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Optomechatronics of laser micro-processing for manufacturing of optical waveguides

Optomecatrónica de micro-procesamiento láser para fabricación de guías de onda ópticas

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Abstract

A prototype optomechatronics system for laser engraving of multimodal optical waveguides is presented herein. This system is based on the optomechanics of micro-positioning used for the optical disk drives. The development consists of a human-machine interface, a CO_2 laser that selectively fuses the substrate, and a two-stage linear micro-positioning system. The first stage uses a servomotor setup that provides a linear displacement of 10mm when is applied a 180° rotation; the second stage is based on a galvanometer, providing a linear displacement of 2mm when varying the voltage at its terminals in a range of ±10V with an 8 bits digital to analog converter. For an optical power density of ~7.5W/mm^2, the results show an average waveguide width of 320μm on polymethylmethacrylate substrates and 270μm for glass substrates. These waveguides could be used in the development of photonic biosensors.

Optomechatronics, Waveguides, CO_2 laser

Resumen

Se presenta un sistema optomecatrónico prototipo para grabado láser de guías de onda ópticas. Este sistema está basado en la optomecánica de micro-posicionamiento empleado en las unidades de disco óptico. El desarrollo está constituido por una interface hombre máquina, un láser de CO_2 que funde selectivamente el sustrato y un sistema de micro-posicionamiento lineal de dos etapas. La primera plataforma utiliza un arreglo de servomotor (piñón-cremallera) que proporciona un desplazamiento lineal de 10mm al aplicar una rotación de 180°; la segunda está basada en un galvanómetro que proporciona un desplazamiento lineal de 2mm al variar el voltaje en sus terminales en un intervalo de ±10V con un convertidor digital analógico de 8 bits. Para una densidad de potencia óptica de ~7.5W/mm^2, los resultados arrojan un ancho promedio en la guía de onda de 320μm sobre sustratos de polimetilmetacrilato y de 270μm para sustratos de vidrio. Estas guías de onda podrán ser empleadas para el desarrollo de biosensores fotónicos.

Optomecatrónica, Guías de onda, Láser de CO_2

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Introduction

In the current environment it is difficult to imagine any technology that does not involve light, whether emitted by a source or received by a detector. Optics is precisely the science that studies the behavior of light and is immersed in areas such as electronics, medicine and communications. The fact that light is and tends to be in even more technologies is because of its speed and because it has no mechanical contact with the body in which it affects.

In this sense, mechatronics, when merged with optics, gives rise to optomechatronics (Cho, 2002), a branch of engineering that automatically controls the movements of devices that detect or emit light, such as laser processing systems (Cho, 2005). Another engineering that uses light is biomedical for biosensing applications (clinical diagnosis), where one of the ultimate goals is the development of integrated nanophotonic circuits for the simultaneous detection of multiple pathological agents present in fluids (lab-on-a-chip).

One of the fundamental components for these biosensors are the optical waveguides, which allow the propagation of light between two points (Čižmár, 2011). Figure 1 shows the schematic of a nanophotonic biosensor which is composed of the substrate that supports a metal nanostructure where the interaction of light with fluids and the waveguide embedded in the substrate occurs. The fundamentals of optics are of great relevance for technological areas such as communications, medicine, industry, etc. and mechatronics is not the exception. This is because the light has properties that distinguish between them their speed (3x10-8km / s), does not produce mechanical efforts and with it can store enormous amounts of information.

One way to develop an embedded waveguide is by locally modifying the refractive index of a substrate following a certain pattern of lines (Alvarado, 2013). For this reason, its manufacture requires appropriate methods and tools. The most used methods for this are the reactive ion exchange (using masks recorded by photolithography), the deposition by flame hydrolysis (FHD) and by laser marking (Aggarwal, 1984). For this last case, systems that can perform micro-positioning for the writing of the guides are required.

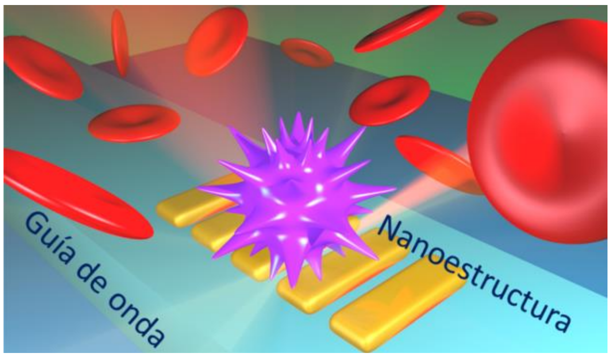

Figure 1 Schematic of a nanophotonic biosensor with the waveguide embedded in the substrate
Source: Self Made

In this sense, the nano-electromechanical (NEMS) and micro-electromechanical (MEMS) systems have been used for the manufacture of these elements at nano- and mico-metric scales (Bao, 2005). In the most used technologies for N / MEMS actuators, the micro motor with electrostatic steps and cantilever plates is found, leaving the nano-positioning to the technology of piezoelectric plates. (Hwu, 2006). There is a wide market of distributors of micro-positioning systems, but the clearest disadvantage is the initial investment to acquire these devices.

