IEEE Instrumentation and Measurement
Technology Conference
Budapest, Hungary, May 21-23, 2001.

A low-cost, optical feedback laser range-finder with chirp-control

T. Bosch (*), S. Pavageau (**), D. d'Alessandro (***), N. Servagent (**),
V. Annovazzi-Lodi (***) and S. Donati (***)

(*) ENSEEIHT-LEN7
2, rue Charles Camichel, 31071 Cedex 7, Toulouse, France
Phone: 33 (0)5 61 58 82 82, Fax: 33 (0)5 61 58 82 37
Email: bosch@len7.enseeiht.fr

(**) Ecole des Mines de Nantes – Department of Automatic Control and Production Systems
4, rue Alfred Kastler, PO Box 20 722, 44307 Nantes Cedex 03, France
Phone: 33 (0)2 51 85 83 35, Fax: 33 (0)2 51 85 83 49
Email: sabrina.pavageau@emn.fr

(***) University of Pavia, Electronic Department
Via Ferrata 1, 27100 Pavia, Italy
Phone: 39 382 505 204/200, Fax: 39 382 422 583
Email: daless@ele.unipv.it

Abstract *– A new laser range finder using optical feedback interferometry and wavelength sweep has been developed. Our aim was to design a high-accuracy sensor for opration on short distances, using a low-cost Mach-Zender interferometer to separately measure the chirp of the laser. Experimentally, on a plain diffusing target, at a 10-cm distance, we were able to demonstrate an accuracy of 100*μ*m. Projected accuracy is down to 20-50* μ*m.*

Keywords *- Optical distance measurement, semiconductor laser, laser sensor, interferometry, ranging, optical feedback.*

I. INTRODUCTION

Optical feedback interferometry (OFI) is a viable technique to develop instrumentation [1] for distance [2-5], velocity [2],[6-9] and displacement measurements [10-13]. As it is well known, this particular setup offers advantage in cost and compactness as compared to conventional interferometry.

The main advantage of the OFI range finder, in comparison with the triangulation method, is that the set-up is inherently self-aligned, has stray-light immunity and no shadowing effects and has basically a minimum component-count.
As in a classical interfererometer, the distance of the target must be smaller than the half coherence length of the laser source. Narrow-linewidth laser diodes, like DBRs, have a coherence length up to tens of meters. At large distance, however, the feedback signal from a diffuser becomes very weak and the laser exhibits mode hopping on the external cavity, preventing operation of the OFI range finder.
As a result, the typical distance range shall be limited usually to several tens of cm.
In this paper, we present the principle of a new OFI range finder with optical chirp control, using a Mach Zehnder Interferometer (MZI) and a normal Fabry-Perot laser diode (LD) as the source.
First, we describe a configuration with the LD protected by an optical isolator from the MZI backreflections.
After assessing the performance of the new approach, we suggest how to eliminate the optical isolator, by developing a novel set-up that minimizes optical feedback due to the MZI, without sacrificing the resolution of the first version.
Experimental results are focussed on operation on white paper target at a distance of 10cm, however the range of measurement may go from a few cm to several tens of cm.

II. PRINCIPLE OF OPERATION

The schematic arrangement of the classical OFI range finder based on self-mixing is outlined in Fig.1. A single mode Fabry Perot LD is used as an active sensor [4], [15].

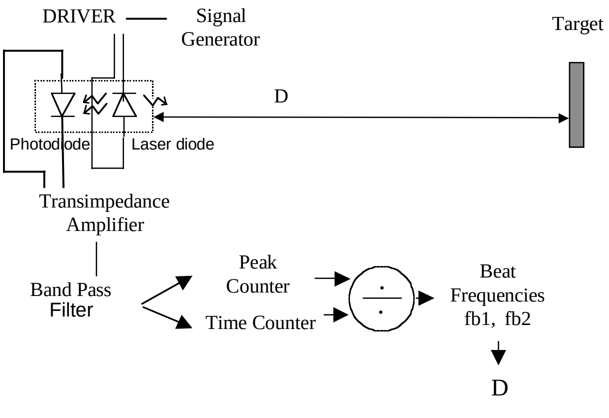

Fig. 1. Block diagram of a classical OFI range finder

The optical beam, back-reflected by a diffusing target into the laser active cavity, causes a modulation of both optical power and wavelength. The laser and the target act as a sort of 3-mirror Fabry-Perot cavity [4]. By modulating the injection current with a triangular signal, periodic spikes appear in optical power, which can be detected with the aid of the monitor photodiode included in most LD packages.

