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Doppler velocimetry using self-mixing effect in a short Er–Yb-doped phosphate glass fiber laser

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ABSTRACT Accurate and highly sensitive speed measurements have been successfully demonstrated by the optical feedback velocimetry technique using the self-mixing modulation effect in a double-clad Er–Yb-doped fiber laser. The sensitivity to back-scattered light has been investigated regarding the Doppler frequency shift or the target distance, and it has been shown that the velocimeter is still sensitive to a target located at 20 m and for speeds as high as 13 m s^{-1}.

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1 Introduction

Optical feedback perturbations in a laser oscillator have been demonstrated as an efficient optical sensing technique for different measurements, such as telemetry, velocimetry, or vibrational analysis [1]. This technique, also known as self-mixing, is intrinsically very efficient in single-frequency class B lasers, such as semi-conductor lasers (vertical cavity surface-emitting laser (VCSEL), distributed feedback (DFB), . . .) [2, 3] or Nd-doped microchip solid-state lasers [4]. In fact, the high sensitivity to optical feedback in a short laser cavity directly results from a short photon lifetime τ_c compared to the emitting level lifetime τ_f [5]. This explains why semiconductor or microchip lasers were first studied for optical sensing applications based on self-mixing.

The key idea consists of using the efficient intensity modulation of the laser output power due to the interference between the lasing field and the auto-coherent weak scattered field reinjected into the laser cavity mode. In velocimetry measurements, the scattered field is frequency-shifted by the Doppler effect on the moving target. The consequence is a strong modulation of the laser intensity at the beat frequency between the two fields, assuming that the fluorescence-to-photon lifetime ratio is high enough (class B lasers). Therefore, the self-mixing technique is characterized by a more sensitive response in contrast to traditional interferometric methods, allowing measurements on relatively poor cooperative targets. Another advantage is that the sensing system is self-aligned, which makes it very simple and robust.

Recently, a single-frequency mini Er–Yb-doped phosphate glass laser has been investigated for velocimetry measurements based on coherent optical feedback [6]. Mini Er glass lasers have the advantage of being eye-safe ($\lambda_s = 1.53\ \mu m$) and are characterized by a long emitting level lifetime ($\tau = 10$ ms) compared to an Nd-based solid-state laser ($\tau = 0.25$ ms), which is favorable to enhance the feedback sensitivity. On the other hand, phosphate glasses are attractive laser oscillators because they combine useful properties, such as high gain, low concentration quenching, low up-conversion losses, and a very high solubility for rare earth ions. These features permit a high doping level, resulting in a short pump absorption length and, hence, a small laser device with high efficiency.

Very recently, a first attempt to observe self-mixing in a fiber laser has been carried out using a DFB fiber laser [7]. However, this type of laser, even if its narrow linewidth is potentially interesting, might not be the most sensitive fiber laser to optical feedback. For instance, a comparative study of many laser diodes has shown that DFB laser diodes have only a high sensitivity if the equivalent output coupler reflectivity R_2 is low (i.e., $R \approx 0.25$) [1]. This means that one way to artificially reduce the photon lifetime and, therefore, enhance the sensitivity to optical feedback, involves using an output coupler with a high transmission coefficient. From the physical point of view, it simply allows a better coupling between the oscillator and the scattered light coming back from the target. However, the transmission coefficient of the output coupler is often limited by the gain into the amplifying medium.

