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# Fast scanner with position monitor for large optical delays

S. Costantino [a,*], A.R. Libertun [a], P. Do Campo [a], J.R. Torga [b], O.E. Martínez [a]

[a] *Laboratorio de Electrónica Cuántica, Departamento de Física, Universidad de Buenos Aires, Pabellón 1, Ciudad Universitaria, (C1428EHA) Buenos Aires, Argentina*

[b] *Laboratorio de Optica y Metrología Aplicada, Universidad Tecnológica Nacional, Regional Delta, San Martín 1171, (2804) Campana, Pcia. De Buenos Aires, Argentina*

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**Abstract**

We present a new fast scan system that employs a stepper motor used in a single step oscillating mode and a position monitor device based on a diode laser. The setup used generates delays as large as 105 ps at 10 Hz, with 100% duty cycle. We also introduce a reliable device based on the shadow of a moving cutter with a laser diode as the light source to avoid power fluctuations problems. © 2001 Elsevier Science B.V. All rights reserved.

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## 1. Introduction

The number of different time-resolved measurements using ultrashort pulses have been increasing during the last 20 years. Usually, in autocorrelations, optical coherent tomography or pump and probe experiments, a known distance is added to one arm in a Michelson-like interferometer setup, and then the light coming from both arms are directed to the sample. In order to analyze the behavior of the sample as a function of time delay between the two pulses, it is necessary to vary the distance that is added one of the arms.

This time delay variation is principally done in two different ways, with a slow or a fast scan. For the case of a slowly movement, the length of one arm is varied using a motorized translation stage, or simply by an actuator, and the signal is measured by modulating one beam and detecting using a lock-in amplifier referenced to the modulator. A chopper or an acousto-optic modulator are the common tools for doing this. The other possibility is to rapidly and repetitively scan the time delay and average the scans so as to reduce the noise.

There are many different systems that do this rapid scanning. The easiest to imagine and the cheapest is to use a mirror mounted on a piezoelectric crystal or on a speaker, depending on the desired frequency and size of the time delay. They must be driven in resonance and for the case of the speaker the amplitude is at best 1 cm (~30 ps), at the same time the movement is not sinusoidal and has temporal and lateral jitter.

* Corresponding author. Fax: +54-11-4576-3357.
*E-mail address:* santiago@df.uba.ar (S. Costantino).


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A very high frequency, but low optical delay range method was originally presented by Kwong et al. [1]. By using a grating, an achromat lens and a scanner it was possible to achieve a 2 ps time window at 400 Hz at that moment. Nowadays the usual frequencies for this technique are in the kHz order [2]. Besides, the use of a grating also carries a power loss that can be a problem for certain applications.

A very good programmable optical delay scanner is described by Edelstein et al. [3] that sweeps out delays up to 300 ps at 30 Hz. Basically the apparatus is made of a galvanometer that drives a little translation stage with a retroreflector mounted on it that can travel 1 in. It is compact and vibration free, but it is very expensive and difficult to build.

The rotating mirrors design that is modified in this work was proposed by Yasa and Amer [4] and a very similar one by Harde and Burggraf [5]. Some modifications have already been proposed to make the system more stable to misalignment, to increase the optical delay by a factor 2 [6] or to make it more compact [7]. It is very easy to build and cheap; mainly it consists in a pair of parallel mirrors mounted on the two ends of a platform rotating at a constant angular frequency as depicted in Fig. 1. The beam first travel to mirror M2 and is reflected towards M3 from which it is directed to the third mirror M4 in a direction parallel to that of the incident one. Following the rotation of the shaft by an angle $\theta$, the light will traverse a different path, emerging from M3 parallel to the original beam and with a varying displacement. The normal reflection on M4 makes the pulses travel back along the same way.

