Lidar detection using a dual-frequency source

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A new technique of dual-frequency Doppler-lidar measurement is investigated. This technique is based on the use of a coherently locked, tunable, dual-frequency laser source and is shown to accurately measure velocities as small as 26 μm/s. It is generated by exploiting the nonlinear dynamics of a semiconductor laser through a proper combination of optical injection and operating conditions. © 2006 Optical Society of America

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Lidar detection has been widely used since the 1970s. Applications in range finding, imaging, and velocity measurement are widely studied. Early Doppler-lidar systems used single-frequency continuous-wave CO_2, He–Ne, or semiconductor lasers. These systems derive the velocity of a moving target from the frequency shift of the backscattered electromagnetic radiation.[1] Continuous-wave, single-optical-frequency systems are shown to measure velocities down to 5 mm/s over ranges of up to 200 m.[1,2] However, they are highly sensitive to atmospheric turbulence.

An alternative approach is the dual-frequency Doppler-lidar (DFDL) method.[3] This method utilizes a microwave beat frequency that results from two different optical frequencies. This has been done in a couple of ways, by externally modulating the laser[4] or by overlapping two laser beams with a known frequency difference.[3] However, these techniques require careful alignment, operate within a limited microwave frequency range (up to 3 GHz), and are bulky, difficult to maintain, and expensive. As a result, research has focused in recent years on creating tunable two-frequency lasers.[4]

In this Letter we present a DFDL system that, for the first time to our knowledge, utilizes a tunable, coherently locked, dual-frequency laser source to measure velocities as low as 26 μm/s. The dual-frequency source is generated by exploiting the nonlinear dynamics of semiconductor lasers.[5,6] There is much research in the area of nonlinear dynamics of optically injected semiconductor lasers.[7–9] The source used here has an optical injection configuration where a master laser optically injects a slave laser.

A schematic of the experimental setup is shown in Fig. 1. In this experiment, we use single-mode distributed feedback semiconductor lasers operating at 1.3 μm. It is important to note that this method is equally applicable for semiconductor lasers operating at eye-safe wavelengths. They are independently controlled and are temperature and current stabilized. The master laser is detuned 2.3 GHz from the free-running frequency of the slave laser. The half-wave plates and the Faraday rotator are arranged such that the master laser injects the slave laser while the output of the slave laser is completely transmitted through the first polarizing beam splitter (PBS1). The injection strength is adjusted with the variable attenuator (VA). Under proper operating conditions, the optical injection drives the slave laser into the period-one dynamic state, where it emits two frequency components.[10] The two components have nearly equal amplitudes and are separated by a broadly tunable microwave frequency. A detailed study of the optical and microwave spectra of the period-one dynamic state is documented in Ref. 6.

The second polarizing beam splitter (PBS2) splits the light into two parts. The transmitted part of the beam is directly detected by high-speed photodiode PD1, which is referred to as the reference photodiode. The reflected part of the beam probes a moving target. The target is an uncoated right-angle prism mounted on a translation stage that is driven at a nearly constant velocity by a motorized actuator. By total internal reflection inside the prism, the beam is reflected back toward a second high-speed photodiode PD2, referred to as the target photodiode. The detected signal at PD2 is Doppler shifted and is extracted by mixing the signals of PD1 and PD2 by using a microwave mixer. The output of the mixer is sent to a data acquisition system and is recorded on a computer. A 5.5 km length of fiber (approximately 8 km optical path) is between the collection lens and PD2 to demonstrate the long-range ability of this system.

