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TECHNIQUE FOR LONG AND ABSOLUTE DISTANCE MEASUREMENT BASED ON LASER PULSE REPETITION FREQUENCY SWEEPING

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Abstract — **In this work we present a technique to perform long and absolute distance measurements based on mode-locked diode lasers. Using a Michelson interferometer, it is possible to produce an optical cross-correlation between laser pulses of the reference arm with the pulses from the measurement arm, adjusting externally their degree of overlap either changing the pulse repetition frequency (PRF) or the position of the reference arm mirror for two (or more) fixed frequencies. The correlation of the travelling pulses for precision distance measurements relies on ultra-short pulse durations, as the uncertainty associated to the method is dependent on the laser pulse width as well as on a highly stable PRF.**

Mode-locked Diode lasers are a very appealing technology for its inherent characteristics, associated to compactness, size and efficiency, constituting a positive trade-off with regard to other mode-locked laser sources. Nevertheless, main current drawback is the non-availability of frequency-stable laser diodes. The laser used is a monolithic mode-locked semiconductor quantum-dot (QD) laser. The laser PRF is locked to an external stabilized RF reference. In this work we will present some of the preliminary results and discuss the importance of the requirements related to laser PRF stability in the final metrology system accuracy.

Index Terms—**Mode-locked Semiconductor laser, Metrology, Pulse Repetition Frequency, Long Absolute Distance Measurement**

INTRODUCTION

This study proposes a new method for absolute long distance measurement based on mode-locked laser diodes (MLLD). The method is supported by using the PRF tuning capability of this kind of lasers, enabled by modulating the saturable absorber response with external electrical control[1].

The critical trade-off when considering this technology as optical source for distance metrology is to assure compliant frequency stability[2] and pulse characteristics, in order to produce distance estimates with the required accuracy. For this purpose we used a QD mode-locked laser diode, with a PRF close to 5GHz and a pulse width of 2 ps[3].

In order to evaluate the PRF stability and PRF tuning capability we built a specific setup that allowed us to scan over the diode parameter space (saturable absorber bias and gain driving current) and map the frequency output of the laser. The laser was operated in both passive and hybrid mode-locking mode in order to measure the limits of the frequency stability and evaluate its impact on the distance metrology solution[4].

In terms of the metrology system solution we built a specific testbed based on a Michelson Interferometer arrangement, coupled to a cross-correlation detector.

GENERAL OPTICAL METROLOGY CONCEPT

The measurement method proposed here makes use of the pulse repetition frequency tuning capability of the QD laser diode to produce absolute distance measurements.

It relies on the following assumptions:

- The mode-locked laser diode pulse repetition frequency is tuned by external electrical control without altering significantly other laser characteristics (pulse width, peak power, linewidth, central wavelength)[5].
- A cross-correlation detector measures the overlap of the pulses travelling in both arms of the interferometer.
- The instantaneous pulse repetition frequency is accessed by down-converting the pulse frequency in a mixing process with a reference oscillator.
- The absolute distance measurement is performed by taking into account the frequency interval between two consecutive correlation events.

The proposed experimental setup, where a fixed arm Michelson interferometer serves as basis of the correlation process, is shown in figure 1.

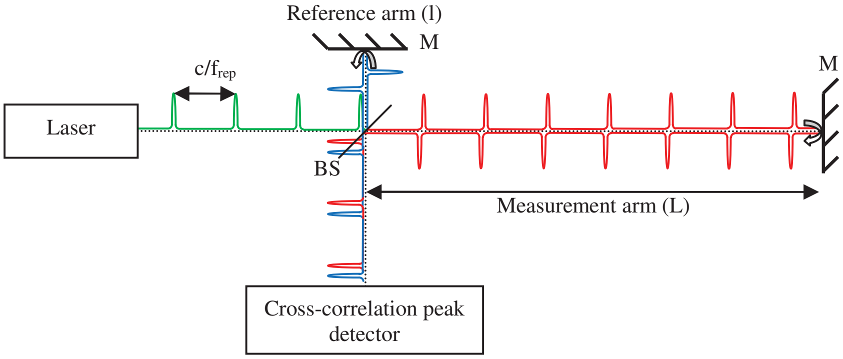

Fig. 1. Schematic of the technique for long and absolute distance measurement based on laser pulse repetition frequency sweeping. Legend: f_{rep}– Laser pulse repetition frequency; M – Mirror; BS – Beam splitter

There are two variations of this concept that can be implemented to extract a distance estimate, subsequently denominated Mode1 and Mode 2.

Mode 1 – PRF scan

In this mode, the interferometer has the reference arm fixed and the pulse repetition frequency of the laser diode is swept over the tuning range. The distance measurement is performed using the frequencies associated to the two successive correlation peaks. This configuration has no moving parts and its performance depends mainly on the uncertainty of the measurement of the exact frequency at which the correlation peaks occur.