The expression that relates the optical path difference ($\Delta l$) introduced by the mirror-pair systems as a function of the rotation angle $\theta$ (for $\psi = \pi/4$ that maximizes $\Delta l$) is [4]:

$$\Delta l = 4R[\sin(\theta) - (1 - \cos(\theta))] \tag{1}$$

where $R$ is the distance from the rotation axis to center of the each mirror and $\psi$ is the orientation angle of the mirrors (Fig. 2). This equation shows a second order nonlinearity of the delay with respect to the angle.

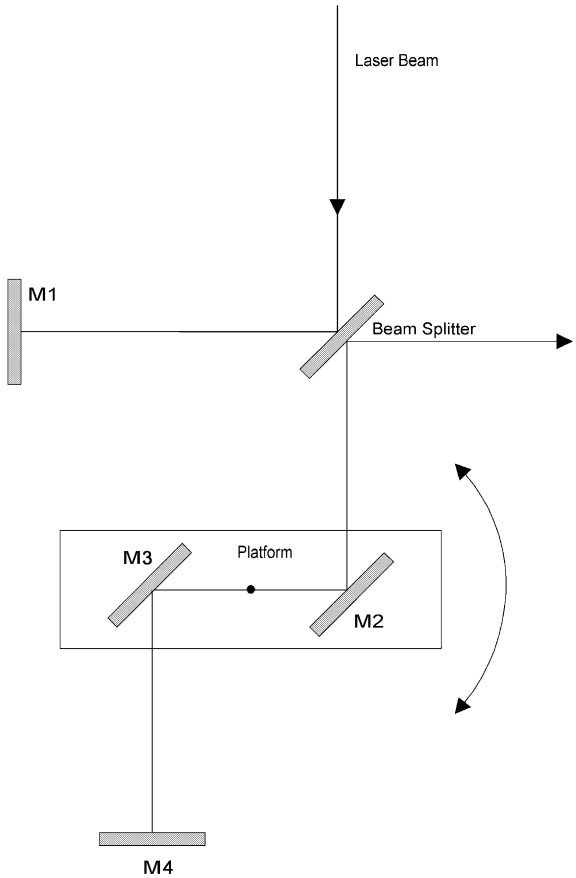


Fig. 1. Schematic of the rotating mirror-pair rapid scanning system. M1, M2, M3 and M4 are mirrors where light is reflected. M2 and M3 are mounted on a rotating platform in the original Yasa and Amer [4] work.

Another possiblity [5] is to mount a rooftop prism instead of a pair of mirrors on the platform or a retroreflector. Passing two times through the systems will easily double the delay [6] (Fig. 3).

In the case of using a hollow retroreflector the change of path length is described by

$$\Delta l = 4R\sin(\theta) \tag{2}$$

where $R$ is the distance from the rotation axis to the retroreflector vertex. The origin $\theta = 0$ corresponds to the situation in which the incident beam is perpendicular to the radius that touches the retroreflector vertex. In this case the nonlinearity is of third order.

In this work we present two innovations. We have used a stepper motor moving as a galva-

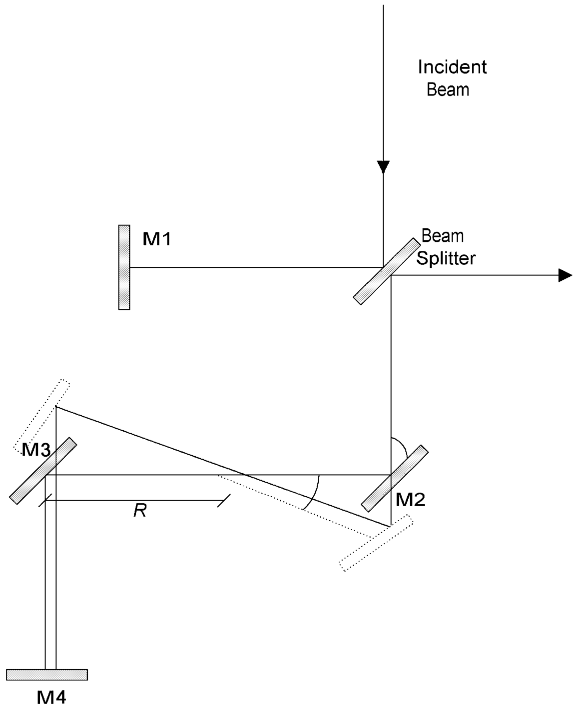


Fig. 2. When the platform moves, the optical path that light travels changes as described in Eq. (1).