To the best of our knowledge, self-mixing using a double-clad fiber laser in a standard Fabry-Perot (FP) laser cavity has not been explored so far. However, these systems are well known for their strong sensitivity to optical feedback, which is always considered as being an issue since it can lead to noise or self-pulsing in the fiber output. The main disadvantage of a fiber laser is obviously the long length of the cavity. Nevertheless, this issue can be overcome, firstly, by using an Er–Yb double-clad fiber (EYDF) and, hence, decreasing the pump absorption length and, secondly, by reducing the reflectivity

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of the output mirror, which is the second parameter acting on the photon cavity lifetime. For example, a fiber laser can use the 4% Fresnel reflection of the cleaved facet of the fiber as the output coupler. Moreover, since the output coupler also plays the role of a filter, a low reflectivity may also increase by more than 10 dB the quantity of reinjected light into the cavity. Another advantage of the fiber laser is the spatial quality of the laser beam, which is naturally nearly diffraction-limited when the fiber core diameter is small enough to authorize only a single transverse mode or when high-order transverse modes are suppressed using spatial filtering. This means a lower beam divergence after a careful collimation of the output beam and, hence, a better resolution for long-range measurements. The final advantage of such a laser source compared to microchip or bulk solid-state lasers is that it can be easily built using commercially available components coming from the optical telecommunications market. It is a reliable laser source with almost no maintenance, perfectly adapted for optical sensing applications.

The main purpose of this paper is to demonstrate the possibility of using self-mixing in a fiber laser while keeping the high sensitivity to feedback required for a laser Doppler velocimeter based on the self-mixing effect.

2 Experimental setup

The experimental setup is shown in Fig. 1. The fiber laser configuration used in our experiments consists of an Er–Yb-doped double-clad fiber (EYDF) and an external cavity comprising a collimating lens of 4.5-mm focal length and a diffraction grating in a Littrow configuration in order to provide wavelength-selective feedback. The EYDF, fabricated using the standard modified chemical vapor deposition (MCVD) process, had a phosphosilicate core of 11-μm diameter, with high Er^{3+} and Yb^{3+} concentrations and 0.21 NA, and was surrounded by a pure silica inner-cladding of diameter 125 μm (NA ∼0.49). The EYDF was pumped by a fiber pigtailed laser diode at 980 nm with 500 mW of maximum power (HTOE, model G098PU11500m). The pump light was coupled into the fiber through a perpendicularly cleaved end-facet via an arrangement comprising a dichroic mirror with high reflectivity at 980 nm and high transmission at 1.5–1.6 μm, and a focusing lens of 9-mm focal length. The end-facet served as a 4% output coupler. The use of a large diameter (multimode) core has the disadvantage that the beam quality is degraded due to multimode transverse lasing. To suppress lasing on higher-order modes, a short length (∼10 cm) of standard telecommunications fiber with a core diameter of 8 μm was spliced onto the EYDF end adjacent to the external cavity. This fiber is single-mode at 1550 nm, and has a high-index coating that suppresses light in the cladding. Besides mode selection, additional advantages are that it reduces amplified spontaneous emission (ASE) and prevents unabsorbed pump light from being reflected back into the fiber. The EYDF was bent into a figure of eight (curvature radius ∼2 cm) in order to improve the overlapping of the pump modes with the fiber core, and allowed the reduction of the fiber length by increasing the pump absorption coefficient.

A small part (4%) of the output light was reflected onto a beam splitter and was detected by a fast InGaAs photodiode (Thorlabs, model D400-FC) and the corresponding electric signal was delivered to a radio-frequency (RF) spectrum analyzer with the resolution bandwidth set to 10 kHz.

3 Results

3.1 *Optimization of the laser cavity*

The key point to reduce the photon lifetime of this laser and keep a simple arrangement is to reduce the fiber length (and, hence, the cavity length L_c) while keeping a 4% reflection as the output coupler. For that purpose, two possibilities can be considered to maintain the high gain necessary for the laser oscillation. The first is to increase the ion doping level of the fiber core, but this is limited by the ion solubility in addition to induced losses, such as strong background losses or losses by up-conversion processes. Therefore, a second solution is to artificially increase the absorption coefficient along the double-clad fiber by increasing the core-to-cladding diameter ratio. However, one of the consequences is the increase of the Yb population inversion under pumping and, therefore, a saturation of the Yb to Er energy transfer when using a typical Yb/Er concentration ratio with a value between 10 and 30. In that case, the gain into the doped fiber might not be high enough to allow a lasing effect with a 4% output coupler. In fact, optimizing the laser cavity requires considering

