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Note: Using an optical phase-locked loop in heterodyne velocimetry

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An optical phase-locked loop was introduced in heterodyne velocimetry to lock the differential frequency between a fiber laser and an external cavity diode laser. An uncertainty less than 1 MHz of the locked beat frequency was achieved during several microseconds, corresponding to a velocity uncertainty at 0.1 m/s level for 1550 nm light. In this way, a measurement with higher precision and better time resolution simultaneously can be obtained during a transient process. Three proof-of-principles shots were performed to measure elastic wave-induced vibrations on surfaces of steel films with submillimeter thicknesses. The surface velocity fluctuations were probed with amplitudes of about 2 m/s and periods of tens of nanoseconds, and propagating times and sound velocities of waves were also well analyzed at a time scale 0.5 μ s. A velocity resolution of 0.1 m/s level and a temporal resolution of a few nanoseconds were achieved in these measurements. © 2013 AIP Publishing LLC. [<http://dx.doi.org/10.1063/1.4813735>]

Dynamic properties need to be measured in order to study a material's response under extreme conditions of density, temperature, and pressure in impact experiments. Some such quantities as shock and particle velocities, are useful to construct Hugoniot and equations of state.¹ The particle velocities are usually deduced from the interface or free surface velocities measured with velocity interferometers, such as velocity interferometer system for any reflector (VISAR),² photon Doppler velocimetry (PDV),³ and displacement interferometer system for any reflector (DISAR).⁴ PDV often uses short time Fourier transformation (STFT) to process data, and thus it is less sensitive to noise than DISAR and VISAR. However, Ref. 5 reports that PDV cannot resolve low velocities accurately due to limitations in STFT, which in turn reduce time resolution at low velocities because of the uncertainty principle. Particularly for low velocity experiments, PDV is not an ideal tool. As an improvement over PDV, a variation called up-converted PDV was developed.⁶ An up-converted PDV system has two lasers, and makes heterodyne detections, so we call it dual laser heterodyne velocimetry (DLHV) in this work. The stability of static beat frequency between two lasers is a key parameter directly related to precision of DLHV. We once found there were small drifts, jumps, and noise modulations in beat frequencies at microseconds scale sometimes, and these affects were unforeseeable and became worse for aged lasers or complex environments. This problem was disgusting for low but fast changing velocity measurements, so our goal is to use optical phase-locked loop (OPLL) in DLHV to fix the problem and to get higher velocity and time resolutions simultaneously.

Figure 1(a) shows the system layout of DLHV with an OPLL. A single wavelength fiber laser around 1550 nm and a tunable laser serve as the probe beam (ν_p) and the reference beam (ν_r), respectively. The probe beam passes through the fiber circulator, and illuminates a spot on the moving target through the probe. We denote the reflected light collected

by the probe as the signal beam (ν_s), carrying Doppler motion information of the target. In order to obtain the velocity, we measure the beat note (f_b) between the signal beam and the reference beam in DLHV, using a high speed detector. Noting the Doppler frequency shift, we have $f_b = |\nu_r - \nu_p - 2u/\lambda_0|$, where λ_0 is the probe beam's wavelength. If $(\nu_r - \nu_p)$ is a constant, we can extract velocity information by analyzing the frequency f_b in beat signals. According to the sign of $(\nu_r - \nu_p)$, DLHV has two working modes: the frequency-down-conversion (FDC) mode for $\nu_p < \nu_r$, and the frequency-up-conversion (FUC) mode when $\nu_p > \nu_r$ [Fig. 1(b)].

As shown by curve f_{dn} in Fig. 1(b), FDC mode brings down the beat frequency of a high speed signal with a base frequency of $(\nu_r - \nu_p)$. At present, this base frequency can be tuned from GHz (0.775 km/s) to THz (775 km/s) by grating or temperature interface of the tunable laser, so we can realize measurements of all velocities that loading means have achieved nowadays. Curve f_{up} of Fig. 1(b) shows beat frequency changes in FUC mode of DLHV. f_{up} rises from a non-zero frequency f_{base} , and it is of benefit to data processing with STFT. Numerical simulations find that STFT can use a shorter time window and get a better frequency resolution by shifting low frequencies up to higher frequencies. Therefore, this measuring mode helps f_{up} avoid low frequencies, and improves the velocity and time resolution in practice.

