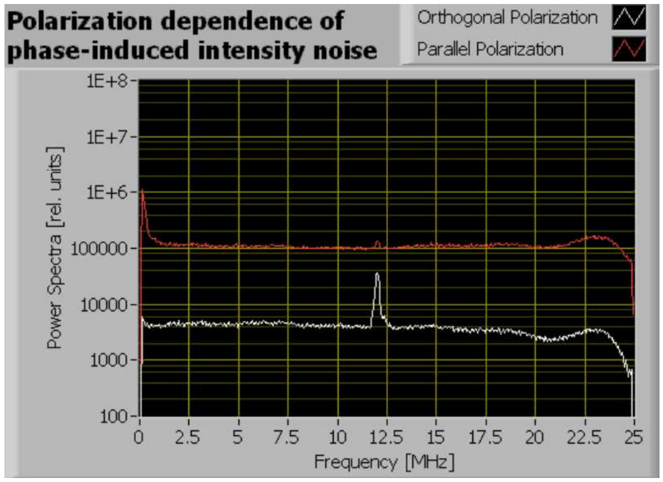

Fig. 4. Comparison of the levels of phase-to-intensity excess noise (Media 1) for two different LO polarization states. The inline polarization controller at port-2 (see Fig. 3) is adjusted so that the LO polarization state is nearly parallel (red curve) or nearly orthogonal (white curve) to that of the principal leakage signal from port-1 to port-3. In the latter case, optimal suppression of PIIN is achieved – enhancing the SNR of the Doppler signal peak at ~12 MHz, which corresponds to ~9.3 m/s LOS-projected tangential speed of the point on the disk where the transmit beam is focused. The received power due to backreflection is in the order of ~0.1 nW.

When the PC is set to bring the polarization states of the LO and the principal parasitic signal (i.e. circulator leakage of few μW) closely parallel, the noise floor (baseline of red curve of Fig. 4) is found to reach as high as ~20 dB above shot-noise. Furthermore, changes in both the baseline noise level (between 5 and 20 dB) and the noise spectral profile (e.g. intermittent noise increase in the low-frequency region) occur in fractions of a second. These observations are reminiscent of those reported in previous studies [15,16]. The linewidth of the high-power MOPA-SL used in the current study was earlier measured to be ~100 kHz [6], which are comparable to that of the laser used in Refs. 15 and 16.

The LO generated from the backreflection at the tip of port-2 and the main signal (reflection from the target) propagate along the same fiber segment of port-2. In the round-trip of the transmit beam between the transmit-receive lens and target used in the experiment, negligible depolarization is observed. It is well known that the degree of depolarization by hard targets depends on the surface type/material and for a painted sandblasted metal surface such as the rotating disk we used the depolarization is known to be negligible [17]. Under this experimental condition, the LO and the main signal have similar polarization states at the detector plane regardless of the PC setting. As the PC is adjusted so that the polarization states of the LO and the leakage signal are almost on opposite sides of the Poincaré sphere, the PIIN correspondingly decreases and reaches a maximum degree of suppression as shown in Fig. 4 (white curve), at which point the much lower average noise level is maintained just slightly above shot-noise. To our knowledge, the demonstrated polarization-based scheme to achieve significant PIIN reduction has not been reported in the literature. Although we still observe sporadic increases in the noise level (up to ~15 dB) in the low-frequency regime (<4 MHz) at the best PC setting, the major reduction of the excess broadband noise is certainly expected to improve the SNR and operational performance of our MOPA-SL based lidar system. Similar to the observations noted in Ref. 15, some possible reasons for the low-frequency noise are other sources of stray light. As a scope of future study, a detailed understanding of the nature of the low-frequency noise needs to be addressed so that suppression schemes (e.g. frequency modulation of the laser [15]) for this noise component could be investigated.