The governing equation can be simply expressed in the following manner:

$$L = \frac{c}{2\left(f_2 - f_1\right)} = \frac{c}{2\Delta f} \qquad (1)$$

Note that the quantity 2L corresponds to the interferometer optical path difference.

This last expression shows that the absolute distance can be obtained directly by measuring the frequency sweep range between two consecutive correlation events.

The accuracy of the process is directly related to the ability of measuring the beat frequency accurately, ultimately dependent on the stability of the reference oscillator and on the error finding the correlation peak.

Mode 2 – OPD scan

The OPD scan mode implies moving the reference arm of the interferometer from position l_1 to position l_2 while the PRF is fixed. The absolute distance measurement is obtained indirectly by evaluating the distance travelled by the reference arm stage between two successive correlation peaks, which are obtained for two different (fixed and stabilized) pulse repetition frequencies. Although presenting the “inconvenience” of exhibiting moving parts, this method is more relaxed in terms of the uncertainty requirements on the frequency measurement. The distance estimate is obtained by the following set of expressions:

$$\begin{cases} L = \dfrac{f_2 l_2 - f_1 l_1}{f_2 - f_1} \\ n = \dfrac{2}{c}\dfrac{\Delta l}{\Delta f} f_1 f_2 \end{cases} \qquad (2)$$

In this last expression, $\Delta l = l_1 - l_2$, $\Delta f = f_1 - f_2$ and n is the number of impulses travelling in the measurement arm of the interferometer.

There are three critical characteristics of the MLLD that enable the technique presented in this work, and these are common for the two operating modes: PRF tuning range, PRF stability and pulse width.

The first one, associated to the capability of changing the PRF of the laser would affect mainly the closest and the farthest distance for which the system is able to perform measurements. As explained before, this technique relies on the capability of changing the pulse repetition frequency (or reciprocally, the pulse period) in order to perform the pulse overlap at the detector on a Michelson Interferometer arrangement. Once the optimum time overlap at the detector is achieved (represented by a maximum signal in the cross-correlator detector), we should be able to measure the frequency at which it has occurred with a specific uncertainty, which is directly dependant on the PRF stability.

It is then crucial to be able to tune the laser pulse repetition frequency over a certain range (dictated by the minimum and maximum measurement ranges) and maintain a reduced RF linewidth – directly related to the PRF stability level, in order to be able to measure the instantaneous PRF with a low uncertainty.

The pulse width produces a similar effect with respect to the jitter associated to frequency instability. Longer pulse widths would produce wider cross correlation events and thus increasing the difficulty to find the frequency of optimal overlap in the presence of detection noise.

Stabilization of PRF

One of the most direct techniques for PRF stabilization is running the laser in hybrid mode, where the laser is driven with constant current at the gain section level, but the saturable absorber is locked to an external RF source, by super-imposing a AC signal over the DC bias[6].

A very simple schematic of hybrid mode-locking is shown in figure 2.a)

Figure 2.b) compares the variation of the PRF in both passive and hybrid mode. A good measure of the level of stabilization that can be achieved is by means of the root Alan variance, allowing to discriminate the stabilization achieved for different integration periods.

Although the increase in stability is not dramatic for shorter integration times (below millisecond level), “slow” variations in frequency show a significant damping when working in hybrid mode-locking. This can be explained by the fact that the RF frequency source we use is a commercial grade device, with fair performance in the short period stabilization.

Correlation detection

The correlation detector is a critical component for this metrology concept as it is responsible for determining the degree of time overlap of the pulses travelling in both arms of the interferometer. In terms of the experimental setup, we implemented two different cross-correlator schemes:

The first setup is a conventional intensity correlator, using a SHG crystal as the nonlinear element. However, the very low pulse energy of the QD laser (<100 pJ), make the pulse correlation a very difficult task, especially if we remember that the second harmonic generation in thin crystals exhibits an efficiency on the order of 10^{-5}.