A low-cost alternative is the technology used for reading and writing optical discs (practically discontinued), since it has a sophisticated optomechatronic system that has a precision and fine positioning scale. (Wilkander, 1992). These systems are able to read repeatedly and without error the tracks (pits) of the compact discs, which are separated distances in the order of μm or nm depending on the format (Taylor, 1998). Taking into account the wide use of micro and nano positioning systems in the area of experimental optics, in this work a micro-positioning system based on the optomechatronics of the optical disc unit for the laser writing of guides was implemented wave.

Optomechatronics for laser micro-processing

The development of this project consists of two main stages: the development of a mechatronic system for the micro-positioning of the substrates based on the use of an optical disc reader, and the development of a control system for turning on and off the laser used for writing the waveguides.

Mechatronic system

Optical disc (DO) drives for CD, DVD or BD disc playback have the same operating principle (Stan, 2013). Its positioning resolution depends on the wavelength of the laser used for reading. The optomechatronic used by these systems consists of two stages.

The first provides a uniaxial motion with stepper motor for a coarse movement of the reading head by means of an arrangement of reducing gears, while the second uses a galvanometric system for micro and nano metric displacement of the lens.

For this project, the thick displacement stage did not have significant changes focusing on the galvanometric actuator. Its displacement depends on the voltage induced between one of the two pairs of terminals with which the electromechanical assembly has.

Each pair of terminals are connected to an inductor that, by the passage of a controlled current, generates an electromagnetic field which induces two possible movements, the linear displacement and the movement to focus the lens, the first being the employee in this project.

Figure 2 shows the diagram of the elements that provide the movement of the galvanometric micro-positioner (where the objective lens is mounted), which are: (1) pairs of copper wires, which provide support for the positioner to be discontinued.

They show deflection due to the interaction of the electromagnetic field and permanent magnets. (2) - (3) pair of terminals of each support wire in which the control voltage is induced, either for the linear or focus movement of the lens; (4) permanent magnets to provide a permanent magnetic field that interacts with the electromagnetic fields caused by the passage of current in the inductors; (5) career stops to limit the displacement of the lens, (6) inductors to generate an electromagnetic field by inducing voltage at the terminals and (7) the objective lens.

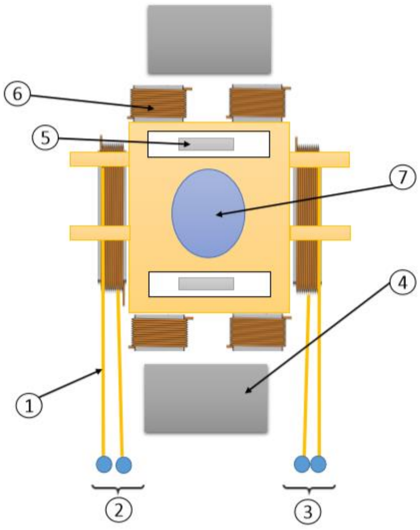

Figure 2 Schematic of a galvanometric actuator
Source: Self Made

The normal actuator position is in the center of the structure. To displace it, a bipolar voltage must be applied. If there is only one unipolar voltage signal to feed the galvanometric system, a unipolar to bipolar signal conditioning circuit can be used (Duke, 2013) as shown in Figure 3. This circuit uses an operational amplifier with negative feedback and three resistors in a modified adder amplifier configuration to generate high voltage bipolar outputs from a unipolar Digital Analog Converter (DAC).