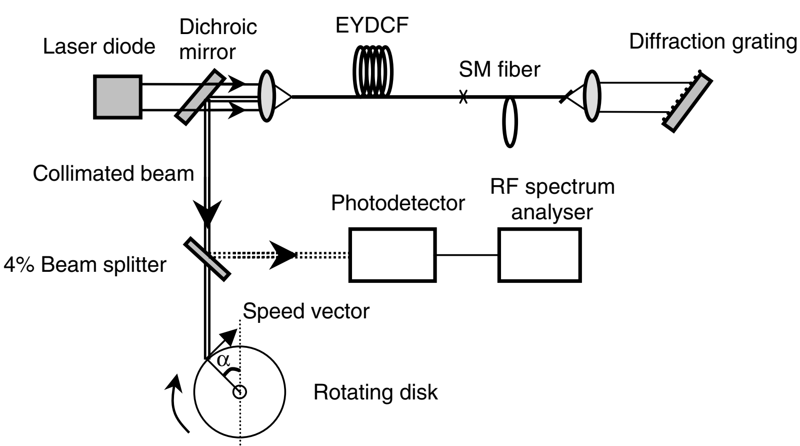

FIGURE 1 Experimental configuration for the self-mixing fiber laser Doppler velocimeter

Laser	L_c	R_2	τ_f	τ_c	τ_f / τ_c
Fabry-Perot laser diode	350×10^{-6}	0.35	1×10^{-9}	2.2×10^{-12}	4.5×10^{2}
Nd-doped microchip [5]	2×10^{-3}	0.99	2.5×10^{-4}	6.6×10^{-10}	3.8×10^{5}
Er–Yb-doped mini laser [6]	12×10^{-3}	0.98	1×10^{-2}	4×10^{-9}	2.5×10^{6}
EYDF Laser	**0.3**	**0.04**	$\mathbf{1 \times 10^{-2}}$	$\mathbf{6.2 \times 10^{-10}}$	$\mathbf{1.6 \times 10^{7}}$

TABLE 1 Predicted optical feedback sensitivity based on the ratio between emitting lifetime τ_f and photon cavity lifetime τ_c for some class B lasers

with special attention the energy transfer between the Er and Yb. Indeed, the energy transfer efficiency depends on several parameters, such as pump wavelength, Er and Yb concentrations, and core-to-cladding diameter ratio. If one of these parameters is not well chosen, the laser effect can be highly compromised by one of these three effects: (i) too slow energy transfer if ion concentration is too low; (ii) a saturated energy transfer if the Yb/Er concentration ratio is too high;or (iii) an insufficient Er population inversion if this ratio is too low. All these effects obviously limit the gain.

By testing some fibers with different ion concentration, we found that the fiber that was best optimized for short devices (i.e., with the lower laser threshold at a given fiber length) has an Yb concentration of 6.3×10^{20} cm^{-3} and an Yb/Er concentration ratio of 10. We had access to higher values for the concentration ratio but, in that case, we had to use a longer length of fiber. The physical reason for decreasing this concentration ratio is that a fiber which is short with respect to the pump absorption length has a high level of population inversion and leads to energy transfer saturation, as explained above. Using this fiber, the total length of the cavity was 30 cm, comprising 14 cm of doped fiber and 9 cm of single-mode fiber. The photon cavity lifetime is, therefore, equal to ~600 ps, which corresponds to a 1-mm-thick Nd-doped microchip laser with a 1% transmission output coupler (see, for instance, [5]). Therefore, as shown in Table 1, the long length of our laser arrangement is not really detrimental to the feedback sensitivity, especially as the erbium ion emitting lifetime is long compared to other rare earth ions like Nd. The prediction of the feedback sensitivity using the fluorescence-to-photon lifetime ratio as the criteria also shows that our system should be the most sensitive among the laser systems given in Table 1. However, this comparison of the intrinsic sensitivity of class B lasers to optical feedback is only valid close to the relaxation oscillation frequency and becomes less accurate far away from this resonance. Therefore, it might have a limited impact in the case of Doppler-based velocimetry, since the beating frequency linearly increases with the speed and cannot be kept close to the resonance.