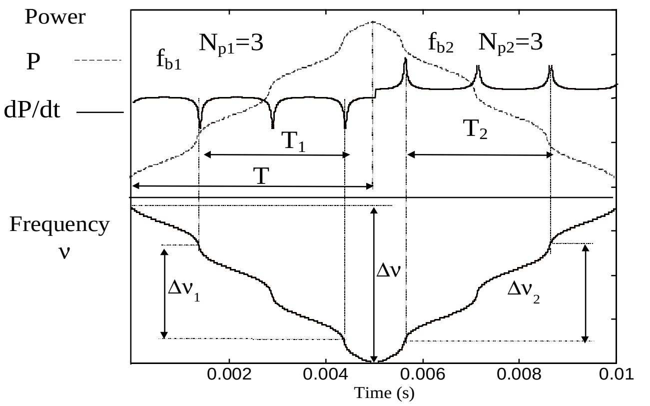

Fig. 2. Theoretical LD optical power and frequency waveforms for operation on a remote target

Fig 2 shows the typical optical power waveform. The signal is pseudo-periodic and has two beat frequencies f_{b1} and f_{b2} respectively determined by the time intervals T_1 and T_2. The corresponding optical frequency shift are $\Delta\nu_1$ and $\Delta\nu_2$. Distance is determined by the following relationship:

$$D = \frac{c}{4}\left(\frac{N_{p1}-1}{\Delta\nu_1} + \frac{N_{p2}-1}{\Delta\nu_2}\right) \cong \frac{c.T}{4\Delta\nu}(f_{b1} + f_{b2}) \qquad (1)$$

Here, N_{p1} (resp N_{p2}) is the number of peaks in the optical power derivative during T_1 (resp. T_2), c is the speed of light, T the half period of the reshaped triangular modulated current [4] and Δν is the total optical frequency shift during the half period T.
Without a control of the optical frequency shift, $\Delta\nu_1$ and $\Delta\nu_2$ are not precisely known and we can get the target distance from Eq.(1) only to an approximation.

III. CHIRP CONTROL

For proper operation, we shall avoid the mode hopping induced by the triangular-modulated injection current.

For this purpose, a Mach-Zehnder interferometer (MZI) has been added to the classical OFI range finding configuration. The experimental set-up, shown in Fig. 3, allows us to convert the optical frequency-shift into an amplitude modulation. The arms of the MZI are unbalanced by an optical path difference (OPD) e, and the optical isolator is added to prevent feedback from the MZI. Because of the OPD, a phase-shift $\varphi = e\nu 2\pi/c$ is found in the fields recombimed at the MZI output, resulting in a sinusoidal beating waveform. Each half period of the power P_{MZI} detected at the photodiode then corresponds to an optical frequency-shift given by $\delta\nu = c/2e$.

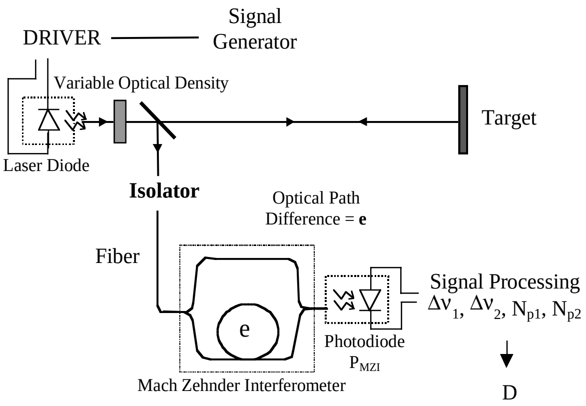

Fig. 3. Proposed set-up for chirp control of the OFI range finder

As an example, we report in Fig.4 the result of a simulation of the ν and P_{MZI} waveforms. Here, the OPD is e= 0.5 m and the target is at a 5-cm distance. Each half period of P_{MZI} corresponds to a 300 MHz frequency-shift. To recover the optical frequency from the power P_{MZI}, a simple strategy is to increment or decrement a counting register in steps of $\delta\nu = c/2e$. No mode hopping shall occur while counting, and we thus require that feedback parameter C is less than 1 [14]. Experimentally, to get C<1 we use a variable optical attenuator in thetarget path, as shown on Fig.3.

