Dual-frequency laser Doppler velocimeter for speckle noise reduction and coherence enhancement

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Abstract: We study the characteristics of a dual-frequency laser Doppler velocimeter (DF-LDV) based on an optically injected semiconductor laser. The laser operated in a period-one (P1) dynamical state with two optical frequencies separated by 11.25 GHz is used as the dual-frequency light source. With a microwave beat signal carried by the light, the DF-LDV possesses both the advantages of good directionality, high intensity, and high spatial resolution from the light and low speckle noise and good coherence from the microwave, respectively. By phase-locking the two frequency components with a microwave signal, the coherence of the dual-frequency light source can be further improved and the detection range can be much extended. In this paper, velocity resolutions of the DF-LDV with different amounts of speckle noise and at different detection ranges are experimentally measured and analyzed. Compared with the conventional single-frequency LDV (SF-LDV), the velocity resolution of the DF-LDV is improved by 8x10^3 times from 2.5 m/s to 0.31 mm/s for a target with a longitudinal velocity \( v_z = 4 \) cm/s, a transverse velocity \( v_T = 5 \) m/s, and at a detection range of 108 m.

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References and links

1. Introduction

Laser Doppler velocimeter (LDV) has been widely used in medical and industrial diagnoses. It has the advantages of good directionality, high spatial resolution, and noninvasive in velocity detection [1, 2]. In the conventional single-frequency LDV (SF-LDV), the single frequency laser light is split into a target and a reference beam. The backscattered light from the moving target beats with the reference light to extract the Doppler-shift frequency for the corresponding target velocity [3]. Ideally, a narrow Doppler-shifted line is expected in the acquired spectrum if the target is moving at a constant velocity. However, due to both the speckle noise from the roughness on the target surface and the optical noise from the coherence property of the laser, the spectral bandwidth of the Doppler-shifted line could be broadened and the velocity resolution measured can therefore be degraded.

The effect of the speckle noise on the Doppler signal has been widely studied [4]. For targets such as rotor, motor, and disk blade that usually have an in-plane motion during the rotational vibration measurements, the pseudo vibrations caused by the speckle noise brings challenges to accurately estimate their real mechanical properties. To reduce the effect of the speckle noise, Denman et al. demonstrated that there exists an optimized position for the detector to detect the light from the target [5]. Based on spatial averaging, Martin and Rothberg showed how the laser beam and detector sizes influence the speckle noise [6]. The crucial spatial resolution supposedly benefitted by using a laser light is however lost after the spatial averaging is applied. Other than the optical methods, Vass et al. presented a statistical technique to estimate the contribution of the speckle noise in the Doppler signal through signal processing [7]. While these methods can all reduce the effect of the speckle noise, the system parameters need to be adjusted and optimized according to different measurement conditions.

Together with the speckle noise, the optical phase noise of the light source also affects the velocity resolution and detection range in an SF-LDV. To improve the coherence property, Mocker and Bjork developed an SF-LDV using an external-cavity semiconductor laser with a linewidth of 40 kHz and achieved a sub-cm/s velocity resolution over a target distance of 80 m [8]. Sharma et al. utilized an all-fiber laser as the light source and demonstrated a velocity resolution of 7.5 mm/s for the precision blood flow measurement [9]. While scientists
are continuing making efforts to develop lasers with higher coherence, the typical linewidths of lasers are still by far much broader than the microwave signals generated with the commercial microwave frequency synthesizers.

To solve the aforementioned problems, a dual-frequency LDV (DF-LDV) with the unique advantages of speckle noise reduction and coherence enhancement is studied in this paper. Instead of using a conventional single frequency laser, an optically-injected semiconductor laser operated in a period-one (P1) dynamical state with two optical frequencies in its spectrum is used as the dual-frequency light source [10–12]. While lidars and radars using nonlinear laser dynamics have been widely studied recently [13–15], to the beset of our knowledge, this is the first demonstration of using a dual-frequency implement to mitigate the influence of speckle noise in laser detection with a diffuse target. Compared to the conventional optical methods that losses the crucial spatial resolution by performing spatial averaging, the spatial resolution remains intact in the DF-LDV proposed. Note that, while a similar dual-frequency implement is used to show the proof-of-concept velocity measurement with an ideal right-angle prism in a previous work [16], the effect of the speckle noise and the important issues of the velocity resolution related to the transverse velocity, the longitudinal velocity, and the range of the target were not studied.