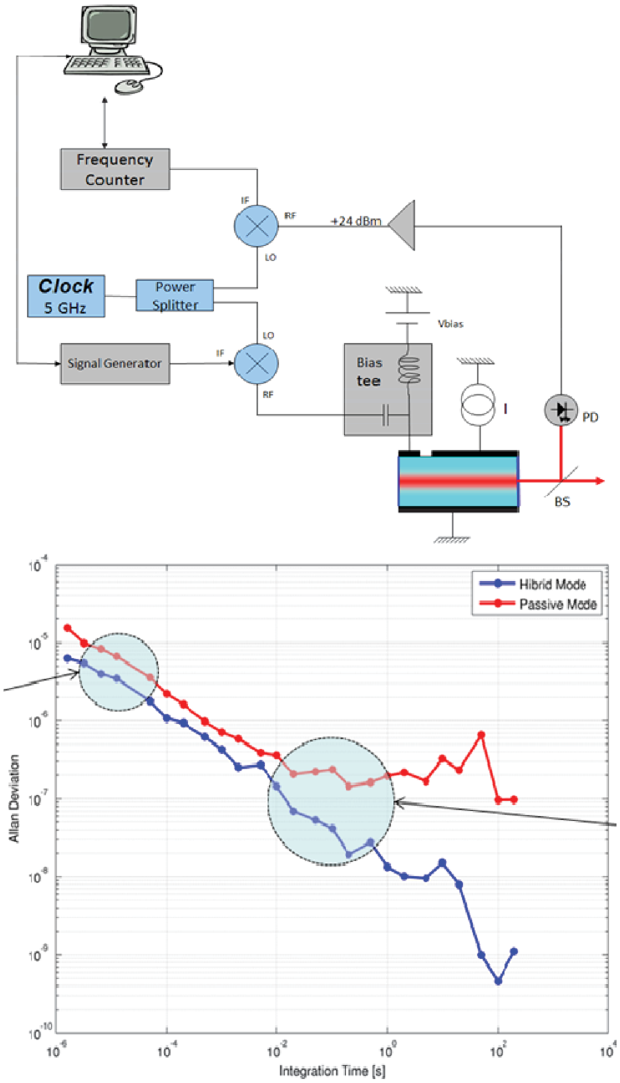

Fig.2. a) General connection diagram for hybrid mode b) Alan variance results for passive and hybrid mode

The second setup is a technique for measuring the degree of polarization (DOP) of the resulting electrical field during the pulse overlap process. In this case, the Michelson interferometer produces two orthogonally polarized copies of the original pulse by means of a polarized beam splitter, one travelling over the reference arm, the other over the measurement arm. When overlapping at the polarimeter detector, they produce an electrical field with a degree of polarization that is proportional to the pulse width and to the degree of pulse overlap[7].

Experimental setup

The next figure (figure 3) shows the setup built for the testing of the instrument concept, using in this case the use of DOP correlation detection. A spool of polarization maintaining fiber with different patch lengths was used to simulate different object distances, from 3 meters up to 100 meters. An additional translation stage located in the measurement arm was introduced to produce small displacements on top of the distance offset resulting from the use of the optical fiber. The images in Figure 3 show the implementation of the metrology concept tested in our labs.

It is important to note that all the components associated to the metrology system, including the laser, interferometer, optics and proximity electronics exhibit a small footprint, with a maximum volume of 3 Liter, weighting less than 3 kg. The power consumption is estimated to be less than 5 W, if we exclude the measurement equipment.

TRADING OFF SYSTEM PERFORMANCE

A brief analysis of the system performance for mode 1 and mode 2 is presented in this section. The analysis covers the main configuration parameters in terms of the laser operating characteristics, evaluating the uncertainty on the distance measurements and the operational limitations of the technique for the long distance measurement.

Mode 1

One of the first conclusions to draw from the expression that allows the evaluation of the absolute distance measure (eq.1) is that the tuning range required is independent of the nominal PRF of the laser used for this application. The required tuning capability only depends on the range of distances to be measured. In general terms, an error analysis regarding the accuracy of the distance measurement shows that it depends only on the accuracy of the PRF measurement,

$$\varepsilon L = \frac{c}{2\Delta f^{2}}\,\varepsilon_{f}^{\;2} \qquad (3)$$

where εL is the error in the distance measurement, c the speed of light, ε_f the tuning range and εf the error in the PRF measurement.

Figure 5 shows the distance measurement accuracy as function of the distance to the object, for several PRF measurement accuracies:

This figure shows that accuracies below 100 micrometer can be achieved up to a 150m measurement range with a PRF measurement accuracy of 1 Hz. This level of measurement uncertainty can be maintained for longer distances if we are able to determine the beat frequencies down to the sub Hertz level. The measurement accuracy of 1Hz requires a stability level of 10^{-9} (at millisecond level period) for a laser with a PRF of 1 GHz.

The vertical axis on the right indicates the amount of tuning needed to be able to perform measurements at different distances.

It is also important to evaluate the amount of frequency tuning that is necessary to produce a complete correlation event.