There is an assumption that f_{base} is a constant during the whole recording time. However, f_{base} is affected by temperature and current variations of lasers. A destabilization of a few MHz in the differential frequency was once found during several microseconds, corresponding to a velocity uncertainty of a few m/s for 1550 nm lasers. This is not acceptable for a transient, low velocity measurement which requires sub-meters per second precision. One could use an acoustic-optic frequency shifter to get high stable f_{base} , but it is impossible to obtain a base frequency over 1 GHz by this way. OPLL can achieve stable base frequencies above 10 GHz, which is beneficial to improve temporal resolution of DLHV, so this work introduces an OPLL to lock f_{base} at a constant.

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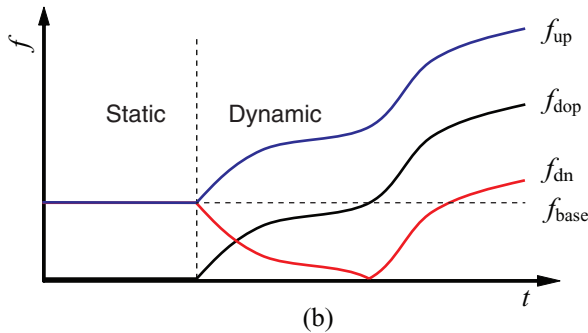
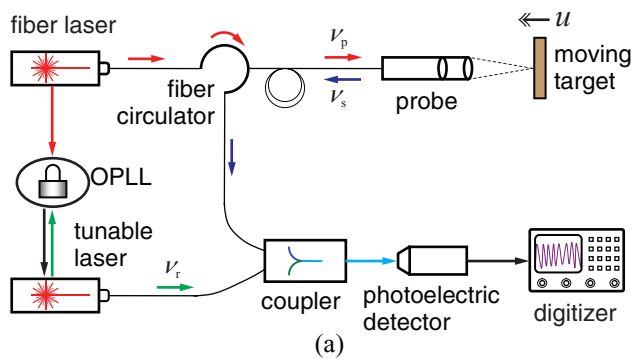


FIG. 1. (a) The configuration of DLHV with an OPLL. (b) Beat frequency curves in measuring processes. $f_{base} = |v_p - v_r|$ and $f_{dop} = 2u/\lambda_0$. f_{up} and f_{dn} are beat frequencies in FUC and FDC modes, respectively.

As shown in Fig. 1(a), OPLL receives optical signals from the fiber laser and the tunable laser, and generates an electrical signal to adjust the output frequency of the tunable laser to follow that of the fiber laser in real time. With OPLL technique, f_{base} can be fixed at sub-Hz level for a long integration time and at sub-kHz level for microsecond time scale,⁷ corresponding to 1 mm/s level velocity. This is particularly beneficial for dynamic low velocity measurements. Basic operations of OPLL are straightforward.^{7,8} The tunable laser in our work is an external cavity diode laser (ECDL), DL100 Pro manufactured by Toptica with a lock bandwidth 50 MHz.

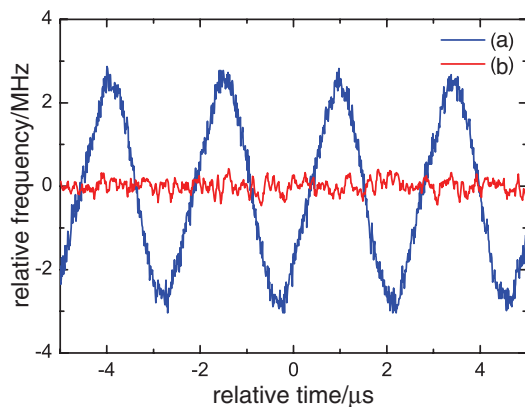


FIG. 2. Stabilization of f_{base} during a 10 μ s period. Curve (a) is the result of two free running fiber lasers with temperature tuning interfaces, with an unanticipated noise modulation at about 400 kHz. Curve (b) shows f_{base} from the fiber laser and a phase-locked ECDL by OPLL.