With a microwave beat signal of 11.25 GHz carried to and back from the target by the light, the DF-LDV utilizing the P1 state proposed is shown to possess both the advantages of good directionality, high intensity, and high spatial resolution from the light and low speckle noise and good coherence from the microwave, respectively. By phase-locking the two frequency components with a microwave modulation at their detuning, the coherence of the dual-frequency light source can be further improved and the detection range can be much extended. To demonstrate the speckle noise reduction and the coherence enhancement of the DF-LDV, the velocity resolutions with different amounts of speckle noise and at different detection ranges are experimentally measured and analyzed. To quantify the improvement, the results from the conventional SF-LDV, DF-LDV without phase-locking, and DF-LDV with phase-locking using the exact same laser are compared.

2. Principles of the DF-LDV

An optically injected semiconductor laser operated in a P1 state having two detuned frequency components is utilized as the dual-frequency light source in our experiment. Unlike the four-wave mixing state generated with a weak injection in the unlocked region that has a relatively weak double-sideband modulation [17, 18], the P1 state generated with a moderate to strong injection in the unstably locked region has a much stronger single-sideband modulation that is suitable to be used as the dual-frequency light source [10]. The dual-frequency light from the laser is split into a reference beam and a target beam. For the reference beam, the electric field of the dual-frequency signal can be expressed as

\[ E_r(t) = E_1 e^{i[2\pi f_1 t + \phi_1(t)]} + E_2 e^{i[2\pi f_2 t + \phi_2(t)]}, \]

(1)

where \( E_1, E_2, f_1, f_2, \) and \( \phi_1(t), \phi_2(t) \) are the electric fields, frequencies, and optical phase of the two main peaks of the P1 state with a microwave beat frequency of \( f_{\text{P1}} \), respectively.

For the target beam, the electric field backscattered from a target that is moving away with a longitudinal velocity \( v_z \) and crossing over the laser beam with a transverse velocity \( v_t \) can be expressed as

\[
E_t(t) = E_1 e^{i[2\pi(f_1 + f_{\text{d1}})t - 2\pi f_1 t + \phi_1(t - \tau) + \phi_{\text{speckle}}(t - \tau)]} \\
+ E_2 e^{i[2\pi(f_2 + f_{\text{d2}})t - 2\pi f_2 t + \phi_2(t - \tau) + \phi_{\text{speckle}}(t - \tau)]},
\]

(2)
where \( f_{d,1} = 2v_z f_1/c \) and \( f_{d,2} = 2v_z f_2/c \) are the Doppler-shifted frequencies of \( f_1 \) and \( f_2 \). \( \phi_{1\text{-speckle}}(t) \) and \( \phi_{2\text{-speckle}}(t) \) are the phase variations from the speckle noise experienced by the two frequency components, \( c \) is the speed of light, and \( \tau \) is the time delay relative to the reference beam, respectively. When the target has a relative movement to the target beam in the transverse direction, the phase variations from the speckle noise can be written as [4]

\[
\phi_{1\text{-speckle}}(t) = \int \frac{2\pi \times 2\gamma(p,t)}{\lambda_1} dS,
\]

\[
\phi_{2\text{-speckle}}(t) = \int \frac{2\pi \times 2\gamma(p,t)}{\lambda_2} dS,
\]

where \( \gamma(p,t) \) is the surface roughness experienced by the light at different positions and times, \( \lambda_1 \) and \( \lambda_2 \) are the wavelengths corresponding to the two optical frequency components \( f_1 \) and \( f_2 \), and \( S \) is the spot size of the laser beam, respectively.

Theoretically, six interference terms will be generated through heterodyning the reference beam and the target beam. Since the frequency difference of \( f_1 \) and \( f_2 \) \((f_1 - f_2 = f_{P1})\) well exceeds the detection bandwidth of the APD used, the interference terms detected corresponding to the Doppler-shifted signals \( f_{d,1} \) and \( f_{d,2} \) are

\[
I_1(t) = 2E_1^2 \cos[2\pi f_{d,1} t + \phi_1(t) - \phi_{1\text{-speckle}}(t) - 2\pi f_1 \tau],
\]

\[
I_2(t) = 2E_2^2 \cos[2\pi f_{d,2} t + \phi_2(t) - \phi_{2\text{-speckle}}(t) - 2\pi f_2 \tau],
\]

By further mixing \( I_1(t) \) and \( I_2(t) \), a Doppler-shifted signal corresponding to the microwave beat signal \( f_{P1} \) is obtained as

\[
I_{\text{mix}}(t) = 2E_1^2 E_2^2 \cos[2\pi f_{d,P1} t + \phi_{P1}(t) - \phi_{1\text{-speckle}}(t) - 2\pi (f_1 - f_2) \tau],
\]

where \( f_{d,P1} = 2v_z (f_1 - f_2)/c = 2v_z f_{P1}/c \), \( \phi_{P1}(t) = \phi_1(t) - \phi_2(t) \), and \( \phi_{1\text{-speckle}}(t) - \phi_{2\text{-speckle}}(t) = \int \frac{2\pi \times 2\gamma(p,t)}{c/f_{P1}} dS \).