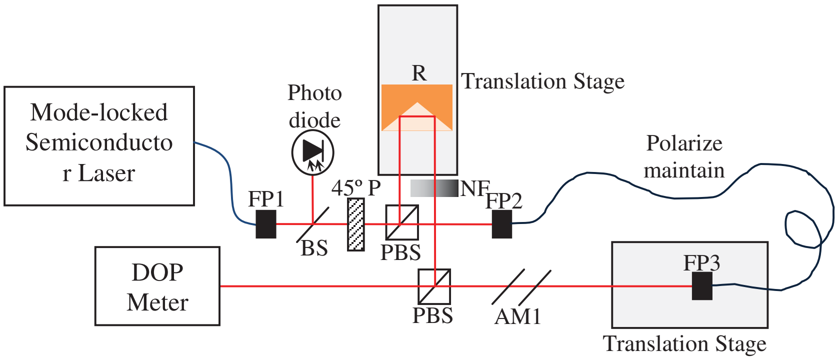

Fig.3. Setup of the distance measurement system using the 'degree of polarization' *technique as a correlation detector*

For a fixed object distance, the total variation of the pulse position (in time due to the jitter) at the correlator detector level results from the sum of all period increments associated to the N pulses travelling in the measurement arm of the interferometer. Thus, frequency tuning requirements for the cross-correlation process decrease with increasing distance, since N increases for longer distances. This fact implies also that mode-locked pulses with shorter pulse width require less PRF tuning producing a complete correlation.

The relevance of the tuning requirements is expressed mainly in the laser stability requirements and in the capability of finding the frequency corresponding to the correlation peak with the highest accuracy. In practical terms, and as expected, narrower pulse widths are more favorable, as the error associated to peak finding is minimized when decreasing the correlation width.

Mode 2

In terms of the measurement accuracy, we can evaluate the average error on the measurement from the first expression of Equation 2.

$$\varepsilon_L = \frac{\Delta l}{\Delta f}\varepsilon_f + \varepsilon_l$$

(4)

Again, $\Delta l = l_1 - l_2$ and $\Delta f = f_1 - f_2$, ε_f is the error associated to the measurement of the PRF and ε_l is the error associated to the measurement of the location of the correlation peak.

The next graph (Figure 6) shows the error in the distance measurement for a baseline frequency of 5GHZ, for two magnitudes of frequency stability (10^{-8} and 10^{-7}). The error on the location of the correlation peaks is assumed to be constant over distance and, in the case presented in the graphs, equal to 5 micrometer.

It is important to note that the error due to the accuracy of the PRF measurement is smaller than the error due to the location of the correlation peaks, for approximately half of the working range. The contribution of the PRF measurement accuracy is in fact very low, even for lower PRF stabilities for ranges up to 150-200 meter. In fact, regarding the overall error budget, the entire weight in terms of distance measurement accuracy is referring to determining the location of the correlation peak, relaxing the requirements regarding the PRF stability.

Even though the value assumed for the correlation peak location error is relatively low, the final accuracy is always topped by this value, with the error associated to the PRF uncertainty only being significant for longer ranges. A simple "back of the envelope" calculation evidences this assumption:

Considering a frequency stability of 10^{-8} we solve the second expression of Equation 2 in order to estimate the influence of the PRF on ε_l.

Using error propagation to evaluate the error due to the frequency stability, we will get a value close to 1 nm for n=1. This corresponds to the error in position location as if the correlation detector worked as an auto-correlator.

If we consider it working as a cross-correlator, the overlap is produced after n>>1 pulses and the error in ε_l due to the PRF instability can be evaluated in the following manner (assuming that the timing jitter of the individual pulses is uncorrelated):

$$\varepsilon_{l,n} = \sqrt{n} \times \varepsilon_{l,1} \qquad (5)$$

Where $\varepsilon_{l,n}$ is the error after n pulses and $\varepsilon_{l,1}$ is the error associated to jitter after the first pulse

