Laser Doppler velocimeter using the self-mixing effect of a semiconductor laser diode

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A laser Doppler velocimeter (LDV) using a semiconductor laser diode (LD) with its self-mixing effect has been developed. A Doppler signal, caused by mixing a returned wave with an originally existing wave inside the LD, is detected with a photodetector in the LD package; it is also picked up from the variation of the LD driving voltage. When the returned light is weak enough, it confirms that there is no change in the single-mode oscillation and its spectral width of the LD. A LDV of this type is compact enough for many applications.

Laser Doppler velocimeters (LDV) have been developed with various configurations and for many uses. The most conventional configuration is the Michelson interferometer type in which, as shown in Fig. 1(a), the light beam emitted from a laser is divided into two: a reference beam and a signal beam reflected by a moving object. The two beams are combined and photodetected with homodyne detection. In this design, optical components such as a beam splitter, a mirror, and a photodetector are needed in addition to the light source. Furthermore, for mixing the reference and signal beams, carefully aligned optics is required.

In another configuration, a mixing effect is used where a small portion of the light reflected from the moving object is returned into a laser cavity and is mixed with the original oscillating wave inside the laser. The resultant beat wave is detected with the photodetector (PD) output. This scheme has been studied using a He–Ne laser,[1] as shown in Fig. 1(b). The lightwave emitted from the rear end of the laser was detected with a PD which gives the beat signal by mixing, demonstrating a self-mixing effect inside the laser.

More recently, a similar arrangement was employed for a LDV using the CO_2 laser,[2,3] but the frequency response for these two cases was about a few megahertz for the He–Ne laser and a few tens of megahertz for the CO_2 laser. These responses determine the upper limit of measured velocity for moving objects.

In recent years, the effects of optical feedback into the laser cavity have been actively investigated, mainly the stability of laser oscillation and the narrowing of spectral width. The change in the terminal voltage of the laser caused by reflected light was proposed as a pickup for optical memory,[4] but this change was due to the intensity modulation caused by the reflected light and not due to the frequency mixing inside the laser cavity. In the microwave region, a Gunn diode has been used as a mixer-oscillator for application to a Doppler radar,[5] in which the Doppler signal was picked up from the bias circuit of the Gunn oscillator.

In this paper we report that the LDV can be operated by using the self-mixing effect of the LD. This effect is experimentally examined and the fundamental characteristics of the LDV are presented.

The experimental setup used for the self-mixing type LDV is shown in Fig. 2. The beam emitted from the GaAlAs LD is collimated or focused by a microlens placed in front of the light-emitting end of the LD. The beam is reflected by a moving object, and a small portion of the scattered light is returned to the microlens and then reentered into the laser cavity. To verify the mixing of the original oscillating wave with the returned wave in the laser cavity, two methods are employed: to detect the resultant mixed wave by a PD placed outside the LD, and to detect a variation of the terminal voltage or driving current of the LD itself induced by the self-mixing. The former is similar to the method adopted for the He–Ne and CO_2 lasers. In the case of a LD, a PD is often accommodated in the LD package for monitoring the laser power emitted from the rear end of the LD. In our experiment, the PIN PD in the LD package was used for the detection. The latter case directly detects a signal with Doppler-shifted frequency through capacitance or inductance coupling to the driving voltage of the LD. In either

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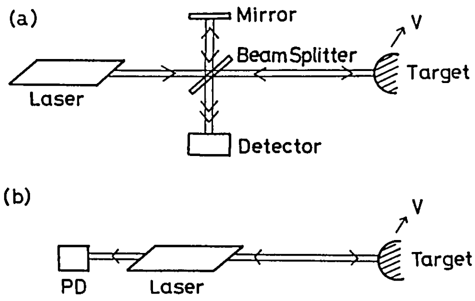

Fig. 1. Schematic configuration of the LDV: (a) Michelson interferometer type, (b) self-mixing type.