For a conventional SF-LDV, as can be expressed with Eq. (5) alone (or Eq. (6)), the bandwidth of the Doppler-shifted signal at \( f_{d,1} \) \((f_{d,2})\) is affected by the optical phase noise \( \phi_1(t) \) \((\phi_2(t))\) and the speckle noise \( \phi_{1\text{-speckle}}(t) \) \((\phi_{2\text{-speckle}}(t))\). For the optical phase noise, it is determined by the coherent property of the light source including the natural linewidth and the frequency instability. In velocity detections based on optical heterodyning, the bandwidth of the Doppler-shifted signal is determined by the correlation of the time-varying phase noise between the reference and the target beams. When the path difference between the target and the reference beams increases, the Doppler-shifted signal will be broadened due to the abrupt variation of \( \phi_1(t) \) \((\phi_2(t)) \) at different times. For the speckle noise, random variations of \( \phi_{1\text{-speckle}}(t) \) \((\phi_{2\text{-speckle}}(t))\) caused by the roughness of the target surface will also broaden the signal. This broadening due to the speckle noise could be significant when the target has a relatively fast transverse velocity. Consequently, with the broadening of the Doppler-shifted signal, the velocity resolution of the SF-LDV could be severely degraded.

On the other hand, for a DF-LDV as shown in Eq. (7), the target can be viewed as being probed by a microwave beat signal with a frequency of \( f_{P1} \). The Doppler-shifted frequency \( f_{d,P1} \), the optical phase \( \phi_{P1}(t) \), and the phase variation due to the speckle noise \( \phi_{P1\text{-speckle}}(t) \) are all related to the microwave beat signal instead of the optical ones. Since the equivalent wavelength of the microwave beat signal \((c/f_{P1})\) is about \(10^4\) longer than that of the laser light, the phase variation from the rough surface of the target \( \phi_{P1\text{-speckle}}(t) \) will be significantly reduced and the spectral broadening due to the speckle noise can be much suppressed. Moreover, the coherence and stability of the microwave beat signal can be much enhanced by locking the phase between \( \phi_1(t) \) and \( \phi_2(t) \) with a microwave modulation at \( f_{P1} \) to reduce the optical phase

### References

1. Received 18 Apr 2012; revised 11 Jul 2012; accepted 13 Aug 2012; published 20 Aug 2012
2. (C) 2012 OSA
3. 27 August 2012 / Vol. 20, No. 18 / OPTICS EXPRESS 20258
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noise [19, 20]. Compared with the conventional SF-LDV, the unique advantages of the speckle noise reduction and the coherence enhancement of the DF-LDV make it especially suitable for applications that require high velocity resolution and long range of detection.

3. Experimental setup

![Experimental setup diagram](image)

Fig. 1. Experimental setup of the DF-LDV based on an optically injected semiconductor laser. ML: master laser; SL: slave laser; SOA: semiconductor optical amplifier; PBS: polarizing beam splitter; ISO: isolator; FR: Faraday rotator; HWP: half-wave plate; QWP: quarter-wave plate; VA: variable attenuator; CL: coupling lens; FC: fiber coupler; L: lens; P: polarizer; M: mirror; APD: avalanche photodetector; MFS: microwave frequency synthesizer; OSA: optical spectrum analyzer; MSA: microwave spectrum analyzer; OSC: oscilloscope.

The experimental setup of the DF-LDV is shown in Fig. 1. A 1.3 μm single-mode distributed feedback (DFB) semiconductor laser is used as the slave laser (SL), which is optically injected by a master laser (ML) through a free-space circulator. By controlling the injection strength and detuning frequency between the ML and SL, the SL can be operated in the P1 state and generated a dual-frequency optical output. To compare with a conventional SF-LDV using the same SL, the injection light from the ML can be blocked so that the free-running SL can have a single frequency output. To stabilize the dual-frequency light source and enhance the coherence length, a microwave frequency synthesizer (Anritsu MG3692B) is used to phase-lock the two frequency components through current modulation. With a 12 GHz high-speed photodetector (Newport 1544-A), the optical and power spectra are monitored by an optical spectrum analyzer (Advantest Q8384) with a resolution of 10 pm and a microwave spectrum analyzer (Agilent E4407B) with a bandwidth of 26.5 GHz. To improve the signal to noise ratio in detection, a semiconductor optical amplifier (SOA) (Covega BOA1130) is used to amplify the light to about 30 mW before sending it to the target.