For a large value of n, associated to long distances, the

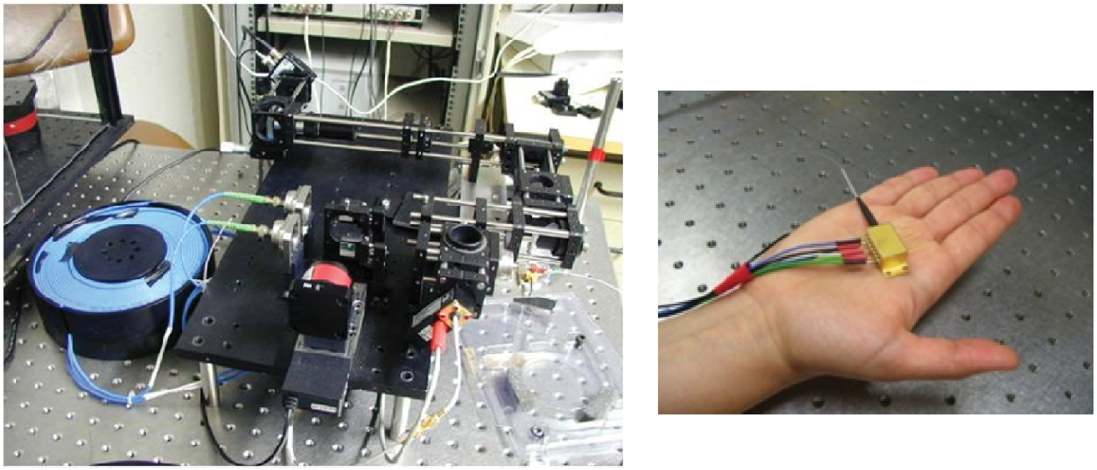

Fig.4. Metrology concept tested and detail of the laser employed in this experience

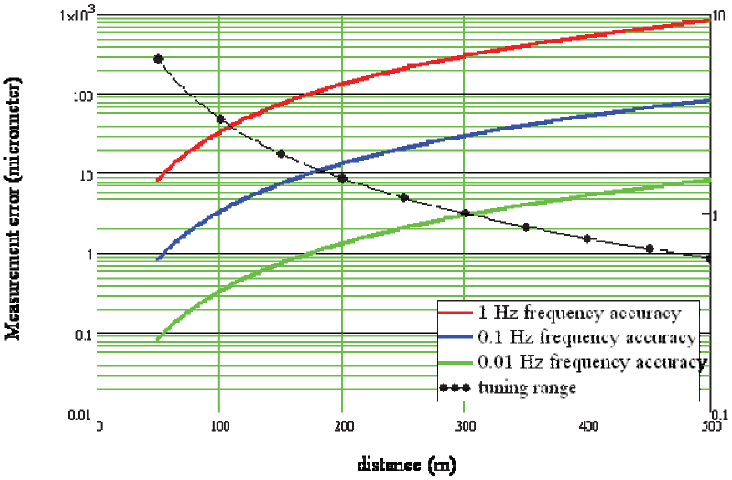

Fig.5 Measurement error and tuning range for mode1

error due to this parameter is still at the micrometer level.

The major source of uncertainty is then associated to the error on the location of the correlation peak, which has two main components: the repeatability of the translation stage and the error associated to the numerical fitting employed to locate the correlation peak. Even if we assume an error of say, 50 micrometers, this will always be much larger than the error due to the PRF measurement uncertainty and we can consider this as the maximum error for the L measurement in Mode 2.

The choice of the baseline PRF will affect directly the minimum requirements in terms of the travel range of the reference arm of the interferometer, since the ε_l defines the minimum distance between the two correlation peaks (one for baseline PRF, the other for the shifted PRF). As an example, a baseline PRF of 10 GHz would require a travel range of a few millimeters while 1 GHz would require tens of centimeters. Clearly, lower PRF present the disadvantage of requiring long OPD travels, surely not compatible with practical metrology systems for space.

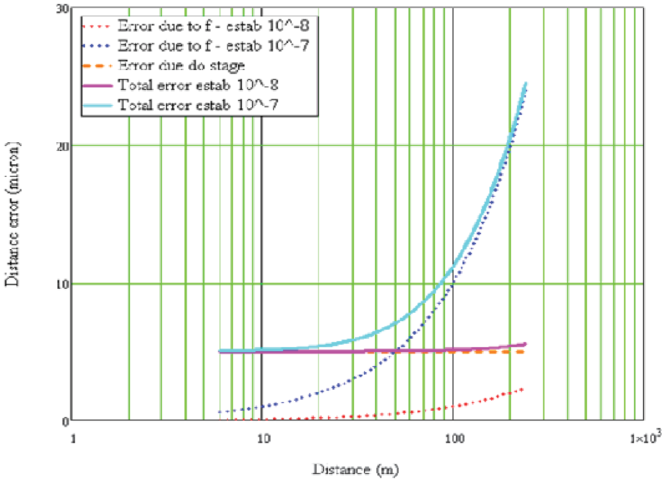

Fig.6. Uncertainty on L measurement for mode 2, for baseline frequency of 5 GHz. ε_l is assumed to be of 5μm.

Update rate

The update rate is strictly limited by two intrinsic factors, associated to the characteristics of the laser.

The first one is the laser stability. We have seen earlier that the requirements in terms of stability are slightly different for Mode 1 and Mode 2, but generally we can statethat the measurement accuracy of the laser PRF should be in the range of 10^{-9} in Mode 1 and 10^{-8} for Mode 2, for measurement ranges up to 150 meter. The averaging time necessary to achieve this accuracy depends on the intrinsic frequency stability of the laser.