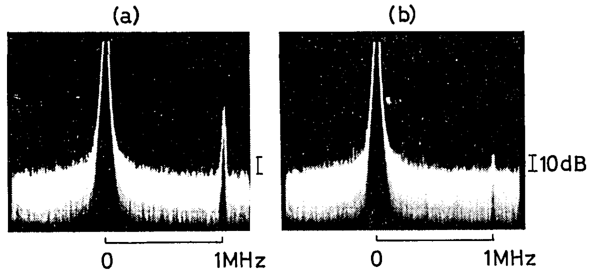

Fig. 3. Typical examples of Doppler signals displayed on the spectrum analyzer with a 10-kHz pass-bandwidth: (a) detected by PD, (b) picked up from the terminal output of the LD.

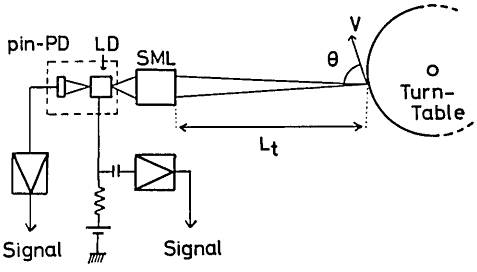

Fig. 2. Experimental setup of the self-mixing type LDV.

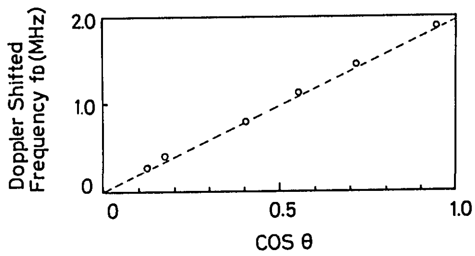

Fig. 4. Variation of Doppler-shifted frequency f_D with the angle θ, velocity of the moving object being constant. The broken line represents $f_D = 1.81 \times 10^{-6} \cos\theta$.

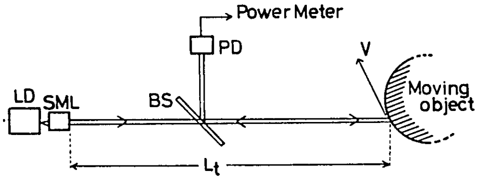

Fig. 5. Measurement setup for the returned light intensity.

case, the arrangement of the system becomes much simpler than that of the conventional system, particularly the additional optics.

Doppler-shifted frequency signals picked up from the electrical output of the PD or the terminal output of the LD can be displayed on the spectrum analyzer. Typical examples are shown in Figs. 3(a) and (b). The signal level in Fig. 3 (b) is lower than that in Fig. 3(a) owing to the low amplification of the circuit used. A similar result was obtained by detecting a part of the laser power emitted from the front end of the LD, instead of detecting from the rear end. The object used is a rotating turntable with rough white paper lapped around its side so that the scattering of the incident beam is almost nondirectional.

The Doppler-shifted frequency f_D is observed by changing rotating speed v of the turntable and/or the angle θ between the direction of the laser beam and that of the rotating velocity v, as indicated in Fig. 2. The theoretical expression for f_D in this case can be written as

$$f_D = 2v \cos\theta/\lambda, \tag{1}$$

where λ is the wavelength of light. For a definite value of v, one example for the change of f_D with respect to $\cos\theta$ is plotted in Fig. 4 for detection with the PD. The relationship observed between f_D and $\cos\theta$ is in good agreement with Eq. (1) for experimental values of $v = 0.71$ m/s and $\lambda = 820$ nm. The same relationship also holds for detection with the terminal voltage of the LD. Thus the self-mixing effect of the LDV is clearly confirmed.

In the present system, injection of the returned lightwave into the LD is essential. Therefore, it is important to clarify how the returned wave influences the oscillation spectrum of the LD. It is known that, if the returned light intensity is not weak, it gives rise to multimode oscillations of the LD. The intensity of the returned beam is strong only in special cases; for example, the reflecting surface of the object has a mirrorlike reflectivity and, in addition, its normal is parallel to the direction of the incident beam. Otherwise, a small part of the reflected beam returns to the LD. Hence the rough white paper used in this experiment can be considered as a typical object.

