Absolute distance measurement using heterodyne optical-feedback on Yb:Er glass laser

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Abstract: Absolute distance measurement based on optical feedback using a single-frequency Yb:Er glass laser is demonstrated via the combination of heterodyne detection and frequency sweep. The technique allows enhancing the sensitivity of the laser response to self-mixing thanks to resonant excitation close to the relaxation oscillation frequency peak. The experimental results on non-cooperative target are in good agreement with the theory and the shape of the resulting signal is analysed both in the temporal and frequency domains considering the specific dynamic of the class B solid-state laser. Suggestions are provided for further improvements on the signal processing.

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Introduction

Optical techniques for distance measurements present many advantages compared to other methods like allowing non contact measuring processes and being non intrusive for the studied target. Therefore, different optical techniques have been developed in the past and are nowadays widely used in the industry for control and automation and for scientific or military purposes. Among the different optical sensors already available, the interferometric techniques usually present a spatial resolution significantly enhanced compared to incoherent methods like triangulation or time-of-flight. On the other hand, an interferometer is significantly more difficult to set up with complex mechanical alignments and necessity to use single frequency lasers with ultra narrow emission spectrum for long range finding applications. Moreover, the loss of coherence on a non cooperative target (diffusive instead of reflective) can only be compensated via a spatial filtering on the detection. It leads to very low amplitude of the detected signals and must be coupled to very efficient signal processing like photon counting. To significantly simplify the optical set-up and to filter both spatially and temporally the optical signal from a diffusive target, one elegant way consists to use the self-mixing (or optical laser feedback) technique. This technique is based on the very high sensitivity of class B lasers (solid-state or semiconductor lasers) to small optical feedback [1, 2]. This effect, being well known as a parasitic effect for many laser physicists, could also become a very useful tool to develop new optical sensing techniques. In this scheme, the laser cavity plays simultaneously four roles: (i) a coherent light source, (ii) an interferometer, (iii) an optical mixer with simultaneously spatial/temporal filtering functions and (iv) an optical preamplifier. Moreover, it is naturally self-aligned and do not need any parallax corrections because the optical lenses used to collimate the emission are reciprocally used for the reception.

Two configurations can be employed to obtain a distance measurement via an optical feedback on a laser source:

- without frequency shift between the emission and the reception, the technique is usually referred as laser feedback interferometry (LFI) [3]. The measurement is obtained through the detection of any variations in continuous wave regime like on the output power, the optical frequency or the polarization of the laser when it is submitted to the optical feedback.

- introducing a frequency shift between the emission and the optical reception via an optical modulator, the technique is usually referred as heterodyne detection. The detection is done on the beating note and could be analyzed using a lock-in amplifier with a reference provided by the modulator to measure the phase difference which is proportional to the distance.

In self-mixing, the heterodyne detection is specially adapted with class B lasers. Class B lasers are described by a photon decay rate inside the cavity γ_c significantly higher than the population inversion decay rate γ_1 ($\gamma_c >> \gamma_1$). The main consequence is that the dynamic of such lasers is characterized by very strong relaxation oscillations after a time dependant perturbation [4]. As soon as the beating note between the oscillating wave inside the cavity and the back-reflected wave is close to the relaxation oscillations frequency of the laser, the response to back reflected light is strongly enhanced. A very small amount of light re-injected into the cavity mode (typically few photons per optical cycle due to the feedback) becomes enough to significantly perturb the dynamic regime of the laser and allow a measurement.

A way to compare the relative sensitivity of different class B lasers to heterodyne optical feedback consists to introduce a factor of merit K [5]. It depends both on the properties of the amplifying medium and the geometry of the cavity and could be defined as:

$$K = \frac{\gamma_c}{\gamma_1} = \frac{\tau_1}{\tau_c} \qquad (1)$$

where τ_1 is the fluorescence lifetime of the emitting level, τ_c is the photon cavity lifetime. The decay rates γ_c and γ_1 which have been already defined above in the definition of a class B laser are simply the inverse of the related lifetimes. The figure of merit K reflects the relative amplitude of the modulated signal when the beating frequency is close to the relaxation oscillation frequency.

Among the different class B laser sources already investigated for self-mixing, semi-conductor lasers have been mainly used because of their low cost and high reliability [6-11]. For example, De Groot et al. [12] have done absolute distance measurements based on self-mixing with a laser diode. The optical frequency emitted by the laser diode was swept using a ramp modulation on the current injected into the laser junction. The resulting beating note between the emission and the back reflection was directly proportional to the time-of-flight. Measuring the beating frequency allows to measure the distance. However, the resulting beat note was far away from the relaxation oscillation frequency and therefore, the system was not very sensitive. The main consequence of this poor sensitivity is a very limited dynamic range. On the other hand, compared to laser diodes, solid-state lasers are potentially more sensitive to optical feedback because the figure of merit K is up to 10^3 times higher due to the very long emitting lifetime (typically τ_1=100 µs to few ms with rare earth or transition ions whereas the emitting lifetime is only few ns in the direct energy gap III-V semiconductors) [5,13-14].

In the heterodyne scheme, the benefit from the exaltation provided by the specific dynamic of class B lasers can only be fully exploited by adjusting the beating frequency to the relaxation oscillation frequency via an external modulator. In general, solid-state lasers present a relatively low relaxation oscillation frequency (between few hundred kHz up to few MHz) which could be indeed very easily reached. Laser diodes present relaxation oscillations up to few GHz.

Such high frequencies could be difficult to obtain via classical modulator (except with high speed electro-optic modulator). Finally, the quality factor of the resonance is lower with a laser diode compared to the resonance with a solid-state laser, as reflects the figure of merit K.

To obtain a distance measurement using optical feedback on a solid-state laser, two approaches have been already investigated. The first approach developed by E. Lacot et al. [15-17] is based on heterodyne detection and phase shift measurement between the beating signal and the reference one applied to the external modulator. A relative distance measurement could be obtained using an unwrapping phase technique. However, an absolute distance measurement is not allowed with this method. The second approach, proposed by P. Nerin et al. [18] is directly adapted from the distance measurement techniques already described with laser diodes. The technique reported in [18] is based on a linear wavelength sweep using an electro optic $LiTaO_3$ modulator implanted directly into a Nd:YAG microchip laser. However, depending on the measured distance, the frequency beating varied between few kHz and few MHz and therefore could not be kept close to relaxation oscillations frequency.