Considering an accuracy of this order of magnitude, at a millisecond time interval (kHz rate), this would represent the minimum acquisition period for each point forming the cross-correlation waveform.

The total number of points necessary to define correctly the correlation waveform depends itself on the pulse width. Furthermore, the uncertainty in finding the position of the waveform peak is itself dependent on the width of the pulse. This would suggest the use of shorter pulse widths.

RESULTS

Mode 1 experiments were performed with the setup shown in figure 3 and the SHG correlation detector.

The laser was operated in passive mode-locking mode by fixing the gain current at 90 mA and sweeping the voltage value of the saturable absorber in order to obtain a PRF scan centered at 4.95GHz.

The setup included a fiber patch of 70 meters (about 105 m of optical path length) and the distance was measured at fixed optical lengths (with no movement at the stage of the measurement arm of the interferometer)

As it can be readily observed from this graph, the signal to noise ratio is very poor due to exceedingly low values of energy per pulse available at the SHG detector. The evident noise is also due to the fact of running the laser in the passive mode-locking mode and, in spite of long integration times for each frequency setting (500 ms), the variance on the measured frequency values is still very high. In this situation it is not possible to scan the laser frequency with a sampling compatible with the required measurement accuracy.

The error associated to the retrieval of the peak location is at the order of several kHz, which leads to non-compliant final measurement accuracies in the order of millimeters.

No further experiments were performed in this mode, although the working principle has been validated with correlation peaks located at the frequency axis with the expected average values, in several other trials.

The poor measurement results are driven by the fact that it was not possible at this stage to build a closed control loop to

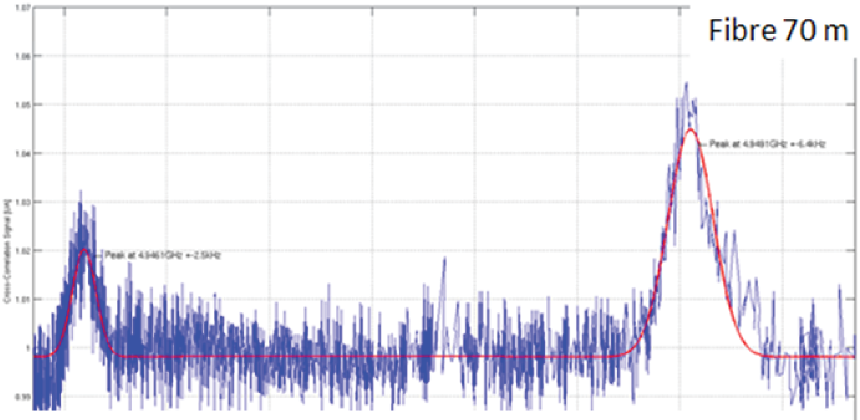

Fig.7. Results of measurement with Mode 1 and with fiber patch of 70 meter. Standard error in peak location is 2.5 kHz and 4.4 kHz for peak 1 and 2, respectively.

stabilize the frequency at rates compatible with the measuring times. We are presently acquiring a PID controller that can support this measurement in hybrid mode-locking mode at very high data rates.

Figure 6 shows some measurement results obtained in Mode 2, using the DOP correlation detector. The method used for measurement is supported by the experimental implementation shown in figure 3, changing the optical path by the use of patches of PM fiber with several lengths (1, 3 and 15 meters). Small incremental displacements over the nominal distance were produced by moving the translation stage in 50 micrometer steps.

The process of running the laser in hybrid mode-locking presented however some problems, due to the fact that it was not always possible to lock the laser at one desire frequency, but make the lock happens at the nearest natural frequency. The fact that the hybrid mode-locking was used in open loop control mode can also explain some variations in the results.

We could verify that the measurement of the correlation peak location lead to an experimental uncertainty with an average value of 2 microns, within the same order of magnitude of the expected values mentioned in the tradeoff section of Mode 2.

The results shown in figure 8.a) are twofold. The upper part shows the linearity of the results when measuring the optical path with incremental displacements of 100 micrometers. The two dots per position represent the results obtained by using f_1 or f_2, for pulse number n calculated with the expressions in equation 2. The lower part of the same figure represents the residue of the estimated values with regard to the expected value.