To measure the intensity of the returned light, as shown in Fig. 5, a half-mirror was inserted about midway between the microlens and the rough surface, to reflect a part of the returned beam to monitor its intensity with the PD. From the known reflectivity and transmissivity of the half-mirror, the relative intensity of the returned beam on the microlens can be evaluated, and it is varied with the distance L_t between the rough surface and the front end of the microlens placed near the LD, decreases in proportion to the inverse square of L_t as shown in Fig. 6. For any value of angle θ, the tendency is the same due to the nondirectional scattering of the rough surface. Thus the relative intensity of the returned beam is found to be lower than 10^{-3}%. For this low level, it has been con-

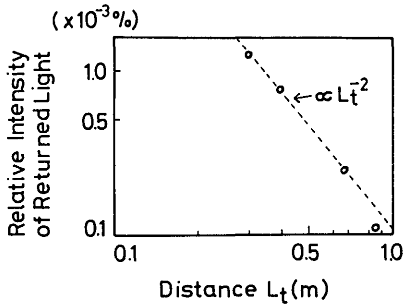

Fig. 6. Relative intensity of returned light on the microlens vs distance L_t.

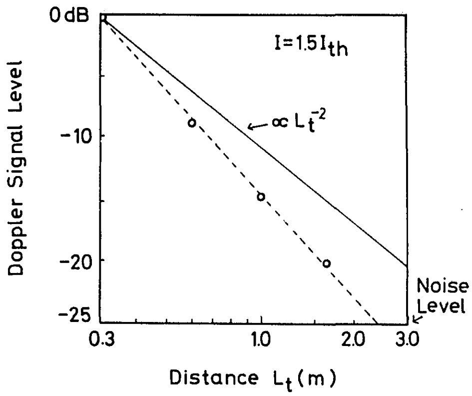

Fig. 7. Doppler-signal level vs distance L_t.

firmed with the optical spectrum analyzer that a single-mode oscillation of the LD is maintained.

The observed Doppler signal level also decreases with the distance L_t as shown in Fig. 7. Although the beam returned to the front end of the microlens is decreased with L_t^{-2} as described in Fig. 6, the signal level resultant from the self-mixing inside the LD is further lowered, giving an additional decrement, ΔL, of ~4.4 dB/m of L_t. As the beam travels twice the distance L_t, the decrement becomes 2.2 dB/m with respect to the optical path difference. If all this additional attenuation is attributed to deterioration of the degree of coherence with increasing optical path difference l_d, the coherence length l_c can be evaluated from[6]

$$\langle I_D(t,l_d)\rangle = \langle I_D(t,0)\rangle \exp(-l_d/l_c), \qquad (2)$$

where $\langle l_D(t,l_d)\rangle$ is the time average of the Doppler signal detected with the optical path difference l_d. From Eq. (2), the additional decrement ΔL (dB) is given by

$$\begin{aligned}\Delta L\ (\mathrm{dB}) &= -20 \log [\langle I_D(t,l_d)\rangle/\langle I_d(t,0)\rangle] \\ &= 20 \log(e)\cdot(l_d/l_c).\end{aligned}$$

From this, the coherence length l_c is estimated at ~4m.

The half-value halfwidth of the oscillation spectrum of the LD is written as $\Delta\nu = c/2\pi l_c$, where c is the light velocity. This gives $\Delta\nu \approx 12$ MHz, which is a reasonable value in accordance with those obtained so far for GaAlAs LDs.

These results show that the returned light is so weak that it has almost no influence on the oscillation mode and spectral width of the LD or on the fundamental characteristics of the LDV.

Conclusions about the self-mixing LDV are now summarized:

(1) The Doppler-shifted signals are detected from the output of the photodetector which receives either forward or backward emitting light from the LD.

(2) The Doppler signals can also be detected from variation of the terminal driving voltage of the LD.

(3) It has been confirmed that, for the objects yielding weak returned light to the LD, single-mode oscillation of the LD is maintained and, therefore, the coherence length and the half-value halfwidth of the oscillation spectrum are not degraded.

By employing this type of LDV, the arrangement of the system is compact enough for many applications, and the high velocity measurement limit can be extended due to the high-frequency response of the LD. Further studies are in progress.

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