Two-Dimensional Velocity Measurements With Self-Mixing Technique in Diode-Pumped Yb : Er Glass Laser

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***Abstract*—Self-mixing laser Doppler velocimeter based on a two beam geometry scheme is investigated using a single-frequency Yb : Er-doped phosphate glass laser. The geometry allows the observation of a beat mode with optical crosstalk between the two optical paths, giving two major improvements: 1) a precise positioning of the optical head compared to the scattering target; 2) the measurement of both the absolute value of the velocity and the orientation of the speed.**

***Index Terms*—Diode-pumped solid state laser, laser Doppler velocimetry (LDV), optical feedback, optical sensor.**

I. INTRODUCTION

CLASSICAL LASER Doppler velocimetry (LDV) is a well-established method for measuring the velocity in fluids or on light-scattering objects. The basic principle of LDV can be presented as an interference effect between two mutually coherent beams or as homodyne detection with frequency beating between a reference beam and a weak diffused part of a second beam which is Doppler shifted [1]. It must be pointed out that the technique allows measuring the transverse component of the velocity vector perpendicular to the optical axis of the sensor.

Compared to classical LDV, the self-mixing technique with Class B lasers has recently become a very popular technique for optical velocity measurement with the event of affordable and reliable Class B lasers like laser diodes [2] or microchip lasers [3], [4]. It is based on the dynamical perturbation of a laser due to the Doppler-shifted backscattered light reinjected into the laser mode. This technique has the advantages of being self aligned, simple, robust, and very sensitive because of the enhancement due to the laser oscillator. However, the main disadvantage is that the measured velocity component is now the longitudinal one, i.e., the velocity component projected along the optical axis of the laser beam. In some cases, this geometry is not practical, especially when measurements must be done on fluids flowing in pipes.

This letter illustrates how a multiplexing technique based on two-beam geometry can allow measuring the scalar velocity with self mixing (simultaneously both the longitudinal and the transverse velocity components). Already reported for the semiconductor laser [5], the technique is used for the first time with a diode-pumped solid state laser.

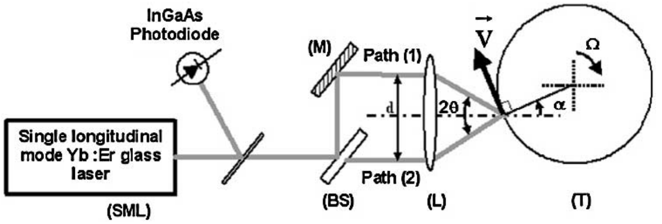

Fig. 1. Experimental setup. SML: single longitudinal-mode Yb : Er glass laser. BS: $50/50$ beamsplitter plate. M: adjustable mirror. L: photographic objective ($f = 50$ mm; NA $= 1.8$). T: rotating target.

II. EXPERIMENTAL SETUP

For an optical sensor based on self mixing, semiconductor lasers like distributed feedback or vertical-cavity surface-emitting lasers presents the advantage of very low cost, but they have limited sensitivity to optical feedback compared to monolithic or microchip solid-state lasers [6].

In this letter, a monolithic diode-pumped Yb : Er phosphate glass laser similar to the one reported by Laporta *et al.* [7] is used. Mini-Er glass lasers have the advantage of being eye-safe ($\lambda = 1.535\ \mu$m) and are characterized by a significantly longer emitting level lifetime ($\tau = 8$ ms) compared to other Nd-doped solid-state lasers which favor the feedback sensitivity. Current laser configuration is a hemispherical cavity longitudinally pumped with a 1-W broad-area laser diode (Spectra Diode Labs (SDL) model 6362, $\lambda_p = 962$ nm). The amplifying medium is a thin disc of QX-Er phosphate glass from Kigre (thickness $e = 710\ \mu$m) codoped with 0.8% Er^{3+} and 20% Yb^{3+} sensitizer ions. The back mirror is directly coated on the glass disc ($R = 99.8\%$ at 1.53 μm; $T > 90\%$ at 962 nm), whereas the output coupler is $T = 2\%$ transmission at 1.53 μm with a radius of curvature ROC $= 15$ mm. Cavity length is about $\ell = 12$ mm in order to reduce the photon lifetime and increase the sensitivity to optical feedback. For self-mixing velocimetry, it is more convenient to use a single frequency laser to avoid any mode beating that could affect the measurements. Therefore, an uncoated etalon ($e = 150\mu$m) is inserted into the cavity to obtain up to 6 mW of output power in single-frequency regime.