For velocity detection, an interferometer is setup where the SL output is split into a target beam and a reference beam. An aluminium plate with surface roughened by sandpapers is used as the target, which is attached to a rotation stage placing on a translation stage to simultaneously provide it with a transverse velocity \( v_t \) and a longitudinal velocity \( v_z \). By mixing the backscattered light from the target and the reference light on an avalanche photodetector (APD) with a detection bandwidth of 50 MHz (Thorlabs APD110C), the Doppler-shifted signals \( I_1 \) and \( I_2 \) are acquired by a 500 MHz oscilloscope (Tektronix TDS7054) and processed in a personal computer to calculate the \( I_{mix} \) and thus the target velocity. Note that, unlike the electric mixing scheme used in Ref. 16 that requires two costly high-speed photodetectors and a microwave mixer that have to cover the frequency difference of the two originally transmitted
optical frequencies \( f_{P1} \) and the frequency difference of the two Doppler-shifted optical frequencies \( f_{P1} + f_{d,1} - f_{d,2} \) (both in GHz), the optical heterodyning scheme adopted here only needs a photodetector with a very low bandwidth just to cover the Doppler shift frequencies of the two transmitted optical frequencies \( f_{d,1} \) and \( f_{d,2} \) (both in MHz).

4. Result

Figure 2(a) shows the optical spectrum of the P1 state obtained from the optically-injected SL, where two frequency components with equal magnitude are generated. The normalized injection strength from the ML to the SL is about 0.46 and the detuning frequency between the ML and the SL is set to 0, where the former is defined as the injected field strength normalized to the emitted field strength and the latter is defined as the offset frequency of the injection measured from the free-running frequency of the SL. The power spectra of the microwave beat signal are shown in Fig. 2(b), where the spectrum acquired with the single sweep mode (black curve, resolution bandwidth of 100 kHz) shows a beat frequency \( f_{P1} \) of about 11.25 GHz with a -3 dB linewidth of 13.9 MHz. With the maximum hold mode (red curve), the -3 dB linewidth of the spectrum is broadened to 58.9 MHz resulted from the frequency instability of the P1 state. To stabilize the frequency and enhance the coherence, a microwave modulation at \( f_{P1} \) through the bias current is applied to the SL to phase-lock the two frequency components. As shown in Fig. 2(c), the -3 dB linewidth of the P1 state after phase-locking is narrowed to less than 1 Hz, which is the resolution limit of the microwave spectrum analyzer used.

For the microwave beat signal at 11.25 GHz of the dual-frequency light source, the corresponding microwave wavelength is about 2.67 cm. While a conventional SF-LDV could be easily affected by the surface roughness of the target in the scale of the laser wavelength (in \( \mu \)m), the phase variation will be substantially mitigated with the DF-LDV due to the much longer microwave wavelength of the beat signal (in centimeters). As the result, the spectral broadening due to the speckle noise is expected to be significantly suppressed in the DF-LDV that detects the target velocity with a microwave carried by light.

To demonstrate the speckle noise suppression in the proposed DF-LDV, an aluminium plate with a roughened surface is used as the target. By rotating the target to generate the phase variation, the spectral broadenings under different transverse velocities for the SF-LDV and DF-LDV are analyzed and compared. Figures 3(a)-3(c) and Figs. 3(d)-3(f) show the time series and power spectra of the Doppler-shifted signals obtained from the SF-LDV and DF-LDV (with phase-locking), respectively. The target is moving away from the interferometer with \( v_z = 4 \) cm/s while rotating with \( v_t = 5 \) m/s. The reference and the target arms are adjusted to have the same optical length so that the broadening due to the optical noise can be eliminated at
Fig. 3. (a) Waveform, (b) its enlargement, and (c) power spectrum of the Doppler-shifted signal from the SF-LDV and (d) waveform, (e) its enlargement, and (f) power spectrum of the Doppler-shifted signal from the DF-LDV (with phase-locking), respectively. The target is moving away from the interferometer with $v_z = 4 \text{ cm/s}$ while rotating with $v_t = 5 \text{ m/s}$.