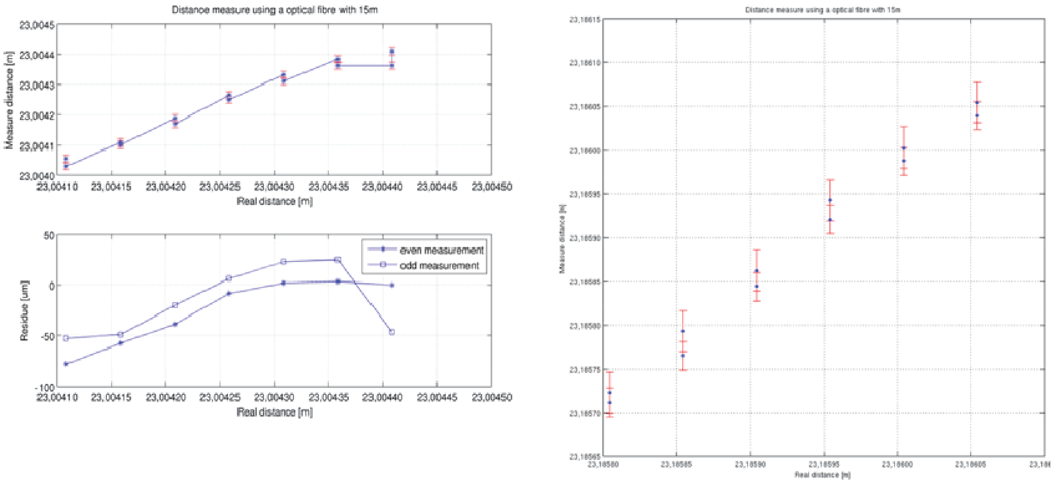

Fig.8. (a) Results for 15m patch cable (b) Measured values and experimental standard deviation.

Although the experimental standard deviation of the results is in the order of 20 micrometers, the residue shows a small drift in terms of target displacement, which could be explained by some drift in the frequency control and/or some non-linearity on the actual path length associated to the movement of the translation stage (we could verify a reasonably strong wobbling along the travel excursion).

Due to a deterioration of the fiber tip, causing some beam non-homogeneities degrading the DOP detector performancewe were not able to measure longer distances.

Although the metrology technique presented in this paper can be considered to have an absolute distance measurement capability within the ambiguity range defined by the lower and higher limit PRF defined by the MLLD tuning range, this feature is not yet fully tested and validated. In our experiments we were able to confirm that it is possible to obtain the correct absolute distance with an error less than one unit pulse path length (3cm @ 5GHz) and measure correctly small displacements on the top of any of the ranges determined by the length of the fiber patches used to simulate long distances. We were not yet able to compare our results with an alternate absolute distance measurement instrument and to evaluate the final experimental accuracy of our technique.

DISCUSSION ON THE MLLD REQUIREMENTS

In this section we summarize the MMLD requirements having in mind space applications for a general set of specifications comprising a maximum measurement range of about 150 m and measurement accuracy better than 100 micrometers.

Pulse Repetition Frequency

This parameter is not critical in terms of the metrology system performance, since the basic principle of measurement is directly related to the frequency difference between two correlation events and not to the nominal laser pulse repetition frequency itself. However, since a fixed amount of PRF tunability is required, the fractional tuning (in relation to the nominal frequency) is higher for lower repetition rate lasers making it more difficult to achieve. In Mode 2, a higher frequency is also more beneficial; as it minimizes the travel range (Δl) required obtaining the two correlation peaks. A generic tradeoff points out to PRFs in the range of 5 to 10 GHz

Tunability

This parameter is directly related to the nominal PRF, but has also a strong implication on the shortest range the system can measure (in Mode 1). The shorter the range, the wider should be the tuning range.

A 10 to 15MHz PRF tuning range should be sufficient to allow measurements down to a 10 meter distance range.

PRF stability

The PRF stability needs to be discussed under two aspects: the stability related to the accuracy obtained when measuring the laser PRF at the correlation peaks, and the maximum period allowed to make this measurement and integrate frequency readings, directly related to the update rate required for the metrology system.

The accuracy analysis for both Mode 1 and Mode 2 results in two different stability requirements. While Mode 1 requires 1 Hz accuracy in the frequency measurement to obtain a measurement precision of better than 100 microns for distances up to 150 meters (with the advantage of having no moving parts), Mode 2 allows to relax this requirement down to a 10^{-8} or less fractional frequency measurement accuracy for the same distance accuracy requirement.

Mode 2 requirements for PRF stability can be considered less restrictive, specifically because the frequency measurement can be averaged over longer periods, depending only on the speed of displacement of the travel stage in the reference arm of the interferometer.

Pulse Duration

The pulse duration has direct implications on the range of frequencies (Mode 1) or on the travel displacement (Mode 2) necessary to produce a correlation event. The accuracy required to define the position of the correlation peak in the Hz range (Mode 1) or with micrometer resolution (Mode 2), in the presence of noise or for low level signals, tends to push for shorter pulse durations.

The basic argument is associated to the fact that shorter pulses produce narrower correlation waveforms (both in Mode 1 and in Mode 2), and for the same sampling the error associated to the location of the peak is lower.