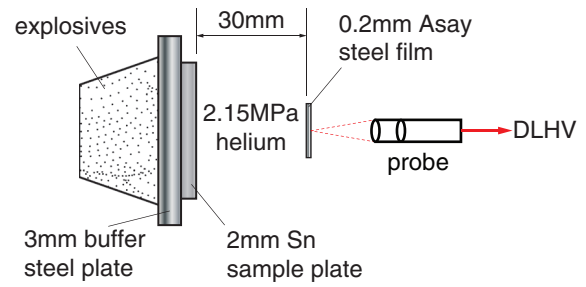


FIG. 3. Configuration of the explosive loading experiment. The Asay film is free under a dynamic loading. DLHV works in the frequency-up-conversion mode.

Figure 2 shows different stabilization curves of f_{base} between the locked lasers and free running lasers.

It is clear in Fig. 2 that the stabilization of f_{base} was improved significantly by OPLL. There was a noise modulation at about 400 kHz under the free running condition [curve (a)], resulting in a frequency change of about 4 MHz within 1 μ s. The main reason could be a noise modulation in the current of an aged fiber laser, and this issue can be serious after years of aging. This frequency change is harmful to a dynamic vibration measurement whose velocity is at 1 m/s level, because a frequency change of 4 MHz corresponds to 3.1 m/s in velocity with a 1550 nm probe beam. f_{base} described by curve (b) is more stable than curve (a), and its deviation is about 0.36 MHz. In addition, the frequency deviation of curve (b) was not completely from lasers, since there were also noise contributions from photoelectric detectors, digitizers, and data processing algorithms. A deviation of about 0.18 MHz was even found by us when a 100 MHz signal from a high stability analog signal generator (SMF100 from Rohde-Schwarz) was processed by STFT, so the stability of the locked beat itself was much better than 1 MHz. OPLL can attenuate the change of f_{base} , and then make measurements more accurate on fast-changing but slow movements.

To investigate the performance of the above method, we designed experiments to measure the elastic precursor in an Asay film.⁹ The setup is shown in Fig. 3. The explosives were detonated, inducing detonation waves propagating into the sample plate (Sn); ejecta were generated from the free surface of the sample along with a planar shock wave into helium. If the ejecta speed is slower than the shock wave in helium, the Asay film will be shocked by helium first, and then ejecta. The former may induce a low amplitude elastic wave trapped in the film. If the velocimeter is sensitive enough, an elastic wave reflected back and forth in the Asay film can be detected.

Three shots were done in all. Two of them were experiments with the chamber filled with helium about 2.15 MPa, and the other one was in vacuum. For the two helium shots, f_{base} was locked at about 15 GHz by OPLL, and the dynamic beat signals were received using 20 GHz photodetectors with a gain of 1.9 V/mW. Velocities were calculated using STFT and polynomial fitting algorithms. Velocity history curves extracted from the DLHV signals are shown in Fig. 4.