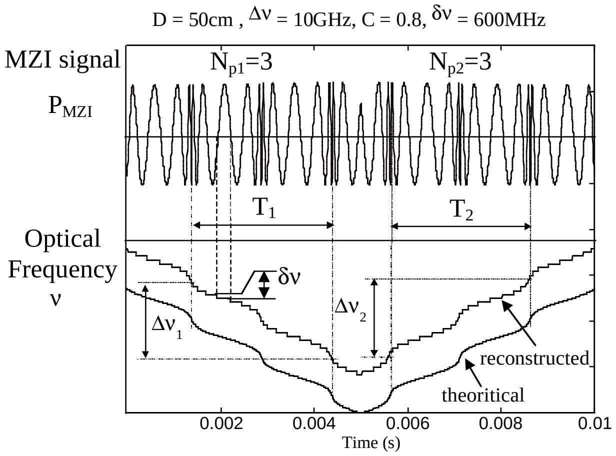

Fig. 4 Signal processing in an OFI range finder using a MZI .

Assuming a ±1 error in the half-period counting of P_{MZI}, we can find the resolution for our OFI range finder. Letting $\Delta\nu_1 \approx \Delta\nu_2 \approx \Delta\nu$ in Eq.(1), we get:

$$\frac{\delta D}{D} = \pm\frac{\delta\nu}{\Delta\nu} = \pm\frac{c}{2e.\Delta\nu} \qquad (2)$$

Actually, the accuracy limit for the discretization is 1/√6=0.4 times the resolution given by Eq.(2).

The accuracy can be improved by increasing the OPD and thus the optical frequency shift. However, the OPD must be smaller than or comparable to the coherence length of the LD to get a MZI signal with good visibility. The maximum allowed chirp with no hopping is specific of each Fabry Perot LD. A search carried out of a dozen different FP laser diodes has shown that $\Delta\nu$ = 100 GHz can be considered a safe value.

IV. EXPERIMENTAL RESULTS

In order to validate the theoretical results, an experimental OFI has been designed with the following parameters:

- Optical path difference of the MZI: e = 1.6 m
- Optical frequency resolution on the MZI signal: $\delta\nu$ = 93.75MHz
- Peak to peak optical frequency-shift of the LD: $\Delta\nu$ = 90GHz

Experiments have been performed on a target distance swinging from 9 to 10 cm. Each distance measurement has been repeated 100 times. Fig. 5 (bottom) is a plot of the difference between each average value and the actual distance. A linear regression has been used to minimize the square error. For each distance, in Fig.5 (top) we also report the ±2σ deviation of the 100-sample measurement (95% confidence level). We can then conclude that resolution is better than ± 100 µm, a result in good agreement with the theoretical value of ± 104 µm supplied by Eq. (2).

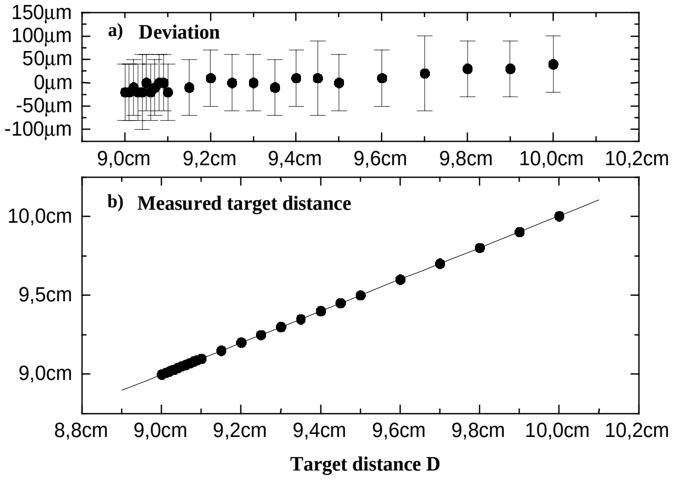

Fig. 5. Experimental results of OFI range finder with chirp control

Of course, accuracy might be also be improved further, by either increasing the OPD or the number of measurements, and values down to 20-50 µm appear feasible (at 10-cm target distance). This result is a significant improvement as compared to the basic OFI range finder set-up. Moreover, the range finder can work on a distance up to 50 cm, with an accuracy estimated in 250 µm (with the identical set-up). In comparison, without the MZI, the obtained resolution was only 1.5-mm [4].

V. COST REDUCTION

In the previous paragraph, the Mach-Zender interferometer was coupled to the range finder section through an isolator. But, as this devices is rather expensive, we should try to get rid of it, without sacrificing performance. Fig. 6 shows one possibility, that is, using an extra attenuator in the MZI path to strongly reduce the unwanted reflection from it. Also, a polarization discriminator (λ/4 waveplate and polarizer) could help in increasing the backreflection attenuation.

