Speckle Noise Reduction of a Dual-Frequency Laser Doppler Velocimeter Based on an Optically Injected Semiconductor Laser

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ABSTRACT

We develop and investigate a dual-frequency Laser Doppler Velocimeter (DF-LDV) based on an optically injected semiconductor laser. By operating the laser in a period-one oscillation (P1) state, the laser can emit light with two coherent frequency components separated by about 11.25 GHz. Through optical heterodyning, the velocity of the target can be determined from the Doppler shift of the beat signal of the dual-frequency light. While the DF-LDV has the same advantages of good directionality and high intensity as in the conventional single-frequency LDV (SF-LDV), having an effective wavelength in the range of microwave in the beat signal greatly reduces the speckle noise caused by the random phase modulation from the rough surface of the moving target. To demonstrate the speckle noise reduction, the Doppler shifted signals from a moving target covered by the plain paper are measured both from the SF-LDV and the DF-LDV. The target is rotated to provide a transverse velocity, where the speckle noise increases as the transverse velocity increases. The bandwidth of the Doppler signal obtained from the SF-LDV is increased from 4.7 kHz to 9.4 kHz as the transverse velocity increases from 0 m/s to 5 m/s. In contrast, the bandwidth obtained from the DF-LDV maintains at 0.09 Hz with or without the rotation limited by the linewidth of the P1 state used. By phase-locking the laser with a RF current modulation, the linewidth of the P1 state can be much reduced to further improve the velocity resolution and extend the detection range.

Keywords: dual-frequency, laser Doppler velocimeter, speckle noise, optical injection, nonlinear dynamics

1. INTRODUCTION

Laser Doppler velocimeter (LDV) has been widely applied in medical and industrial diagnosis due to the advantages of good directionality, high spatial resolution, and noninvasive property.[1,2] However, compared with the Doppler radar which detects with the microwave, the conventional single frequency LDV (SF-LDV) using laser light is vulnerable from the influence of the speckle noise.[3] As the laser illuminates on a target with a surface roughness larger than the laser wavelength, the dephased backscattered light will interfere constructively and destructively to generate the randomly distributed bright and dark spots, which is the formation of speckle noise. During the velocity measurement, when the target moves with a transverse velocity component orthogonal to the propagation direction of the transmitted light, the transition of speckles collected by the photodiode will cause a Doppler signal to be modulated with the random phases, which result in broaden bandwidth to degrade the velocity resolution.

The mechanism of speckle noise introduced by the phase variation in the Doppler signal have been investigated and analyzed in the field of laser Doppler vibrometry, since the tested target such as a rotor, motor, and a bladed disk usually have a in-plane motion during the rotational vibration measurement. Thus, the speckle noise causing the pseudo vibration brings a crucial challenging for the vibration engineers to accurately estimate the mechanical properties. To reduce the speckle noise, Denman et al. demonstrated that there exists an optimized position of detector for receiving the light from the target.[4] Based on the idea of spatial averaging, Martin and Rothberg

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discussed how the laser beam size and detector size influence the amount of speckle noise.[5] Other than the methods emphasized on the optic design, Vass et al. presented a statistical technique for indicating the speckle noise in the Doppler signal by signal processing.[6] Therefore, an undistorted portion of a signal can be selected and further analyzed. However, all of the methods mentioned above require some parameters adjustment and optimization for adapting to different measurement conditions. Moreover, the spatial averaging will loss the advantage of laser light with its high spatial resolution.

In this study, we proposed a concept which utilizes a dual-frequency LDV (DF-LDV) based on an optically injected semiconductor laser for speckle noise reduction. Dual-frequency Lidar based on the nonlinear laser dynamics was demonstrated by Diaz *et al.*,[7] which showed the good linearity between the Doppler shift and longitudinal velocity of a moving target. The proposed detection principle of DF-LDV is based on utilizing the beat signal of the two emitted frequencies for probing the target. Benefitted by the beat signal with an effective wavelength in the microwave range, the speckle noise formed by the intrinsic characteristic of coherent light scattering can be suppressed. To our knowledge, utilizing the dual-frequency light source for reducing the speckle noise of LDV has not been studied previously.