In the present work, the two techniques are combined in order to obtain an absolute distance measurement with a frequency beating note close to the relaxation oscillations frequency. An external acousto-optic modulator creates a frequency shift close to the relaxation oscillations frequency as in classical heterodyne approach. Simultaneously, the instantaneous frequency emitted by the laser is linearly shifted versus time (linear sweep) by scanning the cavity length with a piezoelectric transducer. Added to the external shift imposed by the modulator, this scanning creates a slight frequency detuning between the emission and the feedback. This frequency detuning is therefore proportional to the time-of-flight between the laser and the target. It allows a very sensitive measurement of the absolute distance as well as an extended dynamic because it keeps the beating note close to the relaxation oscillations.

The first part of the paper details the experimental set-up used for this absolute distance measurement. The optical properties of a diode pumped Yb^{3+}:Er^{3+} phosphate glass laser are reported as well as its frequency tuning capabilities. The second part presents a theoretical study leading to a linear relationship between the beating note frequency and the distance. The third part compares the experimental results obtained using the Yb^{3+}:Er^{3+} glass laser with the theory. The amplitude and shape of the detected signals versus the measured distance are also investigated. Finally, the conclusion contains a synthesis of the main results obtained and suggests improvements on the signal processing and on the optical set-up that could improve the global performances of the system.

Experimental setup

The experimental set up used for the investigations of distance measurements based on heterodyne optical feedback is schematically drawn in figure 1. The laser source is a diode pumped Yb^{3+}:Er^{3+} doped phosphate glass [19]. The laser configuration consists of a simple hemispherical cavity with a short cavity length (L=7.5 mm), longitudinally pumped at 980 nm with a 1.5 W fibre-pigtailed laser diode (Roithner, reference G098PU11500M). The gain medium is a thin QX phosphate glass disc supplied by Kigre (thickness e=710 µm) co-doped with 0.8 % Er^{3+} and 20 % Yb^{3+} [20]. Among the different solid-state laser materials commercially available, Er-doped phosphate glass is selected for three main reasons. First, the $^4I_{13/2}$ emitting level of Er^{3+} ions in phosphate glass is characterized by one of the longest fluorescence lifetimes (τ_1=8 ms) among the different rare-earth doped solid-state lasers (for example τ_1=250 μs for Nd:YAG). Selecting a long lifetime favours the sensitivity to optical feedback by increasing the factor of merit K [21]. Moreover, the emission wavelength of erbium doped phosphate glass laser is around λ=1.54 μm which corresponds exactly to an eye-safe spectral domain. Therefore, no specific care in terms of laser security has to be used when the laser beam is sent in free atmospheric propagation. Finally, such gain medium has been already used to fabricate low cost, mass produced microchip lasers which is an important issue to consider for final potential applications [22].

The hemispherical cavity consists of a plane mirror (R=99.8 % @ 1.53 μm; T>90 % @ 980 nm) directly coated on one facet of the glass plate. The other facet of the disc is antireflection coated (T>99 % @ 1.55 μm). The concave output coupler has a radius of curvature equal to ROC=15 mm. As a selective element for single longitudinal mode (SLM) laser emission, a 150 μm thick uncoated etalon is inserted inside the cavity, near the amplifying medium. The output power in SLM regime is typically equal to P_s=12 mW for a pump power equal to 500 mW. To improve the long-term stability of the cavity, all the optical components are inserted without any mechanical adjustments (except for the longitudinal position of the output coupler) into a monolithic home-made mounting structure.

The output mirror is glued on a ring-piezoelectric transducer (PiezoMechanic, model HPST 150/14-10/12 VS22) to sweep the laser output frequency by scanning the cavity length. For a linear dependence of the frequency sweep versus time, the PZT is polarized using a triangular signal delivered by a low frequency generator (Hameg, model HM8030 5). The frequency modulation f_m applied to the PZT should be kept below 200 Hz in order to avoid unstable behaviour of the output power emitted by the laser. Such intensity noise fluctuations are probably due to loss cavity modulations when the output coupler is scanning too quickly. A

Fabry-Pérot (FP) spectrum analyser (Burleigh, model RC-46 with a free spectral range equal to 2 GHz) is used to calibrate the frequency sweep versus the applied voltage ramp. The modulation depth of the optical frequency is measured equal to 1.4 GHz/V for a 7.5 mm long laser cavity. Moreover, the FP spectrum analyser is also used to check that no longitudinal mode hop appears along the frequency sweep. To avoid any mode hop, the frequency sweep amplitude is voluntary limited to a typical range of $\Delta\nu_{opt}$=10–12 GHz, corresponding to a peak-to-peak voltage ramp of 7 to 8.5 V.

The output beam is carefully collimated and sent through an acousto-optic Bragg cell (Isomet, model 1205C-843) for amplitude modulation. The amplitude of the acoustic wave supplied by the Bragg cell driver can be externally driven using a sinusoidal signal from a function synthesizer (Hewlett Packard, model HP 8654A). For a sinusoidal modulation with a frequency ν_{AOM}, the amplitude modulation creates on the zero-order two symmetrical side-bands on both sides of the optical carrier. Therefore, the AOM creates two frequencies respectively at $\nu_{laser}(t)\pm\nu_{AOM}$, slightly shifted from the optical carrier frequency $\nu_{laser}(t)$ which is the instantaneous optical frequency emitted by the laser before the modulator. The external modulation frequency ν_{AOM} is adjusted close to the relaxation oscillation frequency of the laser (typically ν_{AOM}~150-300 kHz) to enhance the sensitivity to optical feedback (see part 3, experimental results).

The frequency difference between the internal oscillating wave and the heterodyne optical feedback creates a beating note inside the laser cavity which modifies the laser dynamic. To detect the resulting time dependant perturbation, 15 % of the output light is extracted using an optical beam splitter and detected thanks to an InGaAs photodiode (PDA400, Thorlabs). The detected signal is sent either on a digital oscilloscope (Tektronix, model 2012) for temporal analysis and/or on a radiofrequency (RF) spectrum analyser (Hewlett Packard, HP 8591) for analysis in the frequency domain.