nometer to make the platform oscillate improving the duty cycle and we have developed a position detector that avoids the necessity of calculating the optical delay as a function of the rotation angle.

The experimental results that we present in this work have been obtained using a retroreflector instead of a mirror pair because the position monitor signal can become strictly linear to the optical delay and the setup is easier to align.

## 2. Description of the system

One of the major problems that suffer the rotating optics methods is the very low duty cycle as the laser beam misses the optics during large portion of the rotation. The first innovation we present is to use a stepper motor in an original way to move the shaft. A sinusoidal voltage is applied to one of the solenoids and a constant current to the other. In this way, the motor moves one step forward and the next one backward following the smooth driving function.

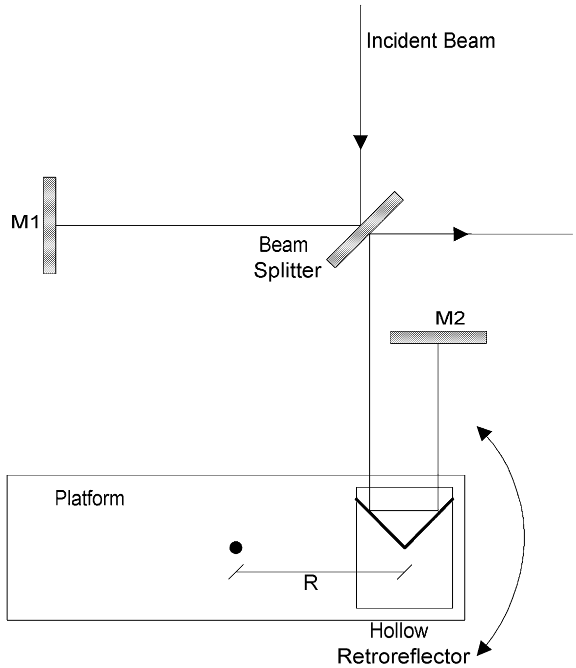


Fig. 3. A hollow retroreflector is mounted on the platform. The optical delay as a function of the rotating angle is described in Eq. (3).

This method allows to increase the duty cycle to 100% by just aligning the optics properly and adjusting the amplitude of the driving voltage.

Just to illustrate and test the idea, we have built an interferometric autocorrelator with an oscillating hollow retroreflector in one arm and a mirror mounted on a translation stage on the other. Using an oscilloscope and moving the translation stage it was possible to measure the length of the time delay at different driving frequencies. We have obtained an optical delay of 26 mm ($\sim$86 ps) at 15 Hz passing just once through the system and less for higher frequencies (21 mm at 20 Hz). The stepper motor we have used is a 5° step angle (*Astrosyn*, Mineba Co. LTD Type 23LQ-C202-01H). The aluminum bar is 10 cm long, 3 cm wide and 5 mm thick and the hollow retroreflector's aperture was 1.5 in.