2. DUAL-FREQUENCY LIGHT SOURCE GENERATION

The dual-frequency light source used for the speckle noise reduction is generated by the optical injection system of nonlinear laser dynamics. There are several perturbation schemes including optical injection,[8,9] optical feedback,[10] and optoelectronic feedback[11] for driving the free-running semiconductor laser into various dynamical states. The different kinds of generated waveforms[12] have been demonstrated for the application of high precision lidar,[13,14] radar[15] and photonic microwave generation.[16–23] Based on the optical injection system where a slave laser is optically injected by a master laser, the P1 (period-one) oscillation state that has a single oscillation frequency in the intensity time series continuously covers a wide area of the dynamic states map. Therefore, it is easy to operate the injected slave laser emitting two frequency components separated with a GHz frequency difference at a P1 state by a proper detuning frequency and injection strength. The P1 oscillation frequency in the range of microwave is tunable through different detuning frequency and injection strength.[24] Moreover, the linewidth of P1 frequency can be reduced by a phase-lock technique,[25] where a weak microwave current modulation is injected to lock the phase between two emitted frequencies.

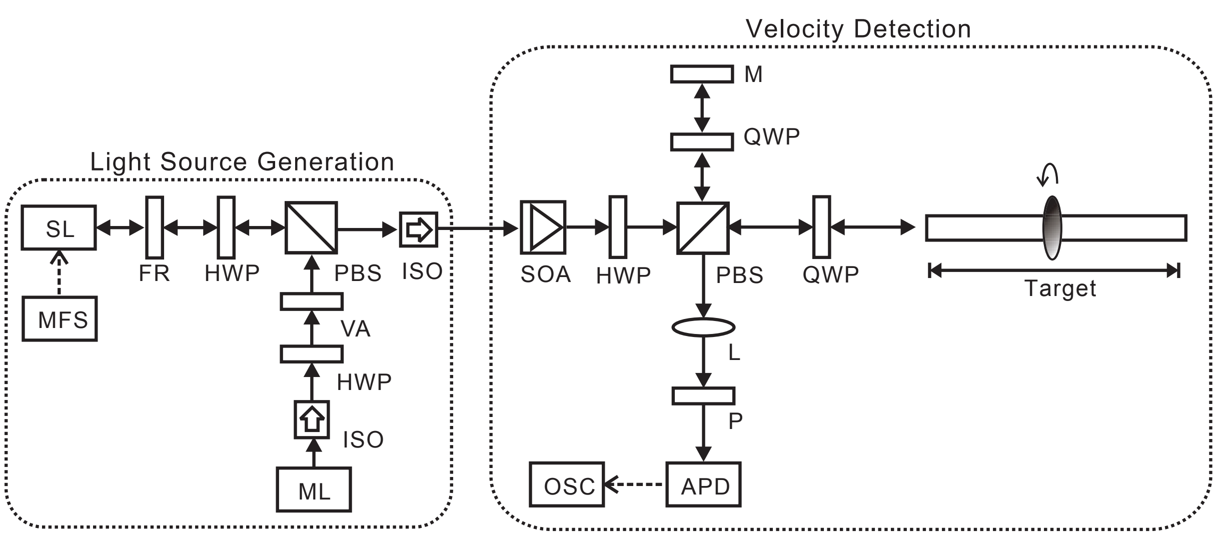

Figure 1. Experimental setup of the DF-LDV. ML, master laser; SL, slave laser; ISO, optical isolator; VA, variable attenuator; FR, Faraday rotator; HWP, half wave plate; QWP, quarter wave plate; PBS, polarizing beam splitter; L, lens; M, mirror; P, polarizer; SOA, semiconductor optical amplifier; APD, avalanche photodetector; MFS, microwave frequency synthesizer; OSC, oscilloscope.

3. EXPERIMENTAL SETUP

The experimental setup can be divided into three stages including light source generation, light amplification, and velocity detection as shown in Fig. 1. In the light source generation, an optically-injected semiconductor laser is used, where a 1.3 μm single-mode distributed feedback (DFB) semiconductor laser (slave laser) with relaxation oscillation frequency about 10 GHz is optically injected by a tunable laser (master laser) (Yenista Tunics-T100S). A free space circulator formed by two half-wave plates (HWPs), a polarizing beam splitter (PBS) and a Faraday rotator (FR) is used to allow the light from master laser to inject into the slave laser while the slave laser output can pass through the PBS. A microwave frequency synthesizer (MFS) gives an external current modulation for phase-locking the P1 oscillation.