this time. For the SF-LDV, the waveform of the Doppler-shifted signal and its enlargement are shown in Figs. 3(a) and 3(b), respectively. The -3 dB linewidth of the Doppler-shifted signal in the spectrum shown in Fig. 3(c) is 7.7 kHz at about 63 kHz corresponding to the longitudinal velocity of the target, compared to a linewidth of 4.4 MHz for the SL. For the DF-LDV, the waveform and its enlargement of the Doppler-shifted signal with a modulation envelope at about 3 Hz corresponding to the longitudinal velocity of the target is seen in Figs. 3(d) and 3(e), respectively. The -3 dB linewidth of the signal in the spectrum shown in Fig. 3(f) is only 0.03 Hz, which is much narrower than the linewidth of the Doppler-shifted signal from the SF-LDV shown in Fig. 3(c). Note that for the single-frequency signal and the microwave beat signal of the dual-frequency source that have the frequencies of 228 THz and 11.25 GHz, the velocity resolutions of the SF-LDV and DF-LDV calculated from the corresponding linewidths of the Doppler-shifted signals shown in Figs. 3(c) and 3(f) are 5 mm/s and 0.39 mm/s, respectively. As the result, by using the dual-frequency light source that has a longer equivalent wavelength in its microwave beat signal, an improvement in the velocity resolution of almost an order of magnitude is achieved.

Figures 4(a) and 4(b) show the velocity resolutions of the respective SF-LDV and DF-LDV with different transverse velocities when the target is moving at $v_z = 4 \text{ cm/s}$, where the means and the error bars from several measurements are plotted. As shown in Fig. 4(a), the velocity resolution of the SF-LDV degrades linearly from 3.1 mm/s to 4.9 mm/s as the transverse velocity of the target increases from 0 m/s to 5 m/s. On the contrary, as shown in Fig. 4(b), the velocity resolution of the DF-LDV without phase-locking maintains at an average level of 0.42 mm/s as the transverse velocity increases. With phase-locking, the velocity resolution is further reduced to an average level of 0.36 mm/s for all the transverse velocities measured.

Note that, with the DF-LDV, not only the speckle noise is suppressed and the velocity resolution is improved, but the Doppler-shifted signals is also much stabilized. The average standard deviation of the SF-LDV for the measurements shown in Fig. 4(a) is 0.21 mm/s, while the average standard deviation of the DF-LDV without phase-locking for the measurements shown in Fig. 4(b) is only 0.02 mm/s. With phase-locking, the microwave beat signal from the dual-
Fig. 4. (Velocity resolutions of the (a) SF-LDV and (b) DF-LDV without and with phase-locking for different transverse velocities when the target is moving at \( v_z = 4 \text{ cm/s} \). The averages and error bars obtained from several measurements are plotted.

frequency light source is further stabilized and the averaged standard deviation is reduced to merely 0.01 mm/s.

Fig. 5. Velocity resolutions of the (a) SF-LDV and (b) DF-LDV without and with phase-locking for different path differences.

The possibility of phase-locking the two frequency components also gives the DF-LDV the advantage of enhancing the coherent length and hence the detection range. To compare the capability of the SF-LDV and DF-LDV in long range measurement, single mode fibers with different lengths are inserted into the target arm. To eliminate the effect of spectral broadening from the speckle noise, here the target is not rotating and only moving away from the interferometer with \( v_z = 4 \text{ cm/s} \). The velocity resolutions of the SF-LDV and the DF-LDV with and without phase-locking at different path differences are plotted in Figs. 5(a) and 5(b), respectively. As can be seen, the velocity resolution of the SF-LDV increases from 3.1 mm/s to 2.5 m/s as the path difference increases from 0 to 108 m. For the DF-LDV without phase-locking, the velocity resolution increases from 0.4 mm/s to 1.0 mm/s as the path difference increases from 0 to 9 m. Due to the frequency instability of the P1 state, tracking the Doppler-shifted signal becomes difficult when the path difference exceeds 9 m. However, with phase-locking, the velocity resolution of the DF-LDV remains at an average level of 0.31 mm/s for a path difference up to 108 m measured. As that is shown, by phase-locking the microwave beat signal of the P1 state, the coherence of the microwave beat signal can be greatly enhanced and the velocity resolution of the DF-LDV can be kept at a very low level for a long detection range.
Fig. 6. Velocity resolutions of the (a) SF-LDV and (b) DF-LDV with phase-locking for different transverse velocities at different path differences, respectively.