To demodulate near the frequency ν_{AOM}, the electric signal from the detector can also be connected to a high frequency lock-in amplifier (Princeton Applied Research, model 5202). The time response of the lock-in amplifier is adjusted below 100 ms during all the measurements. In this case, the reference signal for the lock-in amplifier is supplied by the signal driving the Bragg cell. After demodulation, the output signal is characterized by amplitude modulation at a low frequency due to the sweep imposed to the laser emission frequency. Selecting properly the time response of the lock-in amplifier, it is possible to keep this low relative frequency beating on the output signal while improving the signal-to-noise ratio. The frequency of the filtered signal depends on the voltage sweep applied to the PZT as well as on the time-of-flight between the emission and the optical feedback. Therefore, measuring the frequency of this demodulated signal gives rise to the distance between laser and target.

Theory

One of the classical techniques for absolute distance measurements with a coherent wave (either in the acoustic, radio frequency or optical domains) consists to sweep the emission frequency of a coherent source linearly versus time. It appears a difference between the emission frequency and its echo back-reflected on the target. This difference is linearly proportional to the time-of-flight τ which can be expressed as:

$$\tau = \frac{2D}{c} \qquad (2)$$

where D is the distance separating the laser and the target and c is the propagation wave celerity. Measuring the frequency difference through a beating between the emission and the echo allows determining the distance D.

Figure 2a illustrates this principle for an optical emission frequency $\nu_{laser}(t)$ modulated as a triangular function versus time. When using a semiconductor laser, the optical sweeping can be easily obtained by doing a ramp on the injected current into the laser junction [7]. In our optical set-up, the optical sweeping is possible thanks to the triangular signal applied on the PZT.

The beating frequency $\Delta\nu_{beat}$ depends simultaneously on the excursion of the laser frequency $\Delta\nu_{opt}$, on the sweeping period T and on the distance D. Typically, the scan on the PZT is limited to a low frequency regime to avoid strong instabilities in the laser emission. In this case, the resulting beating frequency $\Delta\nu_{beat}$ is less than few kHz for distance D of about 1m. This beating frequency is too small to benefit from the exaltation that allows the laser relaxation oscillations.

To take advantage of the specific dynamic of our class B solid-state laser, the beating frequency can be easily shifted near the laser relaxation oscillations by adding an external modulation. For example, in our set-up (figure 1), the shift is created by the AOM.

For lack of simplicity in the theoretical presentation, let us first assume that the external modulator only creates a single lateral band with a frequency shift $+\nu_{AOM}$ as shown on the figure 2b. The frequency of the back-reflected light will be different from the emitted one due to two combined effects:

-First shift imposed by the external modulator;

-Second shift due to the frequency sweep imposed directly on the laser emission.

On the figure 2b, the first effect corresponds to the frequency shift along the vertical axis whereas the second effect corresponds to the displacement along the horizontal axis.

The instantaneous frequency $\nu_{reinjected}(t)$ of the back reflected wave just before re-injection inside the laser cavity mode (that is to say near the output coupler) can be written as:

$$\nu_{reinjected}(t) = \nu_{AOM} + \nu_{laser}(t-\tau) \tag{3}$$

where ν_{AOM} describes the first effect and the time delay τ contains the second effect. The absolute beating frequency is given by:

$$\nu_{beat} = \left|\nu_{laser}(t) - \nu_{reinjected}(t)\right| \tag{4}$$

Following the temporal diagram of figure 2b, it becomes straightforward to express both $\nu_{laser}(t)$ and $\nu_{reinjected}(t)$:

$$\begin{aligned} \nu_{laser}(t) &= \nu_0 \pm 2 f_m \times \Delta\nu_{opt} \times t \\ \nu_{reinjected}(t) &= \nu_0 \pm 2 f_m \times \Delta\nu_{opt} \times (t-\tau) + \nu_{AOM} \end{aligned} \tag{5}$$

where ν_0 is the laser frequency at t=0, f_m is the modulation frequency of the triangular signal applied on the PZT (f_m=1/T) and $\Delta\nu_{opt}$ is the modulation depth on the laser emission frequency. The beat note frequency becomes simply:

$$\nu_{beat} = \nu_{AOM} \pm 2 f_m \times \Delta\nu_{opt} \times \tau \tag{6}$$

To clearly separate the effect due to the AOM from the one due to the frequency sweep applied on the laser emission, one can introduce a relative beating note frequency $\Delta\nu_{beat}$ (and represented on figure 2b):

$$\nu_{beat} = \nu_{AOM} \pm \Delta\nu_{beat} \tag{7}$$

By replacing the expression of τ given in formula (2), the relative beating frequency $\Delta\nu_{beat}$ can be directly expressed versus the distance D:

$$\Delta\nu_{beat} = \frac{4 f_m \times \Delta\nu_{opt}}{c} D \qquad (8)$$

Therefore, measuring $\Delta\nu_{beat}$ permits to determine the absolute distance D between the laser and the target whereas the external frequency shift ν_{AOM} due to the AOM ensures to obtain a beating frequency in the laser dynamic close to the relaxation oscillation frequency.

In practise, the amplitude sinusoidal modulation applied on the AOM creates two symmetric lateral bands at $\nu_{laser}(t) \pm \nu_{AOM}$. However, similar results are obtained except from two symmetrical beating frequencies are obtained on both sides of the external shift:

$$\nu_{beat} = \nu_{AOM} \pm \Delta\nu_{beat} \qquad (9)$$

The relation between the relative beating frequency $\Delta\nu_{beat}$ and the distance D remains the one expressed by formula (8).