In the stage of light amplification, the generated light source first passes through a fiber coupler (FC), the 20 % of input light is used for monitoring the status of P1 states by an optical spectrum analyzer (OSA) (Advantest Q8384) with a 10 pm resolution and a electrical spectrum analyzer (ESA) (Agilent E4407B) with a bandwidth of 26.5 GHz, the other 80 % of light is amplified to 40 mW by a semiconductor optical amplifier (SOA) (Covega BOA1130) to achieve the enough output power for measuring a diffused target.

In the stage of velocity detection, a Michelson interferometer is set up for detecting Doppler signals backscattered from the target. The amplified light is first divided into 1 % and 99 % by a FC as the reference beam and the target beam. The following two HWPs are used to control the powers of each two beams. After the reference and the target beam with orthogonal polarizations pass through the polarizer to allow the beating with each other, the corresponding Doppler signals resulted from the target motion are received by the avalanche photodetector (APD) (Thorlabs APD110C) and acquired by the oscilloscope for off-line analysis in a personal computer (PC). Compared with the setup developed by Diaz *et al.*,[7] which determined the Doppler shift based on the electrical mixing, the detection setup based on the optical heterodyne as mentioned above is more flexible to switch between DF-LDV and SF-LDV for comparison. A target used in this study is covered by a plain paper, where two stepper motors simultaneously drive a rotation stage and a translation stage to provide the target with transverse and longitudinal velocities, respectively. To quantify the performance of velocity resolution influenced by the speckle noise, different transverse velocities are applied.

As the dual-frequency laser light source with two frequency components of f_1 and f_2 illuminates on the moving target, both of two frequency components will experience the Doppler-shifted frequency equal to $f_{1d} = 2vf_1/c$ and $f_{2d} = 2vf_2/c$, respectively, where v and c are the longitudinal speed of target and the speed of light. Through optical heterodyning, four frequency components including f_1, f_2 from the reference arm and $f_1 + f_{1d}$, $f_2 + f_{2d}$ from the target arm will mix with each other. Because the frequency spacing between f_1 and f_2 closes to relaxation oscillation frequency of the slave laser is much larger than the -3 dB response bandwidth of 50 MHz of the APD, only the Doppler-shifted signals with the frequency of f_{d1} and f_{2d} are acquired. Through further signal processing in PC, f_{1d} and f_{2d} can be mixed to produce the component of $f_{1d} - f_{2d} = 2v(f_1 - f_2)/c$ which corresponds to the Doppler-shifted frequency of the beat signal of dual-frequency light. Therefore, DF-LDV is equivalent to utilize a microwave with a P1 oscillation frequency for probing the moving target.

The speckle noise suffered by the SF-LDV is generated when the surface roughness of the target is larger than the scale of optical wavelength. The randomly distributed phase of speckle noise between $-\pi$ and π will bring extra phase modulation into the Doppler signal, which leads the pseudo vibration and the broadened Doppler spectrum. Moreover, the faster transverse velocity of moving target can induce the faster phase variation rate which further broads the Doppler spectrum and severely degrades the velocity resolution. However, the speckle noise of DF-LDV can be suppressed. Benefited by utilizing the equivalent microwave wavelength to probe the target, the amplitude of the speckle phase is almost ignored and kept as a constant. Therefore, the velocity resolution can be maintained no matter how fast the transverse velocity of target is.

4. RESULTS

Figure 2(a) and (b) show the optical and power spectra of the dual-frequency light source generated with the P1 state through optical injection. The frequency of the beat signal is about 11.25 GHz with a -3 dB linewidth of 13.9 MHz. The corresponding microwave wavelength of the beat frequency is 2.67 cm, which is much larger than the emitted laser wavelength. Therefore, the speckle noise generated from the measurement of optically