For this particular MLLD characteristic the laser pulses should have the narrowest width possible. Available data on existing MLLDs show that 500 fs width pulses are already attainable.

Output power

The output power is to be considered critical. The main driver here is related to the efficiency of the correlator and of the SHG process (non-linear crystal or two photon absorption), which exhibit efficiencies at the 10^{-5} level.

The laser used in our experiments had a 600mW average power for a 5GHz PRF, which leads to an energy per pulse at the 100 pJ level, which is considered a low value to have a good SNR at the correlator detector.

Wavelength

In general there is no specific requirement in terms of wavelength. The correlator and the 2nd order detection process is wavelength dependent and some restrictions may arise from this subsystem.

Coherence

Any requirement regarding this property depends on the type of cross-correlation detector used. If an intensity correlation method is employed there are no specific restrictions regarding coherence since it’s a second order process and phase independent. However, the Degree of Polarization method as a first order process is radiation phase dependent.

Polarization

The issue of polarization is direct related to the type of cross-correlation detector used. For both of the cross-correlation methods used a linearly polarized laser is needed.

CONCLUSIONS

The objective of this project was to evaluate the performance of a novel concept of high-accuracy absolute distance metrology for space applications based on the use of mode-locked semiconductor lasers. The main driver suggesting the use of mode-locked laser diodes was the optimization of power consumption, volume and mass, while maintaining strict requirements in all the characteristics affecting the system measurement performance in terms of accuracy range and update rate.

The metrology system concept is based on a Michelson interferometer architecture coupled to a cross-correlation detector. The exact measurement of the optical path difference of the interferometer is obtained by evaluating the integer number of pulse period path lengths ($N*c/2f_{rep}$) and the reference arm length. This can be done either by changing the baseline frequency or by moving the reference arm of the interferometer until a complete overlap of the pulses travelling the reference arm and the measurement arm is produced at the correlation detector. These two different approaches to compensate the optical path difference in the interferometer constitute the two basic operating modes of the present metrology scheme, presented in this document as Mode 1 and Mode 2.

The impact of the laser diode characteristics on the performance of these two operating modes is different.

While in Mode 1 the pulse repetition frequency is tuned in order to achieve a pulse overlap atthe correlation detector, in Mode 2 we change the length of the reference arm of the interferometer at two specific PRF with the same purpose.

Mode 1 has as a major advantage in that the system operates without moving parts, and the measurement is performed by electronically sweeping the laser PRF over a specific range. The requirement in terms of frequency stability is comparably high (10^{-9}) and can influence the update rate of the instrument due to the high sampling required to obtain sufficient accuracy at the correlator detector level.

Mode 2 is much less restrictive in terms of the required laser PRF stability (and thus, able to produce higher update rates) but it requires the movement of mechanical parts in the reference arm of the interferometer.

A trade-off of the various laser characteristics and theirimplications on each mode of performance resulted in listof minimum requirements for a mode-locked laser diode supporting the presented metrology system concept.

In order to test in practice all the assumptions regarding both the metrology concept and the critical properties of mode-locked laser diodes, a quantum-dot MLLD was acquired and a set of trade-off experiments wereperformed in a dedicated metrology testbed, demonstrating the feasibility of the novel metrology scheme in the context of the established requirements.

With respect to the stabilization of the laser diode PRF, we have implemented as the technique of hybrid mode-locking resulting in a significant increase of the PRF stability and range. However, these improvements were not sufficient to enable Mode 1 operation at full performance, since the required PRF stability required could notbe achieved. We are currently implementing a new technique of close loop control with a fast PID controller, and we expect to be able to correct PRF jitter at short/mid term, allowing the implementation of Mode 1 with reasonable update rates.

The experimental results validate the principle of operation forboth Mode 1 and Mode 2 and the measurement accuracy of the metrology system was in line with the theoretical predictions. None of the modes were tested for full range (up to 150 m) although the partial results seem to show that measurement accuracy would fall within the value expected from the model.

Based on the experimental results, we established a set of specifications for MLLD's in view of a metrology system capable ofmeasuringdistances up to 150 meters withaccuracy better than 100 micrometers. In particular in Mode 2 operation the maximum distance measurement range could be easily extended to 300 meters or more if we use ancillary techniques to remove the ambiguity in coarse range determination (e.g. by modulation of the laser diode power).

In conclusion, while observing some limitations of using mode-locked laser diodes as the light source of the novel metrology scheme, it has been demonstrated that the general requirements in terms of high accuracy long distance measurement for space can be met, in particular for average ranges up to few hundreds of meters. Most importantly, we have shown that it is possible to obtain a system implementation that is compliant with the power and volume requirements for this type of payload.

Acknowledgements

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