Experimental results

The RF power spectrum of our frequency shifted re-injected laser is shown in figure 3. The peak which appears close to F_{YbEr}=200 kHz is characteristic to the intrinsic noise of our single frequency solid-state laser and can be observed without any optical feedback. It corresponds to the relaxation oscillation peak and its frequency can be related to the fluorescence lifetime τ_1, the photon cavity lifetime τ_c and the ratio between the current pump power and the pump power at threshold. Its value is typically similar to those already reported in the literature for Yb:Er glass laser [23]. On the other hand, the peak at a frequency ν_{AOM}=240 kHz is due to the optical feedback on a diffusive target consisting in an unpolished steel plate. It vanishes when the target is removed from the optical path of the output beam. Moreover, the frequency of the beating peak corresponds exactly to the frequency ν_{AOM} and can be precisely adjusted by controlling the frequency of the signal applied to the AOM. Even for a weakly cooperative target, its amplitude is at least 30 dB higher than the natural intensity noise of the laser. In order to check the sensitivity of our laser to the self-mixing effect, a series of neutral density filters was inserted between the output coupler and the AOM. Attenuation up to –80 dB between the emission and the back reflected light beam was added before the beating note near ν_{AOM} completely vanished. When the RF spectrum is spanned around this beating peak, the spectrum represented in figure 4 is obtained. Without triangular voltage applied to the PZT, that is to say without a frequency sweep applied to the laser emission, the beating peak corresponds to the classical heterodyne optical feedback technique (figure 4, dash curve). The phase of this self-mixing signal corresponds to the phase of the re-injected optical signal. As already demonstrated by E. Lacot et al. [15], it can be processed to obtain a relative distance measurement modulo $m\frac{\lambda}{2}$.

By adding to the external shift a linear sweep on the laser emission frequency via a triangular modulation of the voltage applied to the PZT supporting the output coupler, the beating peak splits into two symmetrical peaks, as shown in figure 4 (solid line curve). The frequency gap between the reference peak and one of these two peaks $\Delta\nu_{beat}$ contains the information about the absolute distance D between the laser and the target. Moreover the spike like structure on the solid line curve of figure 4 corresponds to a regular peak structure with a periodicity equal to f_m and can be attributed to the periodic modulation applied to the output coupler.

When the target is progressively moved along the optical path of the laser beam, the RF spectrum evolves as shown on figure 5a. The different curves reported in figure 5a were obtained for three different values of D using the following experimental parameters: f_m=100 Hz, $\Delta\nu_{opt}$ =1.62 GHz and ν_{AOM}=240 kHz. Figure 5a clearly shows that the relative beating frequency $\Delta\nu_{beat}$ increases proportionally to the distance D, as predicted in formula (8). Moreover, when the distance D increases significantly, the amplitude of the two beating signals tends to become weaker, as expected because less photon are re-injected back into the laser cavity. The two peaks observed in figure 5a appear to be characterized by an amplitude dissymmetry, with higher amplitude for the peak corresponding to the shortest frequency. This tendency illustrates the exaltation effect provided by the specific dynamic of a solid-state laser. As soon as the beating frequency due to the optical feedback becomes closer to the relaxation oscillation frequency, its amplitude significantly increases.

For a better characterization of the relative beating frequency, the detected signal has been further analyzed using a lock-in amplifier. Figure 5b illustrates the temporal evolution of the output signal from the lock-in detection which acts as an efficient selective frequency filter locked on the reference signal ν_{AOM}. The recorded signal has been obtained using the following experimental parameters: f_m=100 Hz, $\Delta\nu_{opt}$=1.65 GHz and ν_{AOM}=240 kHz.

As already mentioned, the amplitude of the beating frequency at $\nu_{AOM} \pm \Delta\nu_{beat}$ strongly depends on the external frequency shift ν_{AOM} which is an adjustable parameter controlling the AOM driver. To fully benefit from the exaltation effect provided by the specific dynamic of a class B solid-state laser, it can be very useful to adjust the AOM frequency ν_{AOM} close to the laser relaxation-oscillation frequency of the laser. This point is illustrated in figure 6 which represents the evolution of the relative amplitude of the signal (compared to the intrinsic intensity noise) versus the modulation frequency ν_{AOM}. It clearly appears that the amplitude presents a maximum near the laser relaxation-oscillation frequency. It means that the laser source acts as a selective pass-band filter centred on the relaxation oscillation frequency.

To improve significantly the efficiency of the heterodyne detection, it becomes interesting to adjust precisely the frequency shift near the resonant frequency of this filter, so near the relaxation-oscillation frequency (F_{YbEr}=200 kHz). Moreover, it also illustrates the advantage of using heterodyne detection (ν_{AOM}~200 kHz) instead of a classical homodyne approach like with LFI. To further illustrate the feasibility of an absolute distance measurement using this technique, the beating frequency $\Delta\nu_{beat}$ has been measured for a series of distances D using the spectrum analyser. The measurements are reported in figure 7 and have been done using similar experimental parameters than those already reported above (f_m=100 Hz, $\Delta\nu_{opt}$=1.65 GHz and ν_{AOM}=240 kHz). For each distance D, the relative beating frequency $\Delta\nu_{beat}$ has been measured and the corresponding distance calculated thanks to formula (8). The measured distance D has been compared to a reference obtained thanks to an industrial telemeter (Leica, model DISTO*TM* pro[4]). Figure 7 shows a good agreement between the distances measured using the optical feedback technique compared to the reference one. Moreover, compared to the measurement reported in the literature based on optical feedback with laser diodes, a significant improvement has been obtained on the dynamic of the distance measurement with a maximum distance measurement up to 10 m. This could be mainly attributed to a better sensitivity of solid-state laser compared to semiconductor laser when the feedback is close to the relaxation oscillation frequency.

In order to estimate the measurement precision, the output signal of the lock-in amplifier is sent into a frequency counter (HP 53131A). The frequency counter is externally triggered with the signal applied on the PZT. A time gate equal to 1 s is selected to average the measured frequency. It results a precision estimated equal to ≈ ± 2.5 mm for a distance of ≈ 1 m. This limited precision obtained nowadays is mainly attributed to the fact than only few periods of modulation appear on each ramp applied to the PZT. Therefore, better signal processing – in fact very similar to those applied in laser Doppler velocimetry (LDV) in which only few modulation are observed for each diffusive particles - could be useful to determine more precisely the frequency contained in such ramp. This could lead to a sub millimetre precision. However significant improvement is expected thanks to a better signal processing as well as restriction on the laser instabilities.