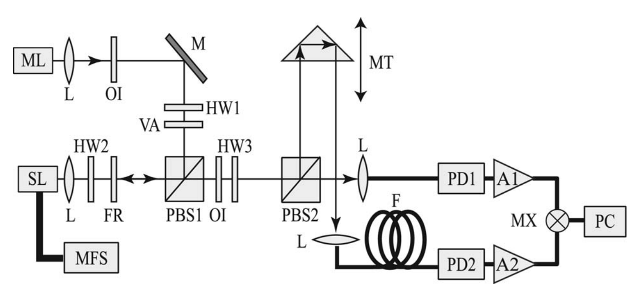

Fig. 1. Schematic of the experimental setup. ML, master laser; SL, slave laser; OI, optical isolator; HW, half-wave plate; VA, variable attenuator; FR, Faraday rotator; PBS, polarizing beam splitter; L, lens; M, mirror; MT, moving target; F, fiber spool; PD, high-speed photodiode; A, microwave amplifier; MX, microwave mixer; PC, computer; MFS, microwave frequency synthesizer.

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Analytically, the dual-frequency optical electric field of the salve laser with frequencies ν_1 and ν_2 and amplitudes E_1 and E_2 received by the reference photodetector is

$$E_{\mathrm{r}}(t) = \{E_1 e^{i\phi_1(t)} + E_2 e^{i[\phi_2(t)-2\pi f t]}\}e^{-i2\pi\nu_1 t}, \tag{1}$$

where $f=\nu_2-\nu_1$ is the microwave frequency difference and $\phi_1(t)$ and $\phi_2(t)$ are the random phase noise terms responsible for the optical linewidths of ν_1 and ν_2, respectively. Upon photodetection, this phase noise contributes to the linewidth of the microwave frequency. The signal received by the target photodiode experiences a delay during its round trip to the target. This is written as

$$E_{\mathrm{t}}(t) = \{E_1 e^{i\phi_1(t-\tau)} + E_2 e^{i[\phi_2(t-\tau)+2Kx-2\pi f t]}\}e^{-i2\pi\nu_1(t-\tau)}, \tag{2}$$

where x is the target position, c is the speed of light, $\tau=2x/c$ is the round-trip delay time, and $K=2\pi f/c$ is the effective microwave propagation constant. The detected current signals from the reference and target photodiodes, respectively, are

$$I_{\mathrm{r}}(t) = 2G_{\mathrm{r}}E_1E_2\cos[2\pi f t - \Delta\phi(t)], \tag{3}$$

$$I_{\mathrm{t}}(t) = 2G_{\mathrm{t}}E_1E_2\cos[2\pi f t - 2Kx - \Delta\phi(t-\tau)], \tag{4}$$

where $\Delta\phi(t)=\phi_2(t)-\phi_1(t)$ and G_{r} and G_{t} are the amplifier gains for the reference and target beams, respectively. These two current signals are sent to an RF mixer giving a signal proportional to the product of $I_{\mathrm{r}}(t)$ and $I_{\mathrm{t}}(t)$:

$$P_{\mathrm{mix}} = 2A\cos(2Kx - \Phi), \tag{5}$$

where $A=G_{\mathrm{r}}G_{\mathrm{t}}E_1^2E_2^2$ and $\Phi=\Delta\phi(t)-\Delta\phi(t-\tau)$. For targets moving at a constant velocity v, $x=d+vt$, where d is the initial distance of the target, we have

$$P_{\mathrm{mix}} = 2A\cos(2\pi f_{\mathrm{D}}t + 4\pi df/c - \Phi), \tag{6}$$

where $f_{\mathrm{D}}=2vf/c$ is the Doppler-shift frequency. The Doppler shift f_{D} is obtained by taking the power spectral density (PSD) of P_{mix}. Therefore, the magnitude of the velocity is measured. While it is not the intent of this Letter to determine the direction of motion, it can be easily determined by implementing an in-phase and quadrature detection as demonstrated by Morvan *et al.*[4]