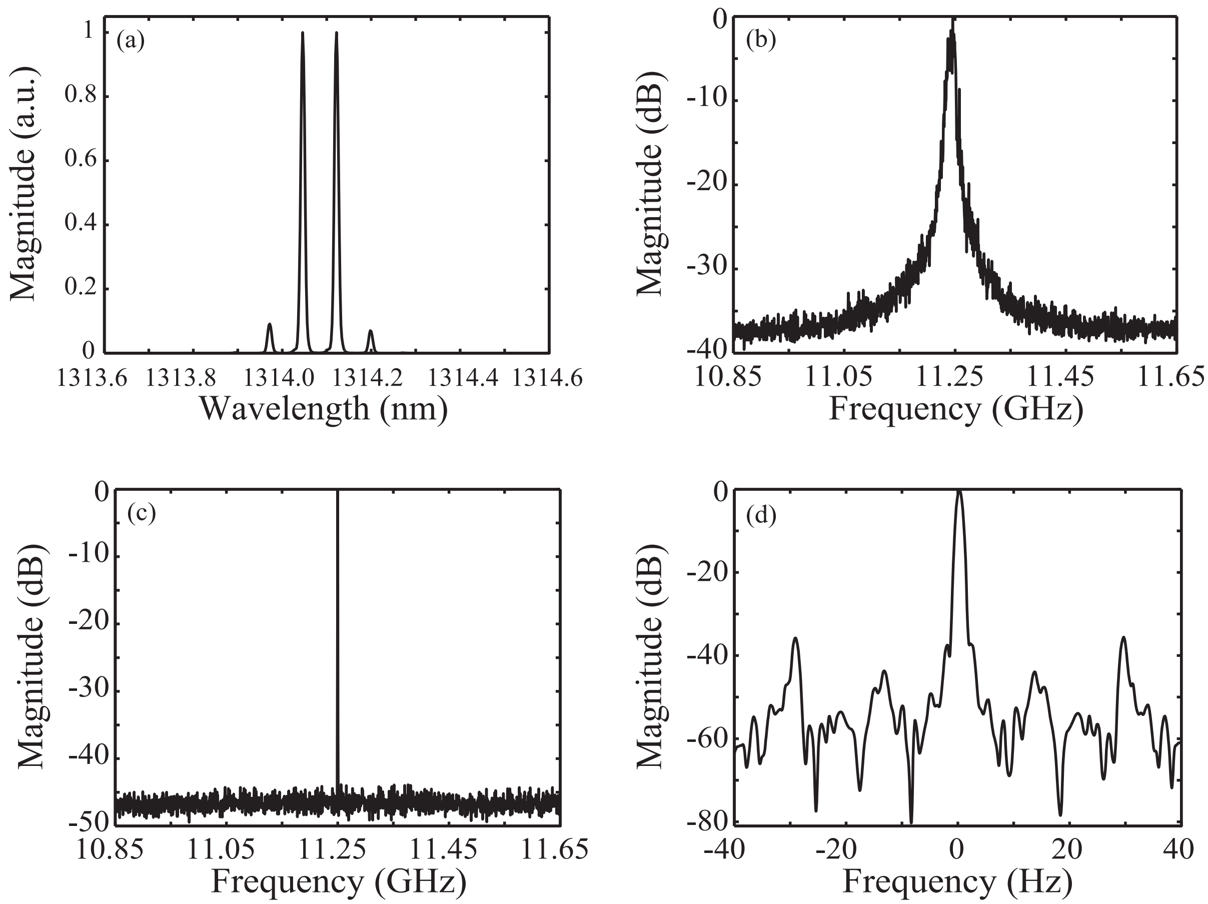

Figure 2. (a) The optical spectrum of the P1 dynamic state. (b) and (c) The corresponding electrical power spectra without and with the phase-lock technique. (d) The enlargement of (c) with the frequency axis offset to 11.25 GHz.