3.2 *Sensitivity to reinjected light*

The first experiments were carried out in order to qualitatively evaluate the device sensitivity. To keep the fiber laser emission spectrum reasonably narrow, the current of the pump laser diode was adjusted slightly above the fiber laser threshold, corresponding to an output power of the order of few mW at $\lambda = 1550$ nm. The resulting laser spectrum was measured with an optical spectrum analyzer (Ando AQ6315E) and the typical linewidth was close to 0.1 nm. The output beam sent on a moving target was carefully collimated in order to avoid any broadening of the beating frequency peak due to the spatial distribution among different incident angles. An example of the power spectrum of the modulated beam output is shown in the Fig. 2. The low-frequency peak P_{RO} corresponds to the relaxation oscillations ($P_{RO} = 150$ kHz), whereas the second peak P_S is due to the self-mixing effect and is centered on the Doppler shift. Additionally, a third peak P_H corresponding to the second harmonic of the main signal can appear if the reinjected light intensity is too high. With a rotating disk covered by a layer of white paper and located at a distance equal to 50 cm, we achieved a maximum signal-to-noise ratio (SNR) of 46 dB, which is much higher than the values obtained using a VCSEL laser diode [3] or a mini Er–Yb-doped phosphate glass laser [6]. Varying the laser output power in the range 0.5–5 mW did not significantly change the SNR and one can then conclude that the SNR depends more on the relative fraction of the emitted light intensity reinjected into the cavity after being scattered on a diffusing object rather than on the absolute back-scattered light power.

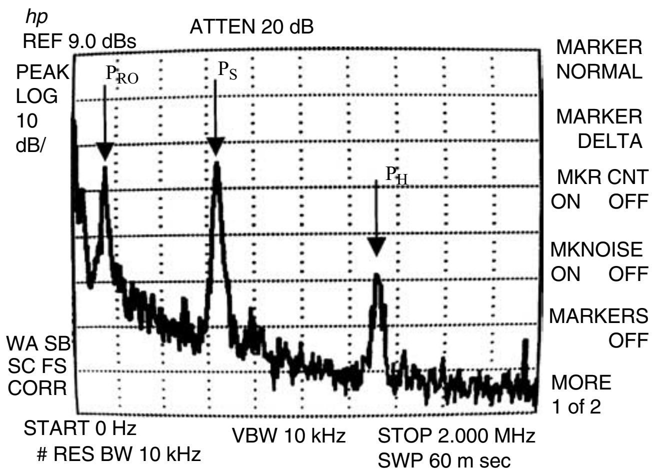

FIGURE 2 Power spectrum of the laser output modulated by the beating frequency. (*Vertical axis*: 10 dB/div, *horizontal axis*: 200 kHz/div)

Figure 3 represents the SNR as a function of the detected Doppler frequency shift. This was obtained by measuring the rotation speed of the disk while keeping the setup adjustment constant. Therefore, the SNR gives the sensitivity of the device when the beating frequency peak retreats far away from the relaxation oscillation peak. With the present configuration, the maximum frequency that we were able to measure was 16 MHz, corresponding to a speed of 13 m s^{-1}. One can also notice that the SNR tends to reach a constant value close to 25 dB and this lets us hope that a higher frequency and, hence, a higher velocity might be detectable.