The other problem to solve is that the delay these oscillating optics introduce is nonlinear with the angle they move, although analytically calculable. So as to avoid the necessity of making very precise measurements of the characteristic of the

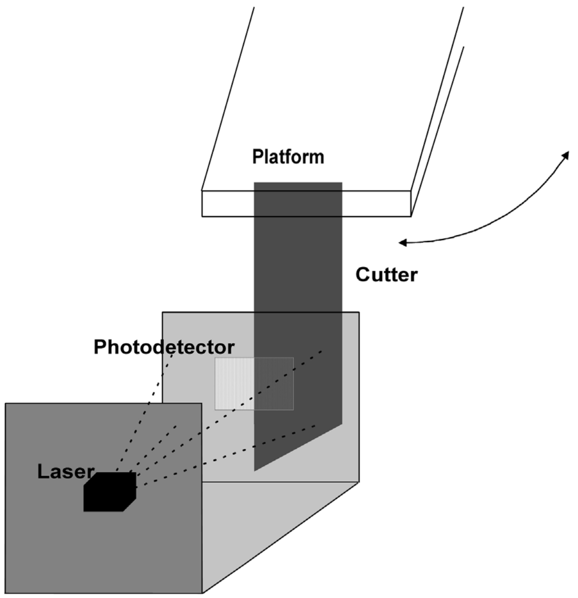


Fig. 4. Schematic of the position monitor. A laser diode shines a photodiode that can be shadowed by a cutter attached to the moving platform.

apparatus to be able to calculate the delay as a function of the angle, we have developed a low cost and easy to build position transducer. It consists in a laser diode (Sanyo DL3150-101) without collimating optics that shines a large area photodiode, a cutter is attached to the oscillating stick and blocks the laser light varying the photodiode signal (Fig. 4).

In Fig. 5 we show a plot of the driving voltage applied to the stepper motor and the photodiode signal of the positioning monitor. It is possible to see that the platform follows the driving signal.

With this setup it becomes very easy to obtain the calibration curve of the photodiode signal as a function of optical delay that would be necessary to real-time software correct any nonlinearity. This calibration can be done in many manners, we have used a 100 fs mode-locked Ti:sapphire autocorrelator because the system was already operative. Using an oscilloscope operating in XY mode, it was possible to obtain this curve with an error comparable to the pulse width. The X channel is connected to the position monitor photodiode and the Y channel shows the autocorrelation signal. The position signal at the peak of the autocorrelation is then plotted as a function of the delay of the other arm. In Fig. 6 we present calibration curves obtained at four different frequencies.

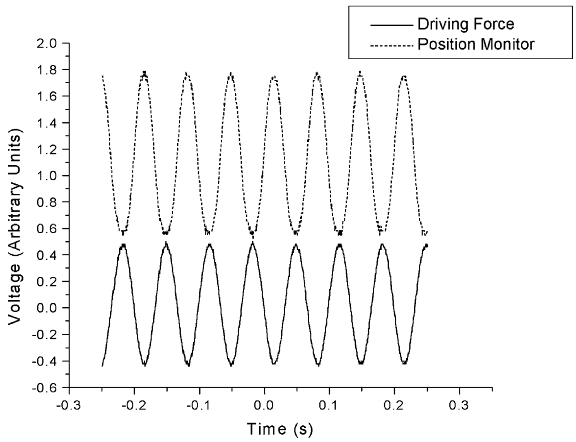


Fig. 5. Plot of the driving voltage applied to the stepper motor and the position monitor signal for an arbitrary frequency.

The position monitor calibration allows to correct intrinsic nonlinearities of the spinning optics method, evident in Eqs. (1) and (2), and also compensate other systematic errors due to optical misalignments or nonuniform illumination of the monitor photodiode. Whether if there exists a misalignment or a positioning problem, calibration

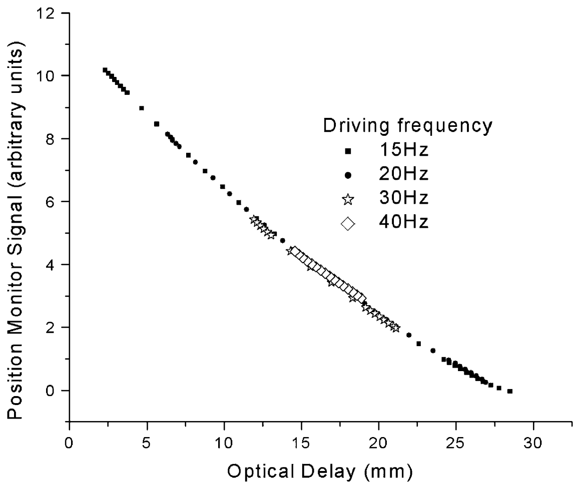


Fig. 6. Calibration curves of the fast scanner system. One arm of the interferometer was moved and compared to the position monitor signal. The results are presented for four different driving frequencies.