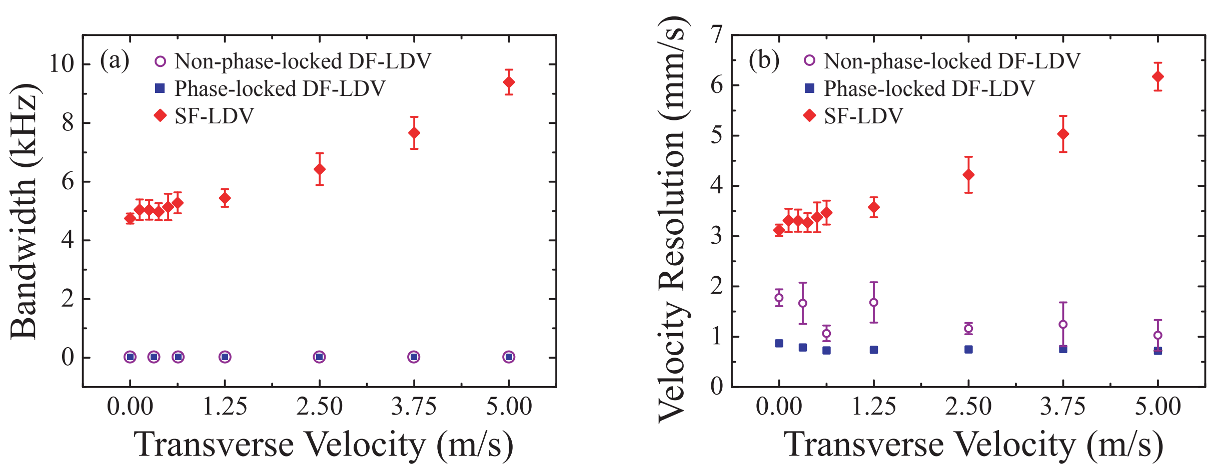

Figure 3. (a) -6 dB Doppler bandwidth measured from the received Doppler signals under different transverse velocities. (b) Velocity resolution under different transverse velocities.

rough surface can be much suppressed. By the phase-lock technique to lock the phase noise between two optical frequencies, the -3 dB linewidth of the P1 frequency can be narrowed to 0.9 Hz as shown in Figs. 2(c) and (d), which is limited by the frequency resolution of the observation instrument. Compared with the other methods for generating dual-frequency light source such as the direct current modulation of the semiconductor laser, the P1 state shows the single sideband in optical spectrum that provides larger modulation depth and avoids the velocity ambiguity resulted by the strong harmonics. In addition, the frequency tuning range is broader due to the bandwidth enhancement effect of the optical injection. Compared with an alternative approach by optically mixing the two laser beams with a frequency difference, the coherence of the beat frequency generated by P1 state can be enhanced by phase-lock technique for providing more stable velocity resolution.

Figure 3(a) shows the Doppler bandwidth of the DF-LDV (with and without double phase-lock) and the conventional SF-LDV. As can be seen, the bandwidth of the Doppler signal obtained from the SF-LDV increases from 4.7 kHz to 9.4 kHz as the transverse velocity increases from 0 m/s to 5 m/s. On contrary, the bandwidths of the phase-locked and non-phase-locked DF-LDVs remain at about 0.05 and 0.09 Hz for the same range of the transverse velocities. DF-LDV significantly mitigates the spectral broadening from the speckle noise, which is resulted from its effective wavelength of 2.67 cm that is much larger than the surface roughness of a typical plain paper. As shown in Fig. 3(b), the velocity resolution of the phase-locked DF-LDV is 6-fold smaller compared with the conventional SF-LDV, where the improvement of the velocity resolution can be expected to become more obvious for measuring the target with higher transverse velocity. Moreover, the fluctuation of the velocity resolution at different transverse velocities for the phase-locked DF-LDV is much smaller than the non-phase-locked DF-LDV due to its better coherence and frequency stability.

5. CONCLUSIONS

Reducing the effect of the speckle noise by the proposed DF-LDV based on an optically injected semiconductor laser has been demonstrated. Compared with the conventional SF-LDV, the velocity resolution of the DF-LDV can be improved up to 6 folds. With the phase-locked technique, the velocity resolution and the system stability of DF-LDV can be further improved.

The detection principle of DF-LDV can be regarded as utilizing a light-carried microwave for probing the target, that possesses the duality of the laser light and microwave. The laser light plays a role of a carrier for delivering the microwave, which provides the good directionality, high spatial resolution and high intensity. The performance of velocity detection is determined by the loaded microwave, supplying the speckle noise reduction and small measurement fluctuation due to its longer equivalent wavelength and higher coherence by phase-locking. For reducing the speckle noise, the proposed DF-LDV does not need to loss its high spatial resolution. In addition, optimizing the operating parameters in optical design and signal processing are not required. Compared with other methods for generating dual-frequency light source, the P1 state of optical injected semiconductor laser has the advantages of larger modulation depth, less velocity ambiguity, broader tuning range, and possible to lock the phase of the beat frequency of the two emitted frequencies.

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