The measured speed V is the tangential component of the speed vector and is directly proportional to the measured

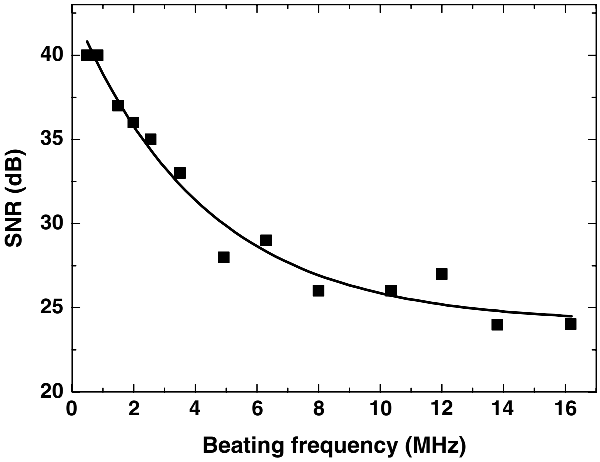

FIGURE 3 Measured SNR versus laser beating frequency

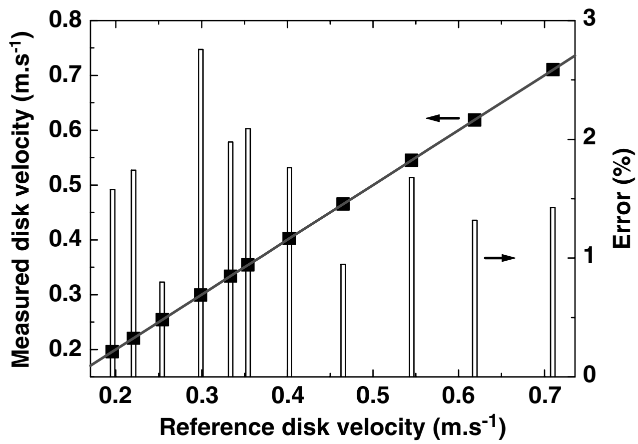

FIGURE 4 Measured velocity and relative error as a function of the target longitudinal reference velocity using the laser Doppler velocimeter

Doppler frequency f_m:

$$V = \frac{\lambda f_\mathrm{m}}{2\ \sin(\alpha)}$$

where α corresponds to the angular orientation of the incident beam compared to the rotating disk (see Fig. 1) and λ is the laser wavelength. The modulation frequency f_m was measured for different voltages applied on the electric motor controlling the rotating disk. To check the accuracy of our measurements, an optical tachometer was fixed directly on the rotating disk and allowed to directly measure its speed. The comparison between the two measurements is shown in Fig. 4. The results obtained using the beat frequency are in good agreement with those obtained with the tachometer, confirming the possibility of using self-mixing in a fiber laser for Doppler optical velocimetry. The root mean square (RMS) deviation corresponding to that shown in Fig. 4 is equal to 1.7%. This relative error largely comes from the imprecise measurement of the angle α and the resolution of the RF spectrum analyzer. Indeed, by adjusting the angle value, the RMS deviation can be decreased to 0.9%. This remaining error is probably due to experimental errors and shows that electronic processing has to be improved in order to allow better accuracy for the frequency measurement. One can also note that speeds lower than 0.2 m s^{-1} could not be measured. This is due to a strong interaction with the oscillation relaxation peak and, hence, laser instabilities preventing any measurements.

In order to test the sensitivity to the reinjected light, the SNR was measured for different distances between the laser and the target. The results are presented in Fig. 5a. The SNR corresponding to the detected frequency peak seems to present a linear evolution with the target distance. Considering that the amount of reinjected light decreases like the inverse of the squared distance, the evolution of the SNR should be logarithmic if the response of the laser oscillator is linear. However, because of the inevitable beam divergence, it is difficult to keep a good level of accuracy in the signal frequency measurement over a long distance. With a collimating lens of 8.6-mm focal length, the increase of the beam diameter after a few meters leads to a broadening of the frequency peak (because the target is a rotating disk) and, hence, deteriorates the measurement accuracy. It might also contribute to the decrease in the SNR. However, this issue does not occur when the speed vector is collinear to the laser beam and we noticed that no peak broadening is present if the a target is moving perpendicularly to the laser beam. Another series of experiments in which the rotating disc was replaced by a planar target with a similar surface (i.e., white paper) moving along the optical axis of the laser beam has shown that no peak broadening is present. Moreover, in that specific case, the target was still detectable at a distance of 20 m with a frequency peak of more than 10 dB SNR. This result confirms the high sensitivity to back-scattered light and its potential use for instantaneous speed measurements on targets moving in a large distance range, which is not achievable with standard systems using a laser beam focused on the target.