This system can be viewed as a microwave Doppler system, except that the microwave is carried by an optical wave. Doppler measurements depend on only the optical frequency difference, not on the optical frequencies themselves. The target range for accurate velocity measurement thus depends on the microwave stability rather than the optical frequency stability. When the system operates in the period-one state, the resulting beat frequency has a microwave linewidth of about 10 MHz.[6] However, it is easily and significantly reduced by injecting a weak microwave modulation (at the period-one frequency) from a microwave frequency synthesizer (MFS), using the double-lock technique demonstrated by Simpson and Doft.[5] This locks the two optical lines in phase with each other. As a result, the linewidth of the detected microwave beat frequency is narrow (less than 1 kHz). Note that the optical linewidth does not affect the performance of the system. Any optical noise, such as that from an optical amplifier and that from attenuation and scattering along the beam path, that can change the optical linewidth does not affect the range and accuracy of the measurement as long as it does not affect the microwave linewidth. Velocity information is obtained from the Doppler-shifted microwave signal (10–100 GHz). Accurate determination of the Doppler-shift frequency, f_{D}, is possible as long as the random phase Φ is negligibly small. For a variance of Φ less than unity, the round-trip travel time τ must be less than the microwave coherence time $\tau_c=(2\pi\Delta f_{1/2})^{-1}$, where $\Delta f_{1/2}$ is the microwave linewidth. Hence, this sets an upper limit for the range of the target, that is, $d<c/(4\pi\Delta f_{1/2})$. Without the external modulation on the slave laser, the range is limited to approximately 2.4 m since the microwave linewidth is 10 MHz. Adding the external modulation significantly improves the range limit to more than 24 km, as the microwave linewidth is less than 1 kHz.

Experiments were carried out to demonstrate the performance of the DFDL. The first experiment was done with $f=17$ GHz, and 1000 s of data were acquired to achieve millihertz frequency resolution. The resolution can be improved by increasing the acquisition time. Figure 2 shows the normalized PSD of the mixer output data shown in the inset of Fig. 2. The Doppler-shift frequency $f_{\mathrm{D}}=3$ mHz yields a velocity of 26 μm/s, which is in excellent agreement with an independent measurement of the target velocity that also yielded 26 μm/s.

To demonstrate the tunability and usefulness of this system at any frequency, an experiment was carried out where the velocity of the moving target was unchanged while the period-one oscillation frequency was tuned. The optical path of the target beam was 15 m. As the period-one frequency f was increased, f_{D} increased proportionally, while the uncertainty in determining f_{D} was unchanged for a given observation time. Therefore, according to $v=cf_{\mathrm{D}}/2f$, the error in v decreased.[11] This system is capable of generating frequencies of up to 100 GHz.[10] However, due to electronic bandwidth limitations, the period-one oscilla-

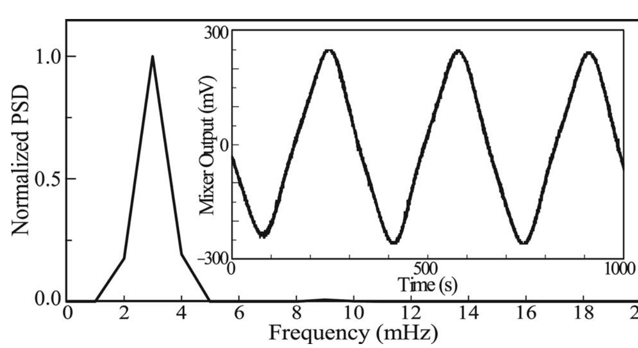

Fig. 2. (a) Mixer output for $f=17$ GHz. The target moves away from the detector at 26 μm/s. (b) Normalized PSD for $f=17$ GHz. The measured Doppler shift is 3 mHz.