#122841 - $15.00 USD Received 15 Jan 2010; revised 25 Feb 2010; accepted 25 Feb 2010; published 26 Feb 2010

The dependence of the excess noise to polarization state differences between LO and residual signals, although straightforward, has not been thoroughly discussed in the literature. Previously proposed models generally treated the level of PIIN to be dependent only on scalar quantities [15,16]. It was shown that for delay times τ_d between LO and a stray signal much shorter than the laser coherence time τ_c (in our CDL, $\tau_d \approx 11$ ns and $\tau_c \approx 1.6$ μs), the PIIN contribution to the spectra in the typical CDL frequency region may be approximated as a constant noise offset S_{PIIN} to the shot-noise level [15,16], such as

$$S_{PIIN} \propto P_{LO} P_R \left(\frac{\tau_d^{\ 2}}{\tau_c} \right), \tag{1}$$

where P_{LO} and $P_R << P_{LO}$ are the powers of the LO and the residual signal, respectively. One assumption that was made in arriving at Eq. (1) is that the polarization states of the LO and the parasitic signal at the detection plane are identical, i.e. $\hat{e}_{LO} = \hat{e}_R$. If one takes into account the more general case where $\hat{e}_{LO} \neq \hat{e}_R$, Eq. (1) can be rewritten as

$$S_{PIIN} \propto P_{LO} P_R (\hat{e}_{LO}^{\ *} \cdot \hat{e}_R)^2 \left(\frac{\tau_d^{\ 2}}{\tau_c} \right), \tag{2}$$

where the additional factor $(\hat{e}_{LO}^{\ *} \cdot \hat{e}_R)^2$, which involves the scalar product of the two generally elliptic polarization states, is some value between 0 to 1. Equation (2) suggests that if we can make the polarization states of the LO and the stray light orthogonal, the excess noise can be fully suppressed. This is the basic principle behind the noise suppression scheme experimentally demonstrated for the first time in the results of Fig. 4. Although the PIIN suppression was not complete (i.e. residual noise is still present especially at low frequencies), a reduction of the excess noise level by more than an order of magnitude is said to be considerable and valuable particularly in situations where the main Doppler signal is very weak (e.g. backscattered light from aerosols of low concentration or received power in the order of 10^{-11} or 10^{-12} watts).

We believe that our proposed polarization technique can work in conjunction with the other approaches [15,16] that will reduce PIIN as seen from Eq. (1) and Eq. (2). If the linewidth of the laser is fixed, PIIN can be reduced by (a) shortening of port-2 fiber segment to decrease τ_d and (b) decreasing P_R by using circulators with extremely weak port-1 to port-3 leakage or crosstalk. The addition of polarization as a third control parameter for the reduction of PIIN can potentially relax the requirements for the other parameters (e.g. there may be physical or design constraints as to how much the fiber segments can be shortened). Furthermore, the future use of an electrically driven polarization controller with feedback mechanism will also be beneficial as ambient temperature fluctuations over time may cause variations in the (SMF) fiber's birefringence, which affects the polarization states of the LO and residual signals. We are also currently investigating the implementation of the proposed technique using polarization-maintaining (PM) fiber based components that can potentially improve the CDL's thermal stability.

4. Summary

We have observed the presence of the so-called phase-induced intensity noise for a fiber-based coherent Doppler lidar that employs a MOPA-SL. Previous studies [15,16] have shown that PIIN can be attributed to the broadband spectral component of the beating or interference between any two signals that are echoes of a laser source having a significant phase noise (e.g. semiconductor laser). In the CDL system we presented in this study, the PIIN contribution from the interference between the LO (~10^{-3} W) and the circulator leakage

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(~10^{-6} W) dominated other sources of beat noise such as that caused by the beating of the LO with the weak target backreflected signal (~10^{-10} W). It was found that the experimentally observed PIIN can lift our CDL's measurement noise floor up to 20 dB above the optical shot-noise level within the relevant instrument bandwidth – easily drowning a typical Doppler lidar signal. We also demonstrated a novel, straightforward, yet effective approach to considerably reduce the observed excess noise. The method employs an inexpensive inline polarization controller that enables adjustment in the polarization state (ellipticity and orientation) of the local oscillator of our CDL. We experimentally showed the apparent dependence of the level of PIIN on the relative polarization states of the LO and the residual signal. The excess noise is greatly reduced when the two polarization states are made as orthogonal as possible. The proposed polarization scheme for improving the achieved SNR in a heterodyne detection system is believed to further promote the use of semiconductor lasers, such as the MOPA-SL, in the development of fiber-based CDLs for laser-based anemometry applications.

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