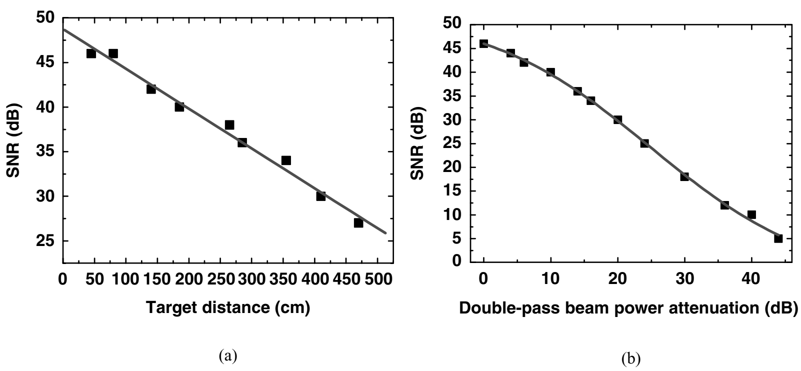

FIGURE 5 Measured SNR versus target distance (**a**) and beam power attenuation (**b**)

To test the response of the fiber laser, a series of neutral density filters were inserted in the beam path in order to attenuate the amount of reinjected light in the laser cavity. The evolution of the SNR with respect to the double-pass beam power attenuation is given in Fig. 5b. One can conclude that the dependence is not linear since it decreases slowly at the beginning, roughly following a sigmoid curve. This is, therefore, in agreement with Fig. 5a and confirms, as expected, that the laser cavity reacts in a nonlinear way.

4 Conclusions

In this paper, we have demonstrated a highly sensitive and novel laser Doppler velocimeter based on a short Er–Yb-doped fiber. This system has shown the ability to scan the speed of a target located up to 20 m from the laser. Because of the high sensitivity, this can be achieved without focusing the beam on the target, which is an improvement compared to other systems based on self-mixing. Further improvements, such as reducing cavity length by optimizing the features of the doped fiber are underway and we also expect that single-frequency operation would improve both the stability of the system and its sensitivity. Considering the simplicity, the robustness, and the low cost of fiber laser technology, as well as the eye-safe character of the Er emission, it appears very attractive to investigate in more detail the potential of self-mixing in these systems for different sensing applications.

REFERENCES

1 G. Guiliani, M. Norgia, S. Donati, T. Bosch, J. Opt. A: Pure Appl. Opt. **4**, S283 (2002)
2 S. Shinohara, A. Mochizuki, H. Yoshida, M. Sumi, Appl. Opt. **25**(9), 1417 (1986)
3 P.A. Porta, D.P. Curtin, J.G. McInerney, IEEE Photonics Technol. Lett. **14**(12), 1719 (2002)
4 R. Kawai, Y. Asakawa, K. Otsuka, IEEE Photonics Technol. Lett. **11**(6), 706 (1999)
5 K. Otzuka, IEEE J. Quantum Electron. **QE-15**(7), 655 (1979)
6 L. Kervevan, H. Gilles, S. Girard, M. Laroche, IEEE Photonics Technol. Lett. **16**(7), 1709 (2004)
7 O. Hugon, E. Lacot, F. Stoeckel, Fiber Integr. Opt. **22**(5), 283 (2003)