Taking both the effects from the speckle noise and the optical phase noise into account, Figs. 6(a) and 6(b) show the velocity resolutions with different transverse velocities while at different path differences for the SF-LDV and the DF-LDV with phase-locking, respectively. As shown in Fig. 6(a), the velocity resolutions of the SF-LDV degrades both with the increase of the transverse velocity and the path difference. The spectral broadening is dominated by the effect of the speckle noise at shorter path differences, while it is dominated by the effect of the optical phase noise at longer path differences, respectively. On the contrary, as shown in Fig. 6(b), the velocity resolutions of the DF-LDV with phase-locking remains at a low level for transverse velocity up to 5 m/s with a path difference up to 108 m. For the target with the largest transverse velocity of $v_t = 5$ m/s and the longest path difference of 108 m tested, the DF-LDV shows $8 \times 10^3$ improvement in the velocity resolution compared to the conventional SF-LDV (from 2.5 m/s to 0.31 mm/s).

Note that, as can be seen in Fig. 4(a), even when $v_t = 0$ and the initial path difference is set to 0, the velocity resolution of the SF-LDV still has a minimum value of about 3.1 mm/s. This is mainly caused by that the path difference is constantly changing as the data are acquired, where the target is moving at $v_z = 4$ cm/s to create the Doppler effect. To show the spectral broadening contributed from the changes of the path differences due to the longitudinal velocity, Figs. 7(a) and 7(b) show the velocity resolutions for different longitudinal velocities at different path differences for the SF-LDV and the DF-LDV with phase-locking, respectively. For the SF-LDV, as can be seen in Fig. 7(a), the velocity resolution increases notably with the longitudinal velocity especially when the initial path difference is small. On the contrary, the velocity resolution of the DF-LDV with phase-locking shown in Fig. 7(b) is almost constant under different longitudinal velocities. These results again show that the velocity resolution of the SF-LDV is easily affected by the speckle noise and the coherence property of the signal, where the transverse velocity of the target, the path difference, and the longitudinal velocity of the target all contribute to the spectral broadening of the Doppler-shifted signal. For the phase-locked DF-LDV, on the other hand, the velocity resolution remains at a relatively low level independent of the transverse velocity, the path difference, and the longitudinal velocity. Compared to the conventional SF-LDV, the phase-locked DF-LDV shows the advantages of speckle
Fig. 7. Velocity resolutions of the (a) SF-LDV and (b) DF-LDV with phase-locking for different longitudinal velocities at different path differences, respectively.

noise reduction and coherence enhancement, which is especially suitable in velocity measurements of targets with rough surfaces, high transverse and/or longitudinal velocities, and/or at a long detection distance.

5. Discussion and conclusion

In conclusion, we have studied the detection characteristics of the SF-LDV and the DF-LDV under the influences of the speckle noise and the optical phase noise. Using a dual-frequency P1 signal from an optically-injected semiconductor laser as the light source, the DF-LDV is essentially probing the target with a microwave beat signal carried by the light. Compared with the conventional SF-LDV, the speckle noise from the rough surface of the target can be much suppressed in the DF-LDV. By locking the optical phases of the two frequency components in the P1 state through microwave modulation, the coherence of the microwave beat signal can be much improved and the detection range can be significantly extended. For the target with $v_z = 4\text{ cm/s}$, $v_t = 5\text{ m/s}$, and at a path difference of 108 m, an average level of the velocity resolution of about 0.31 mm/s is obtained with the phase-locked DF-LDV, which is $8 \times 10^3$ better than that of the conventional SF-LDV (2.5 m/s) using the same SL. As have been shown, the unique advantages of the speckle noise reduction and the coherence enhancement of the DF-LDV make it suitable in those applications require high velocity resolution and long detection range.

Compared with other methods to generate the dual-frequency light, the P1 state from an optically-injected semiconductor laser has the advantages of large modulation depth (almost equal amplitude of the two frequency components), broad frequency tuning range of the microwave beat signal, no need for the high-speed EO modulator and electronic devices, and the possibility of locking the phases of the two frequency components to enhance the coherence and stability. While direct modulation on a semiconductor laser can also generate the microwave beat signal on the light, the modulation depth is relatively small and the double-sideband signal (three frequency components in the optical spectrum) could cause ambiguity in velocity detection. Optically mixing two detuned single-frequency signals directly can also generate a light with two frequency components. However, the coherence and stability of the microwave beat
signal are still governed by the two individual optical signals, where their relative phase cannot be locked as efficiently and easily as in the P1 state.

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