Conclusion

To summarise, an original approach to the problem of distance measurement using optical feedback on a single frequency solid-state laser has been investigated. It combines heterodyne detection based on an external frequency shift and a direct frequency sweep of the laser allowing an absolute distance measurement. The heterodyne detection uses a frequency shift obtained thanks to an external acousto-optic modulator and allows enhancing the sensitivity because of the specific dynamical response of the laser. This enhancement is due to the higher sensitivity of a class B laser to optical feedback when the resulting beating note is located near the relaxation oscillation frequency. To demonstrate the principle, a single frequency solid-state laser using QX Yb^{3+}:Er^{3+} phosphate glass laser has been used. The choice of this specific solid-state laser material is mainly based on arguments concerning its higher potential sensitivity compared to semiconductor laser or other solid-state laser like Nd-based ones. Moreover, its emission wavelength is centred into the eye-safe spectral domain and it is technologically possible to obtain single frequency microchip lasers using this gain medium. After a brief theoretical description of the beating frequency resulting from the combination of an external frequency shift and a frequency sweep directly applied to the laser, experimental results obtained have been systematically compared to the theoretical formulae and a good agreement between theory and experiments has been obtained. This technique allows absolute distance measurements on an extended range because of the enhancement provided via the heterodyning.

Further developments could also be investigated concerning this technique. First of all, the signal processing currently used to measure the relative beating frequency can be clearly improved by adjusting simultaneously the voltage ramp and its offset applied to the PZT. This adjustment must be done automatically via a control-loop to obtain no phase hop at the transient times between rise and decrease on the triangular voltage. In this case, the peak on the RF spectrum corresponding to the beating note should be narrowed and the distance measurement precision should become significantly improved. Finally, fine adjustments on the linearity of the frequency ramp applied to the laser frequency should be further controlled.

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Figures captions

Figure 1: Experimental set up : DO, digital oscilloscope; SA, RF spectrum analyser; LA, Lock-in-Amplifier; AOM, acousto-optic modulator; FLD, Fiber Laser Diode; G, Yb:Er glass; E, etalon; OC, output coupler; L, L_1, L_2, lenses ; BS, beam splitter ; PZT, piezoelectric transducer , PD, InGaAs photodiode ; T, target.

Figure 2: Theoretical evolution of the optical frequency versus time: a) homodyne detection b) heterodyne detection: — laser frequency before the AOM; —•— frequency after the AOM; ---- reinjected into the laser by target.

Figure 3: RF spectrum of the detected signal in heterodyne detection without frequency sweep ν_{AOM}= 240 kHz.

Figure 4: RF spectrum of the detected signal in heterodyne detection: - - - - without frequency sweep; — with frequency sweep for D=35 cm, $\Delta\nu_{opt}$ =1.79 GHz and f_m=100 Hz. The bandwidth and the sweep time of spectrum analyser are respectively equal to 3 kHz and 1 s.

Figure 5: (a) Evolution of the RF spectrum versus the distance D; (b) Temporal signal for a target located at D=38.5 cm.

Figure 6: Evolution of the signal amplitude versus the modulation frequency applied to the AOM.

Figure 7: Comparison between the distance D deduced from the optical feedback measurement and a reference provided by an industrial telemeter.

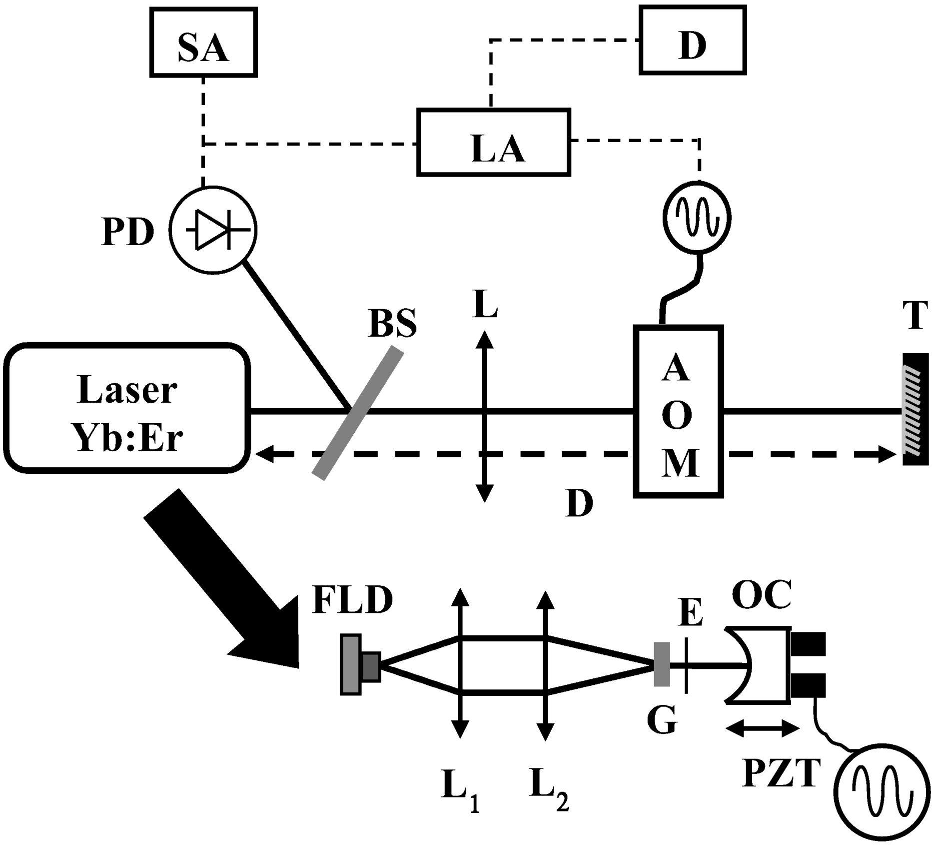


Figure 1 :