The schematic of the experimental setup is shown in Fig. 1. The output beam of the Er^{3+} laser was split into two beams using a $50/50$ beam splitter plate BS. The reflected beam (1) was realigned parallel to the beam (2) using mirror M. The two beams were separated by $d = 25$ mm and were finally focussed

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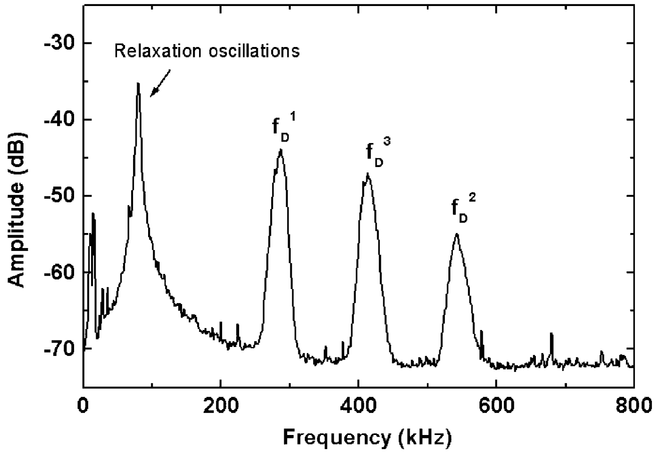

Fig. 2. Power spectrum showing the three frequency peaks at f_D^1, f_D^2, and f_D^3.

with a high aperture photographic objective ($f = 50$ mm; numerical aperture NA $= 1.8$). The focal plane corresponds to the overlapping region and is positioned right on the scattering edge of a rotating disc (radius $R = 40$ mm) mounted on the axis of an electric motor. The edge is covered by white paper and can be considered as purely diffusive surface. A home-made optical tachometer allowed us to check in real-time the angular rotation speed Ω and, therefore, the velocity using $v = R\,\Omega$.

Part of the laser output was picked up and monitored using a fiber pigtailed fast InGaAs photodiode (Thorlabs, D400-FC). Finally, the detected signal is analyzed using a digital oscilloscope (Tektronix model 2012) or a spectrum analyzer (Hewlett–Packard HP 8591).

III. EXPERIMENTAL RESULTS AND THEORETICAL INTERPRETATION

When the edge of rotating disc is exactly located at the focus point, a spectral analysis of the output intensity of the laser gives a radio-frequency (RF) signal similar to the one reported in Fig. 2.

The first peak observed around $f_R = 100$ kHz is present even without optical feedback and corresponds to the laser relaxation oscillations. The three other peaks located at f_D^1, f_D^2, and f_D^3 frequencies are due to the backscattered light frequency Doppler shifted. Their frequency positions depend on both the scalar value of the velocity v and also its angular orientation α. With the classical single beam configuration, only one beating signal would have been observed in the RF signal. Here, two of the three peaks, respectively, at f_D^1 and f_D^2 are attributed to light backscattered following the same optical path as the incidence beams [respectively, Paths (1) or (2)] as in the case of multiplexed measurements on different points on the target, as already suggested elsewhere [8]. On the other hand, the third peak at frequency f_D^3 is singular to our experimental setup. This original beating frequency corresponds to the crosstalk between the two beams. The frequency f_D^3 corresponds to an incident beam located on optical Path (1) and backscattered on the optical Path (2) or inversely. It only appears at the focus point and disappears as soon as the target is moved outside the focus point, as illustrated in Fig. 3.

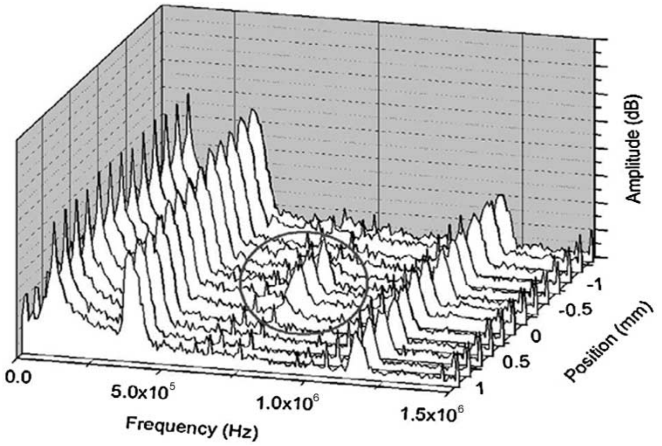

Fig. 3. RF spectrum versus the longitudinal position of the target showing the spatial selectivity. The circle is added to underline the third peak at frequency f_D^3.