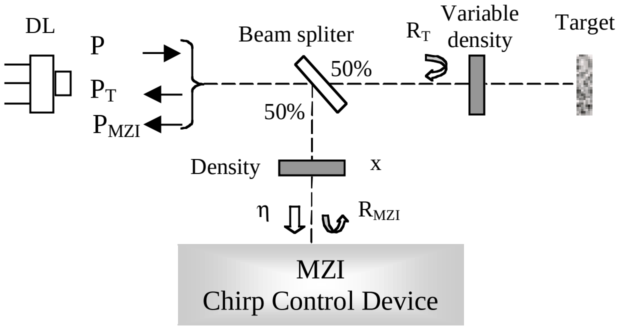

Fig. 6. New set-up with an added attenuator to dispense for the optical isolator.

Experimentally, we have found evidence that the chirp control section does not disturb the OFI range-finder operation provided that the MZI feedback is 1% or less than the target feedback intensity, i.e.:

$$P_{MZI} = \varepsilon\, P_T \quad \text{with } \varepsilon = 1\% \tag{3}$$

To keep the LD in the single mode operation with no hopping, the feedback parameter shall be C<1. In our experiment, we have chosen C= 0.8 for D = 10 cm. Explicitly, the feedback parameter is given by [1]:

$$C = \frac{\tau_D}{\tau_l}\zeta\sqrt{1+\alpha^2} \quad \text{with } \zeta = \frac{\sqrt{R_T}.(1-R_2)}{\sqrt{R_2}} \tag{4}$$

where R_T is the target power reflectivity, R_2 (typ. 0.32) is the output LD facet reflectivity, α (typ. 6)is the linewidth enhancement factor, τ_D (0.67 ns) is the time of flight from LD to target, and τ_l (typ. 9ps) is the cavity time of flight (FP cavity length : 300µm) [14].Using these realistic parameters in Eq.(4), we get $R_T = 8.74\ 10^{-6}$ = -50.6dB for C = 0.8, D = 10cm, and an ideal (δ=1) diffusivity of the target.

Considering the experimental set-up of Fig.6, the required optical attenuation x can be calculated as:

$$x = \sqrt{\frac{\varepsilon . R_T}{\eta . R_{MZI}}} \tag{5}$$

where η (typical value: 0.1) is the MZI coupling coefficient and R_{MZI} is the MZI power reflectivity.

Last, a compact, all-fiber MZI has been designed to minimize the return loss (Fig.7). All fiber pigtails are cleaved at 8° and APC8°-connectors are used for joining. With this provision, the MZI section has a total power reflectivity better than –50dB.

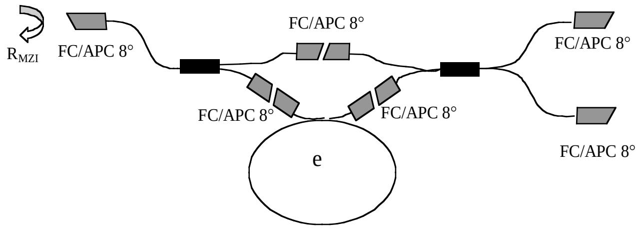

Fig. 7. Low return loss Mach Zehnder interferometer layout

Using Eq.(5), the required optical attenuation is now x=≈30%. Therefore, with a 50-mW LD, we have a reasonable 0.75-mW available to feed the MZI and associated photodetector, enough to get a useful signal and determine the chirp. Experimental results for this modified OFI configuration are shown in Fig.8. No significant perturbations of the self-mixing signal due to MZI section is apparent.

VI. CONCLUSIONS

In this paper, we have demonstrated a new approach to the optical feedback interferometer for absolute distance measurement. By separately measuring the frequency sweep with a MZ interferometer, we have improved substantially the instrumental resolution while keeping the set-up complexity to a reasonable level.