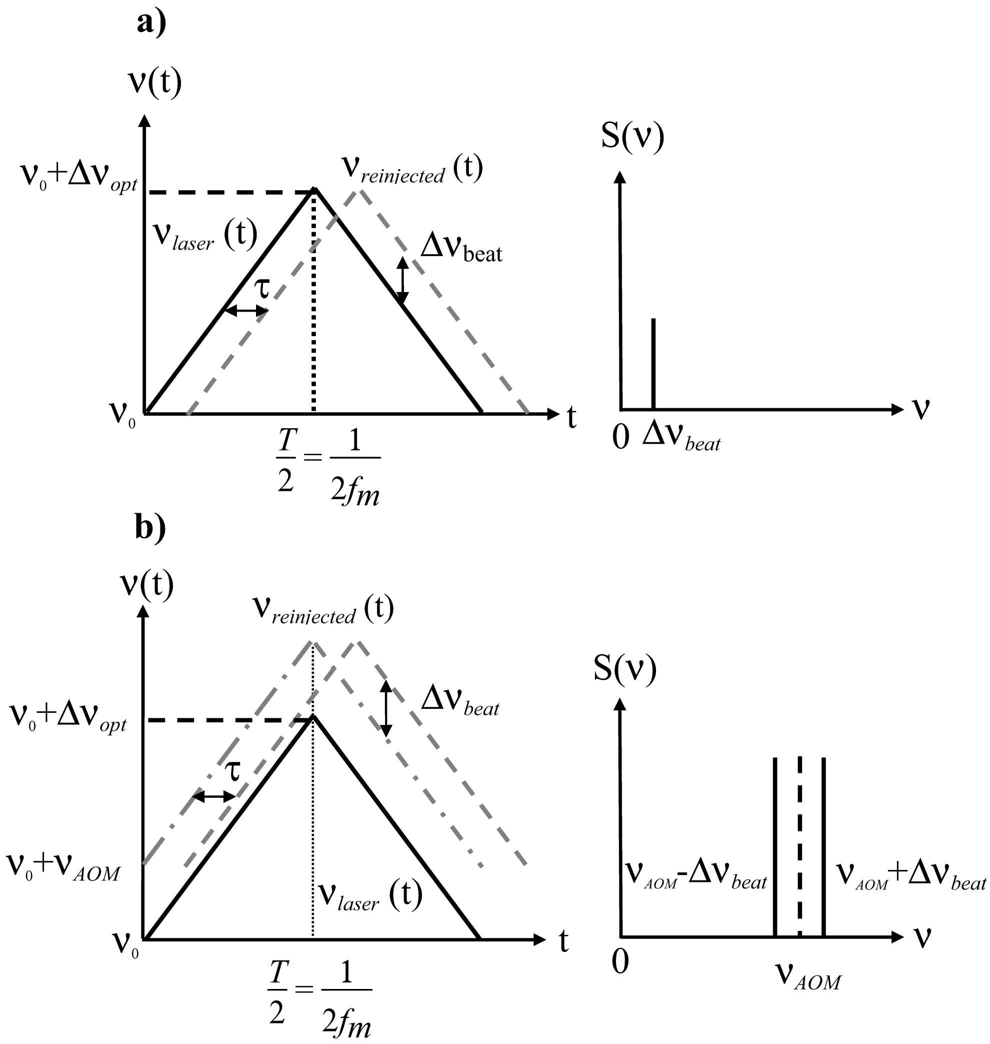

a)
ν(t)
ν₀+Δν_opt
ν_reinjected (t)
ν_laser (t)
Δν_beat
τ
ν₀
t
T/2 = 1/2fm
S(ν)
0
Δν_beat
ν
b)
ν(t)
ν_reinjected (t)
Δν_beat
ν₀+Δν_opt
τ
ν₀+ν_AOM
ν_laser (t)
ν₀
t
T/2 = 1/2fm
S(ν)
ν_AOM-Δν_beat
ν_AOM+Δν_beat
0
ν_AOM
ν