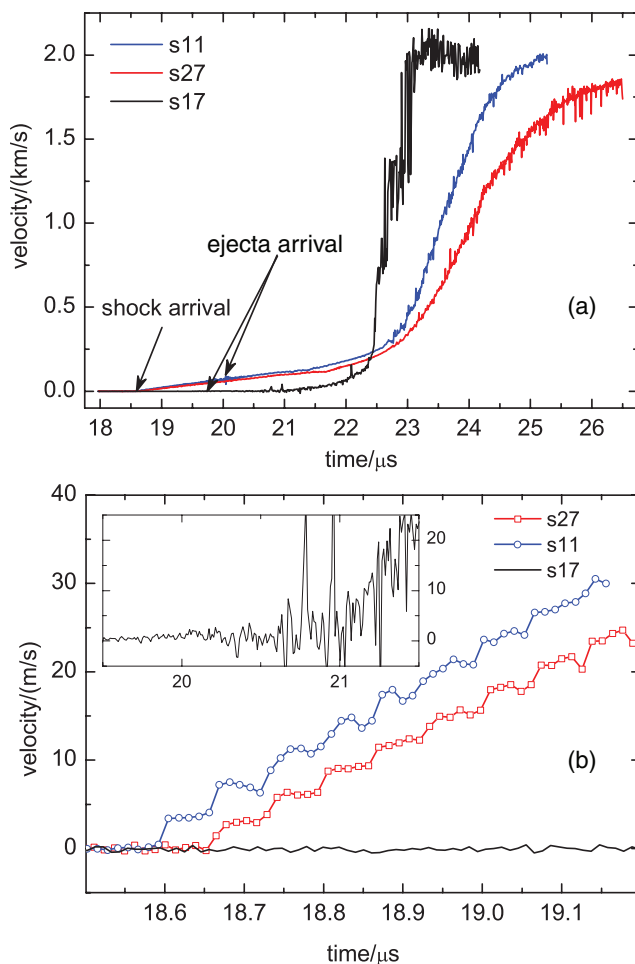


FIG. 4. The surface velocity histories of Asay films during the whole process (a) and before ejecta arrival (b). Helium was used in shots s11 and s27, and vacuum was adopted in shot s17.

Figure 4(a) shows the velocity histories of the whole process, from nearly the shock arrival at the surface of Asay films to the impact of Asay films by lots of ejecta. It is clear that the signal-to-noise (SNR) of helium filled experiments was better than the vacuum one. The shock in helium was obviously faster than the ejecta velocity in s11 and s27, so it hit Asay film first and induced slow motion of the films, and then the ejecta followed. [The ejecta impact caused small but noticeable motion, and the ejecta arrival can be identified from such plots as that shown in the inset to Fig. 4(b).] The Asay films moved for about one microsecond between the helium shock and ejecta arrival. The surface velocity curves of s11 and s27 were almost linear before ejecta arrival, owing to the constant acceleration from shocked helium [Fig. 4(a)].

There are periodic oscillations in the velocity curves of s11 and s27 [Fig. 4(b)], with an amplitude of about 2 m/s initially. This phenomenon is due to an elastic wave which was induced by helium shock, and reflected back and forth in the Asay film. The amplitude decayed upon each reflection. The periods of the oscillation deduced from the Fourier transformation are about 66.3 ns and 67.8 ns, for of s11 and s27, respectively. The corresponding elastic wave velocities are 6.0 km/s and 5.9 km/s. From the velocity curves of s11 and s27, a velocity resolution better than 1 m/s and a ns-level time resolution were achieved. In contrast, the velocity curve of s17 does not show periodic oscillations prior to or after ejecta impact [the inset to Fig. 4(b)]. Upon ejecta impact, the random ejecta arrival time and impact locations on the Asay film essentially smeared, in space and time, any periodic oscillation features that could have been present due to wave reflections in the film.

In conclusion, we have discussed a method using an OPLL to lock laser frequencies to stabilize the static base frequencies in heterodyne velocimetry, in order to get high precision and good time resolution for transient low velocity measurements. An uncertainty less than 1 MHz was demonstrated in the locked base frequency, which corresponds to a velocity uncertainty at 0.1 m/s level with a 1550 nm laser. Three shots were conducted to measure the elastic wave-induced vibrations on surfaces of steel films of submillimeter thicknesses. The amplitude of velocity fluctuation due to elastic waves was about 2 m/s, and the wave histories were well recorded and analyzed. However, the rise times of the elastic waves were not resolved very well owing to limited signal-to-noise ratio, which remains to be improved in the future.

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