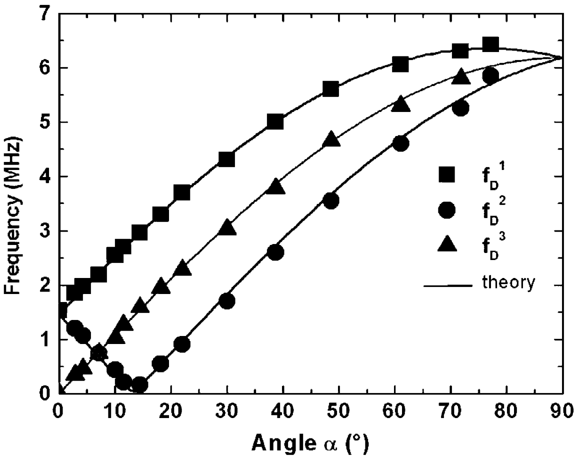

Fig. 4. Measured frequencies f_D^i (with $i = 1, 2$, and 3) versus the angular orientation α of the target ($\theta = 13.3°$) and comparison with theoretical calculations using (1).

The calculation of the three resulting beat frequencies f_D^1, f_D^2, and f_D^3 is straightforward using the different parameters defined in Fig. 1 and gives

$$\begin{aligned} f_D^1 &= \frac{2v}{\lambda}|\sin(\alpha+\theta)| \\ f_D^2 &= \frac{2v}{\lambda}|\sin(\alpha-\theta)| \\ f_D^3 &= \frac{2v}{\lambda}\sin(\alpha)\cos(\theta) \end{aligned} \tag{1}$$

where v is the absolute velocity, α is the angular orientation of the target displacement with respect to the optical axis of the setup, and 2θ is the angle between the two beams. Using the three f_D^i (with $i = 1, 2$, and 3) frequencies, it becomes easy to obtain the two parameters α and v independently. Fig. 4 reports the measured frequencies f_D^i (with $i = 1, 2$, and 3) versus the angular orientation α of the target. The theoretical curves calculated using (1) show a good agreement between theory and experiment. In fact, there is a redundancy of information (three frequencies (f_D^1, f_D^2, and f_D^3) for only two adjustable parameters v and α). However, it appears from (1) that f_D^3 is simply the average value of f_D^1 and f_D^2. Therefore, the frequency peak f_D^3 can be simply assimilated to a signature ensuring that the scattering target is correctly positioned at the focus point. In this

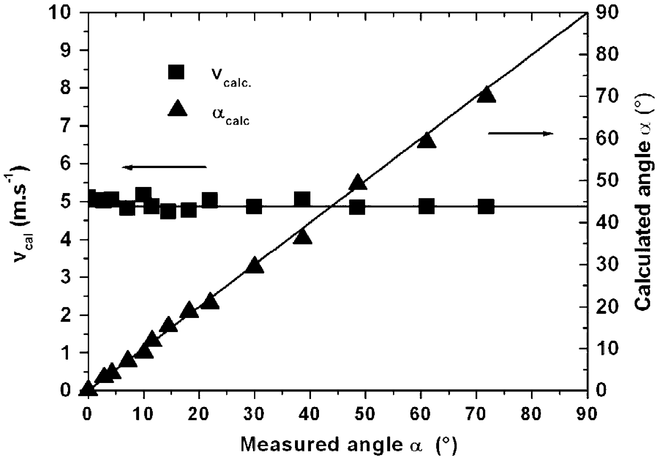

Fig. 5. Calculated values for v and α by using the three measured frequencies f_D^I ($i = 1, 2$, and 3) for various orientations of the target.

case, the frequencies f_D^1 and f_D^2 are attributed to correlated measurements made at the same point on the target.

Moreover, it is straightforward to deduce from (1) that the best compromise for the angle between the two beams would be $\theta = 45°$. In practice, it is limited by the objective aperture ($\theta = 13,3°$ in the present experimental setup), but could be increased using fiber components.