Figure 2

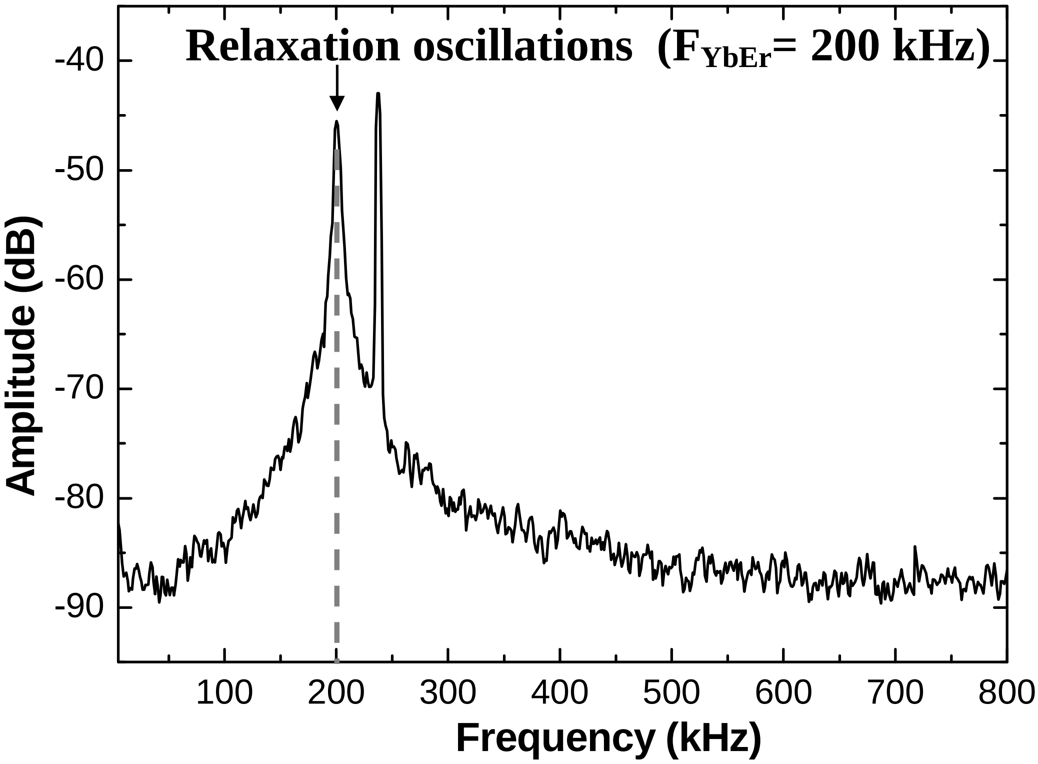
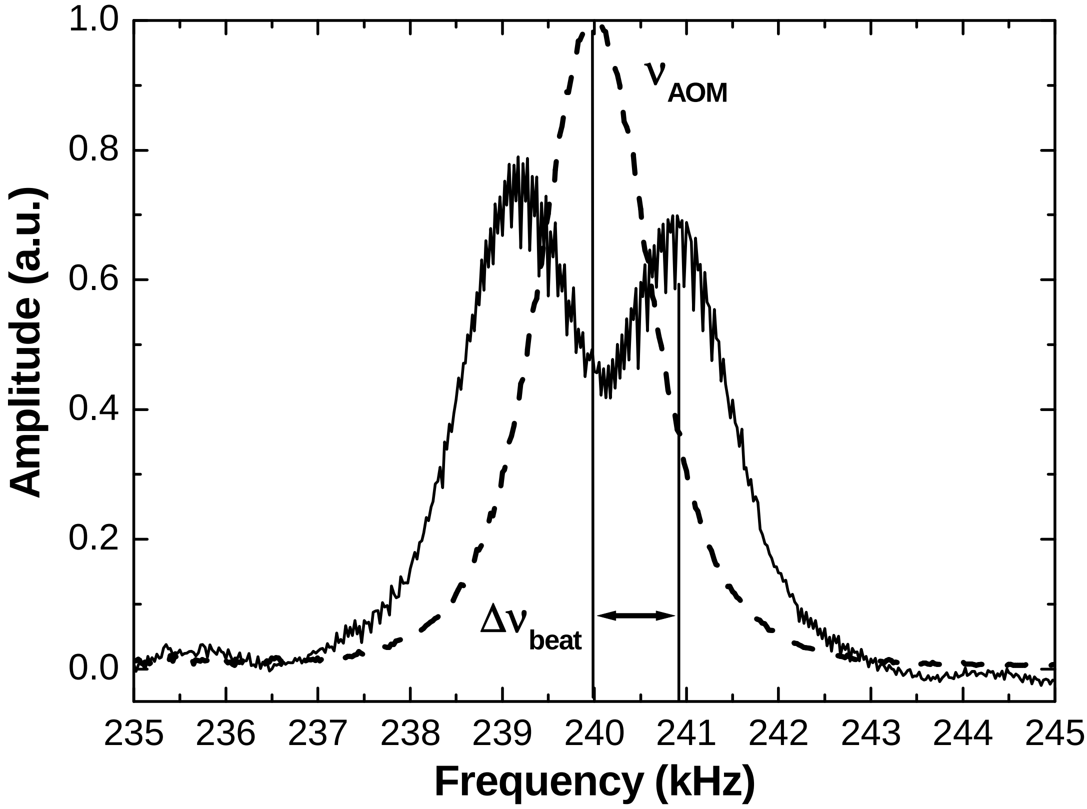
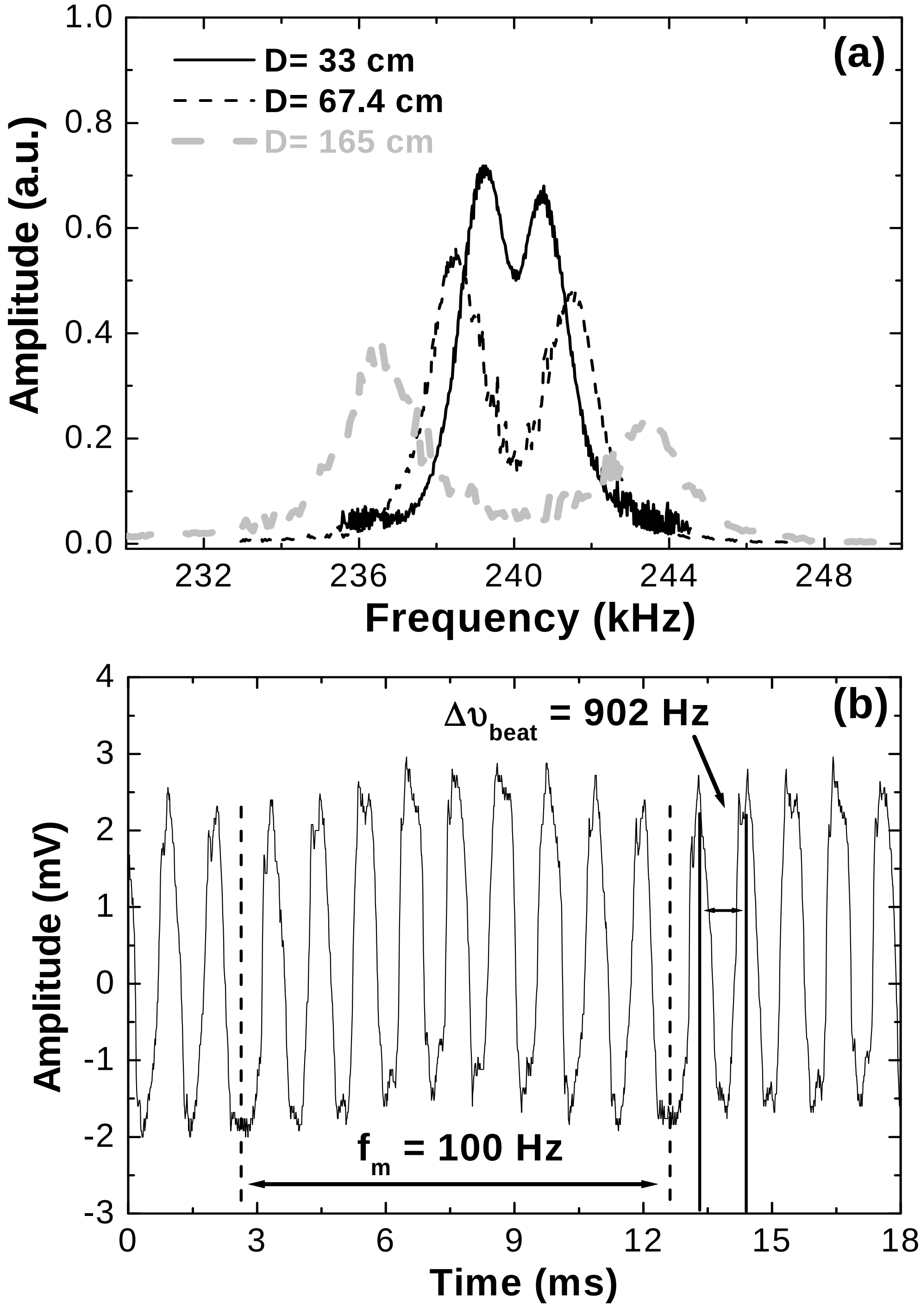