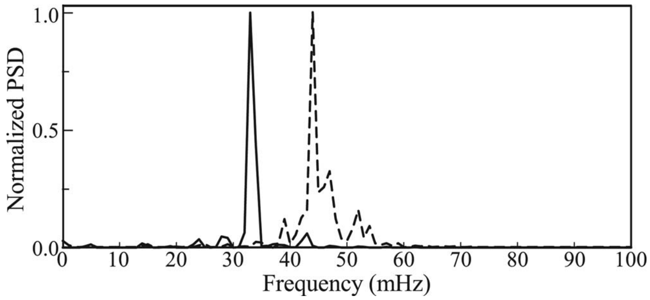

Fig. 3. Solid curve, normalized PSD for $f=12.9$ GHz. The measured Doppler shift is 33 mHz. The target moves back and forth at 384 μm/s. Dashed curve, normalized PSD for $f=17$ GHz. The measured Doppler shift is 44 mHz, therefore the target velocity is 388 μm/s.

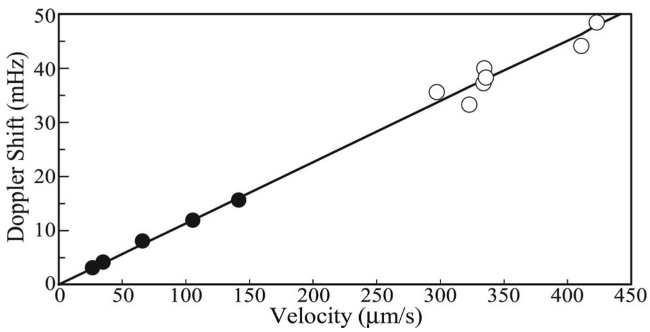

Fig. 4. Summary of velocity measurements. The open and solid symbols are data taken with two different actuators. The straight line shows the observed velocities plotted against the expected Doppler shift. The open-symbol data were taken with a motor that moved at various different speeds over the 1000 s data acquisition time. The solid-symbol data were taken with a slower, more reliable motor.

tion frequency was kept below 20 GHz throughout our experiment reported here.

The solid curve in Fig. 3 shows the normalized PSD for $f=12.9$ GHz, where the Doppler-shifted frequency is $f_D=33$ mHz. Solving for the velocity, we have $v=384$ μm/s. The dashed curve shows the normalized PSD for $f=17$ GHz. The measured Doppler-shifted frequency $f_D=44$ mHz yields a velocity of 388 μm/s for the moving target. Slight disagreement between these two values can be attributed to slight variations in the velocity of the actuator between the two runs of measurement. A summary of various Doppler-shift data is shown in Fig. 4. These data were all taken at a range of 15 m. The straight line shows the expected Doppler shift plotted against the physical velocity. The open and solid symbols represent actual Doppler-shift frequencies measured with this system using two different actuators. This was done to measure a wide range of velocities. The open-symbol data were taken with an actuator that moves at fast non-uniform speeds during the data run. Since it moves irregularly, some errors are apparent. The solid-symbol data were taken with an actuator that moves at slow constant speeds. These measured Doppler-shift frequencies are in excellent agreement with the expected values, since the motion is uniform. The slowest measured speed is 26 μm/s, but it is possible to extend the measurement to an even slower target.

We have demonstrated the use of a coherently locked dual-frequency beam that is generated by using nonlinear laser dynamics for Doppler-lidar detection. The two optical frequencies are separated by a tunable microwave frequency and are locked by an external microwave modulation, resulting in an intensity that oscillates at the beat frequency. When the beam is incident on a moving target, both optical frequencies experience a Doppler shift, resulting in a shifted beat frequency. The shift of the beat frequency is extracted by electrically mixing with the original signal, hence yielding the velocity. Due to the stability of the microwave and the elimination of common noise, accurate velocity measurement is possible. Experiments of velocity measurement are carried out to demonstrate the feasibility of the DFDL. Using a coherently locked dual-frequency beam with the frequencies separated by 17 GHz, we are able to accurately measure velocity as low as 26 μm/s at short and long ranges. Future work will involve optical amplification of the dual-frequency beam for field testing. With the advantages of compact size, low cost, and light weight, DFDL has great potential in applications such as remote and portable detection.

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