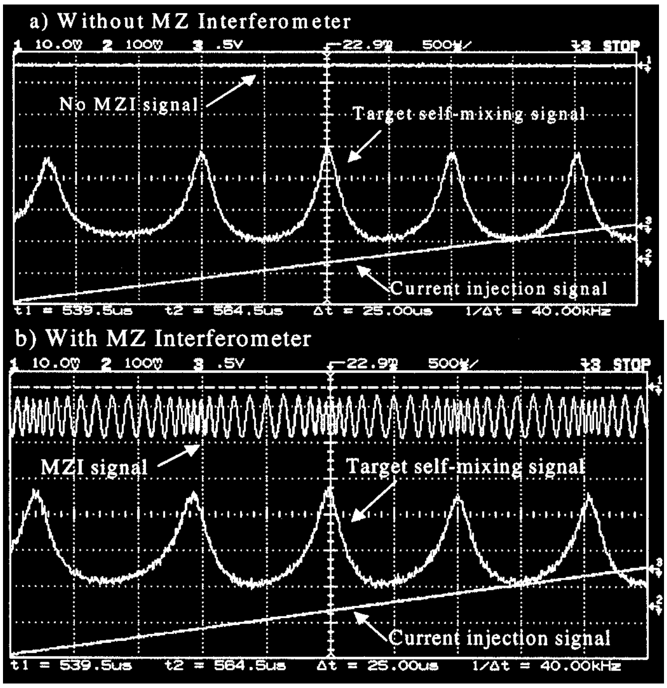

Fig. 8. No influence of the MZI section on the OFI range finder is found with the modified setup (no optical isolator).

VII. REFERENCES

[1] T. Bosch, N. Servagent and S. Donati, “Optical feedback interferometry for sensing applications “, Optical Engin., vol. 40, n°1, Jan. 2001.

[2] P.J. de Groot, G.M. Gallatin and S. H. Macomber, “ Ranging and velocimetry signal generation in a backscatter-modulated laser diode ”, Appl. Opt. vol. 27, pp. 4475-4480, Nov.1988.

[3] S. Shinohara, H. Yoshida, H. Ikeda, K. Nishide and M. Sumi, “ Compact and high-precision range finder with wide dynamic range and its application ”, IEEE Trans. Instrum. and Meas., vol. 41, pp. 40-44, Feb.1992.

[4] F. Gouaux, N. Servagent and T. Bosch, “ Absolute distance measurement with an optical feedback interferometer ”. Applied Optics, vol. 37, n° 28, pp 6684-6689, Oct. 1998.

[5] T. Bosch, N. Servagent, R. Chellali and M. Lescure, “ 3-D object construction using a self-mixing type scanning laser rangefinder ”. IEEE Trans. on Instr. and Meas., vol.47, n° 5, pp.1326-29, Oct. 1998.

[6] T. Shibata, S. Shinohara, H. Ikeda, H. Yoshida, T. Sawaki and M. Sumi, " Laser speckle velocimeter using self-mixing laser diode " IEEE Trans. IM vol. 45, n°2, pp. 499 - 503, April 1996.

[7] S. K. Ozdemir, T. Takasu, S. Shinohara, H. Yoshida and M. Sumi, “Simultaneous measurement of velocity and length of moving surfaces by a speckle velocimeter with two self-mixing laser diodes”, Appl. Opt., vol. 38 (10), pp 1968-1974, April 1999.

[8] R. Kawai, Y. Asakawa and K. Otsuda, “Ultrahigh-sensitivity self-mixing laser Doppler velocimetry with laser-diode-pumped microchip “$LiNdP_4O_{12}$ lasers”, IEEE Phot. Techn. Lett. vol.11, pp 706-708, June 1999.

[9] S. K. Ozdemir, S. Ito, S. Shinohara, H. Yoshida and M. Sumi, “Correlation-based speckle velocimeter with self-mixing interference in a semiconductor laser diode”, Appl. Opt., vol.38, n°33, pp. 6859-6865, Nov. 1999.

[10] S. Donati, L. Falzoni and S. Merlo, “ A PC-interfaced, compact laser-diode feedback interferometer for displacement measurements ”, IEEE Trans. on Instr.and Meas., vol. 45, n°6, pp. 942 - 947, Dec. 1996.

[11] S. Merlo and S. Donati, “ Reconstruction of displacement waveforms with a single-channel laser diode feedback interferometer ”, IEEE J. Quantum Electron., vol. 33, n°4, pp. 527-531, April 1997.

[12] N. Servagent, T. Bosch and M. Lescure, “ A laser displacement sensor using the self-mixing effect for modal analysis and defect detection ”, IEEE Instrumentation and Measurement, vol. 46, n°4, pp. 847-850, Aug. 1997.

[13] Koltchanov, K. Petermann and J. Roths, “New modulation technique for unambiguous measurements of phase changes in diode laser interferometers”, Proc. SPIE vol. 3098, pp . 325-333, 1997

[14] K Petermann, “ Laser diode modulation and noise”, Kluwer academic Publishers, Dordrecht, 1991.

[15] S. Donati: “Photodetectors”, Prentice Hall, Upper Saddle River, NJ 2000.