Relaxation oscillations (F_YbEr= 200 kHz)
-40
-50
-60
-70
-80
-90
Amplitude (dB)
100
200
300
400
500
600
700
800
Frequency (kHz)

Figure 3



1.0
0.8
0.6
0.4
0.2
0.0
Amplitude (a.u.)
235
236
237
238
239
240
241
242
243
244
245
Frequency (kHz)
ν_{AOM}
$\Delta\nu_{beat}$

Figure 4



(a)
D= 33 cm
D= 67.4 cm
D= 165 cm
Amplitude (a.u.)
Frequency (kHz)
1.0
0.8
0.6
0.4
0.2
0.0
232
236
240
244
248
(b)
Δυ beat = 902 Hz
f m = 100 Hz
Amplitude (mV)
Time (ms)
4
3
2
1
0
-1
-2
-3
0
3
6
9
12
15
18

Figure 5

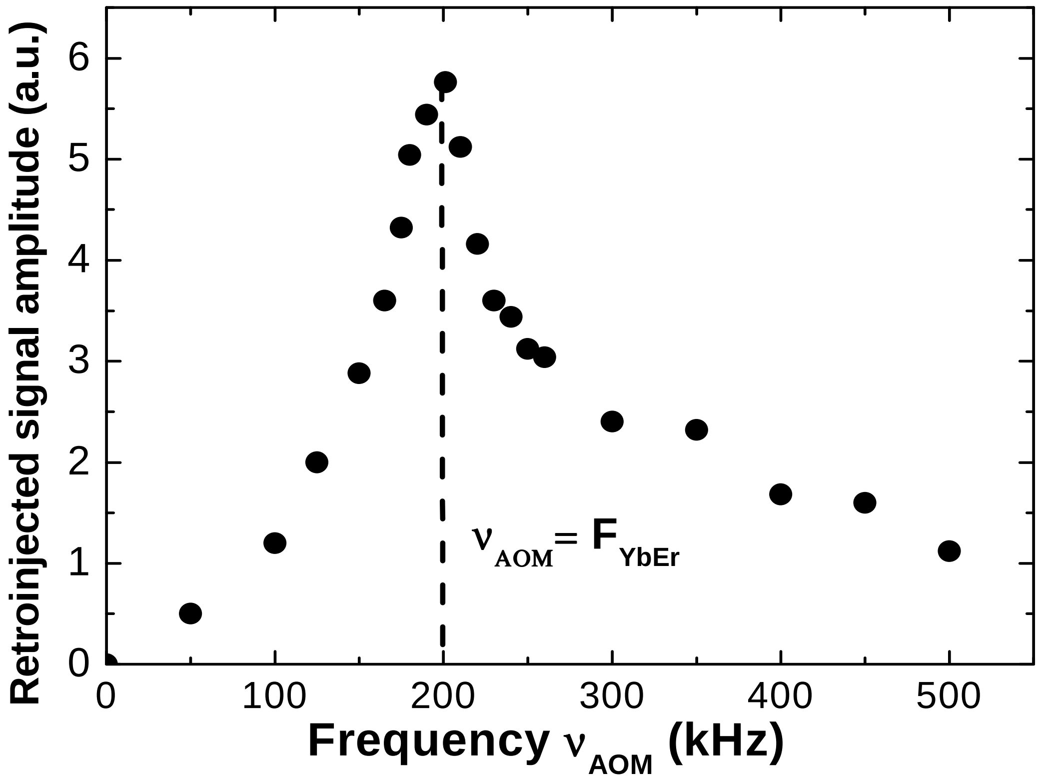

Retroinjected signal amplitude (a.u.)
0
1
2
3
4
5
6
0
100
200
300
400
500
Frequency ν_AOM (kHz)
ν_AOM = F_YbEr

Figure 6

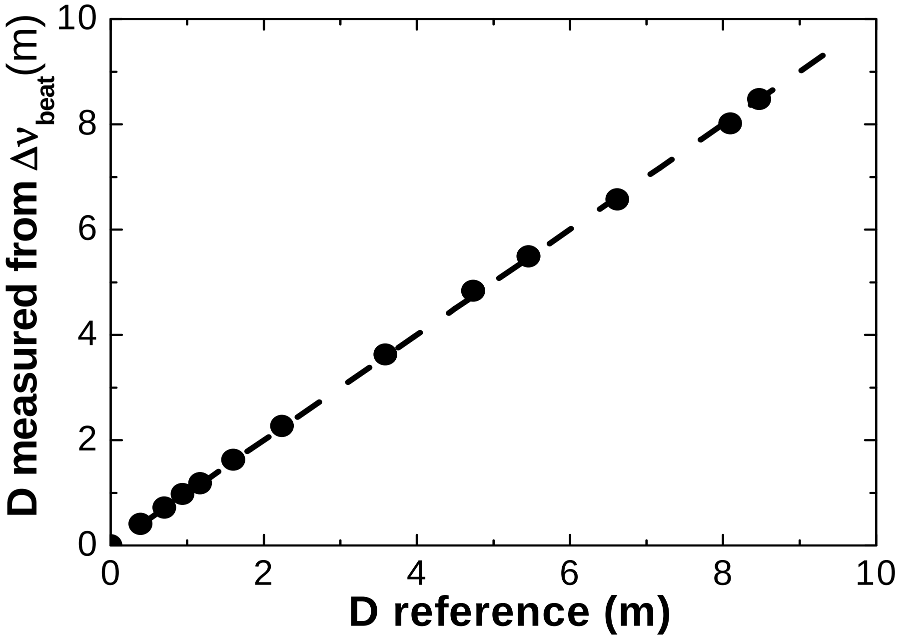


Figure 7