One can wonder if the beat frequency signal at f_D^3 can be really attributed to optical crosstalk between the two optical paths or if it is simply some nonlinear frequency mixing appearing into the laser dynamics because of a correlation between the two backscattered signals at f_D^1 and f_D^2 when the beams illuminates the same position. To check that point, an optical isolator (OFR model IO-2.5-l-VLP) was added on the optical Path (1). The optical diode allowed the incident beam (1) to illuminate the target but the light from the beam (1) could not be backscattered following the same optical Path (1). At the same time, the light from the beam (1) could still be backscattered following Path (2). When the optical isolator was added on Path (1), the peaks at f_D^2 and f_D^3 remained, whereas, the one at f_D^1 disappeared as expected if the effect was purely optical crosstalk. Similar conclusion has been also observed when the isolator is located on Path (2) (f_D^1 and f_D^3 remained, whereas, f_D^2 disappeared in this case).

IV. APPLICATION TO VELOCITY MEASUREMENTS

The main advantage with the novel setup is that the absolute velocity can be deduced whatever the orientation of the speed vector is. Using (1), the velocity v can be expressed using f_D^1, f_D^2, and f_D^3 following:

$$v_{\text{calc}} = \frac{\lambda}{2} \times \sqrt{\frac{(f_D^1 - f_D^2)^2}{4 \times \sin^2(\theta)} + \frac{(f_D^3)^2}{\cos^2(\theta)}}. \qquad (2)$$

Fig. 5 illustrates this point with the calculated velocity v_{calc} using the three f_D^1, f_D^2, and f_D^3 measured frequencies for different incident angles α and the same rotation speed Ω (the measured values used for these calculations are those already reported in Fig. 4 for consistency). Currently, the maximum measurable velocity is about 10 m/s to keep the beating frequencies close to the relaxation oscillation. But an extra frequency shifter can be added to significantly increase the dynamics of the velocimeter.

The signal–noise ratio is 20–30 dB on a cooperative diffusing target (Fig. 3) but decreases when the orientation α becomes higher than 80° because of too low backscattered signal.

It is obvious that the setup with two beams allowed us to calculate the scalar value of the velocity v independently of the angular orientation. Following similar arguments, it is also possible to determine the absolute orientation α of the speed vector in the plane containing the two beams as reported on Fig. 5.

V. CONCLUSION

This letter has described a novel method for self-mixing velocimetry based on two-beam geometry. In this scheme, the detected signal is formed by three beat frequencies and contains two main interesting advantages compared to classical optical velocity measurement technique.

1) It ensures a perfect alignment of the optical head of the sensor compared to the target.
2) It leads to an absolute measurement of the velocity in a two-dimensional plane, whereas, a classical technique like LDV or single-beam self-mixing just allows the measurement of one component of the speed vector.

Further improvements like directional discrimination can also be investigated by adding extra frequency shifting on one of the two beams using an acoustooptics modulator, for example.

REFERENCES

[1] F. Durst, A. Melling, and J. H. Whitelaw, *Principles and Practice of Laser-Doppler Anemometry*. New York: Academic, 1976.
[2] S. Shinohara, A. Mochizuki, H. Yoshida, and M. Sumi, “Laser Doppler velocimeter using the self-mixing effect of a semiconductor laser diode,” *Appl. Opt.*, vol. 25, no. 9, pp. 1417–1419, 1986.
[3] K. Otsuka, “Effects of external perturbations on LiNdP$_4$O$_{12}$ lasers,” *IEEE J. Quantum Electron.*, vol. QE-15, pp. 655–663, July 1979.
[4] R. Kawai, Y. Asakawa, and K. Otsuka, “Ultrahigh-sensitivity self-mixing laser Doppler velocimetry with laser-diode-pumped microchip LiNbP$_4$O$_{12}$,” *IEEE Photon. Technol. Lett.*, vol. 11, pp. 706–708, June 1999.
[5] M. Imamura, H. Sema, I. Yoshiyasu, and O. Mikami, “Self-mixed semiconductor laser velocimeter using two beam irradiation,” *Jpn. J. Optics (Kougaku)*, vol. 30, no. 11, pp. 748–753, 2001. in Japanese.
[6] E. Lacot, R. Day, and F. Stoeckel, “Coherent laser detection frequency-shifted optical feedback,” *Phys. Rev. A*, vol. 64, pp. 043 815-1–043 815-11.
[7] P. Laporta, S. Longhi, S. Taccheo, and O. Svelto, “Single-mode CW erbium-ytterbium glass laser at 1.5 μm,” *Opt. Lett.*, vol. 18, no. 1, pp. 31–33, 1993.
[8] K. Otsuka, “Ultrahigh sensitivity laser Doppler velocimetry with a microchip solid-state laser,” *Appl. Opt.*, vol. 33, no. 6, pp. 1111–1114, 1994.