function is useful to recalculate the optical delay while acquiring data in an experiment.

The system as described requires an online computer processing to calculate the delay as a function of the position monitor signal. To make the position signal strictly linear to the time delay two facts should be taken into account. The first, and obvious one, is that the photodiode should be homogeneously illuminated. This can be easily accomplished by increasing the distance between the laser diode and the photodiode until the desired homogeneity is achieved.

The second fact is that if the detector is illuminated as just described the photodiode signal $S$ is:

$$S \propto \sin(\varphi) - \sin(\varphi_0) \tag{3}$$

where $\varphi_0$ is the angle at which the photodiode is totally covered by the cutter. The origin $\varphi = 0$ is the position at which the line that passes through the cutter edge and the center of rotation is parallel to the diode laser beam. If the system is aligned so that $\varphi = 0$ coincides with $\theta = 0$, then a linear relation holds between the delay (Eq. (2)) and the position monitor signal (Eq. (3)).

In Fig. 7 we show the achieved optical delay as a function of the driving frequency of the stepper motor showing the limits for this particular model.

It should be mentioned that the main advantage of a diode laser as the illumination source of the position monitor is that it comes with a sensing photodiode that can be used as a normalization reference or in a feedback circuit to keep constant emission power. In this manner the calibration is not altered by fluctuations in the emission power.

As a final comment, if a path duplication scheme [6] is used and a second retroreflector is mounted on the same platform opposite to the first one, for the other arm of the interferometer, an eightfold increase for the total delay can be easily achieved, yielding up to 840 ps for our present device.

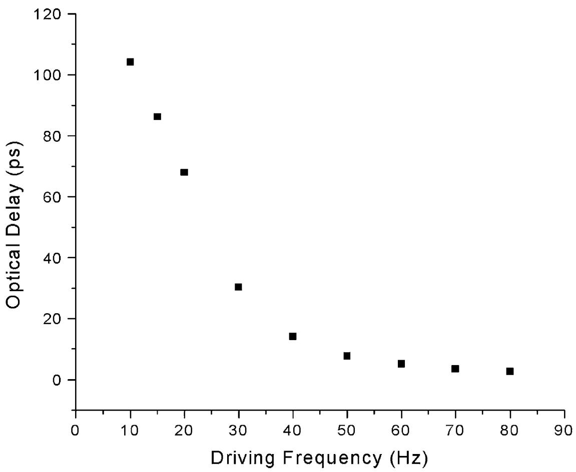


Fig. 7. Plot of the maximum optical delay achieved as a function of the driving frequency.

## 3. Conclusions

We have described a new fast scan system based on a stepper motor used in a single step oscillating mode and a position monitor device based on a diode laser.

The motor used in our setup yielded delays as large as 105 ps at 10 Hz, dropping to 30 ps at 30 Hz. This scheme has an increase of the duty cycle to almost 100%, as compared to less than 3% obtained in typical spinning optics schemes.

The oscillating stepper motor requires a sensing device in order to monitor the position. Instead of using an angular encoder, we introduced a simple, reliable device based on the shadow of a moving cutter. The use of a diode laser avoided the errors arising from power fluctuations that normally appear in shadow schemes with other light sources. Furthermore, if the optical elements are precisely positioned, the nonlinearities are cancelled and the signal results proportional to the introduced path difference, not requiring computer aided corrections.

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