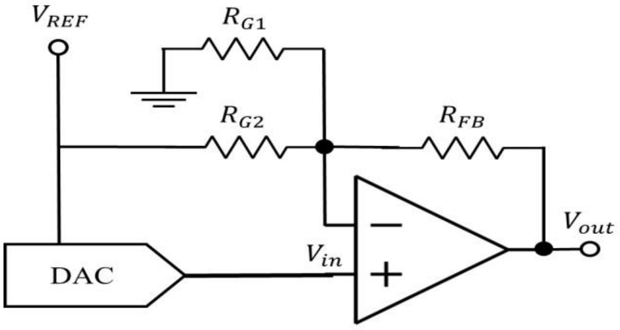

Figure 3 Circuit conditioning of unipolar signal to bipolar
Source: Self Made

The CD transfer function of the circuit, given in equation (1), is based on the ratio of the R_{FB} feedback resistor and the gain adjustment resistors R_{G1} and R_{G2}:

$$V_{out} = \left(1 + \frac{R_{FB}}{R_{G2}} + \frac{R_{FB}}{R_{G1}}\right) V_{in} - \frac{R_{FB}}{R_{G2}} V_{REF}. \qquad (1)$$

When the output of the DAC ($V_{DAC} = V_{in}$) is 0V, the inverting input is a virtual ground so that no current flows through R_{G1}, making the circuit operate as an inverting amplifier with gain equal to R_{FB}/R_{G2}.

When the output of the DAC is V_{REF}, the potential of the inverting input is equal to V_{REF} so that no current flows through R_{G2}, causing the circuit to operate as a non-inverting amplifier with gain equal to (1 + R_{FB} / R_{G1}). For the calculation of the resistive components in case the full scale of V_{out} is ± 2V_{REF} it is necessary to:

$$R_{G1} = R_{FB}, \tag{2}$$

$$R_{G2} = R_{FB}/2. \tag{3}$$

Optical system

The laser manufacturing process of waveguides embedded in substrates consists of engraving lines on a substrate by melting the material. This modifies the refractive index in the irradiated area. For this the parameters that have to be considered in the laser process are the optical power density, and the speed of movement as a function of the substrate material.

The power density is defined as the power P that affects an area A and is given by the expression:

$$DO = \frac{P}{A} \tag{4}$$

The area is defined by the expression $A=\pi(d/2)^2$ where the diameter d is provided by the laser equipment manufacturer. This power density can be increased by placing a lens in the laser path, which can theoretically focus the beam diameter up to half the wavelength (λ) emitted by the laser (diffraction limit), determining the theoretical limit of the width of our waveguide.

Experimental arrangement

For the experimental tests, the arrangement shown in figure 4 was implemented. The assembly includes the micro-positioning galvanometric system (1), the servo motor for pre-positioning (2) and the CO_2 laser with λ = 10.64μm (3), all controlled by computer. Within the optical arrangement used is a mirror at 45 ° (4), which reflects the laser beam towards the target, and it passes through a lens (5) where theoretically the spot is reduced to λ / 2., For the tests of etching, different substrates (6) were used, keeping the average optical power and the speed of displacement fixed.

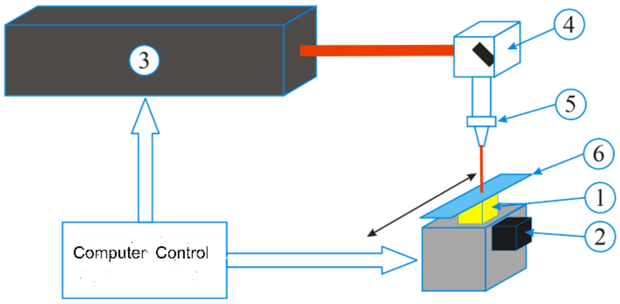

Figure 4 Schematic of the experimental arrangement
Source: self made

Results

Optomechatronics

For the galvanometer used, it was found that for an input voltage of 1.53V and a current demand of 0.4A (3.9Ω), the head makes contact with one of its stroke stops approximately 1mm away from the origin, ie, to have a total displacement of 2mm, requires a bipolar voltage of ± 1.53V. To decrease the signal-to-noise ratio of the control voltage it was increased to ± 10V and a series resistor of 20Ω was added to maintain the current ratio.

To control the movement of the galvanometer, a National Instruments USB-6008 data acquisition card was used that has digital-to-analog converters (8 bits) on a scale of 0V to 5V. To convert this unipolar control output to a bipolar ± 10V output, the circuit of Figure 3 was constructed, using an LM3886 power operational amplifier. The calculation of the components based on a feedback resistance R_{FB}=20KΩ resulted in R_{G1}=20KΩ and R_{G2}=10KΩ, having an error of ± 0.2V in the output voltage.

The control of gross movement of the detector head did not have significant changes. For this purpose, a rack-and-pinion servomotor arrangement was used, which, by applying a 180 ° rotation, provided a linear displacement of 10mm. Figure 5 shows a laser processing image of a substrate with the optomechatronics developed.

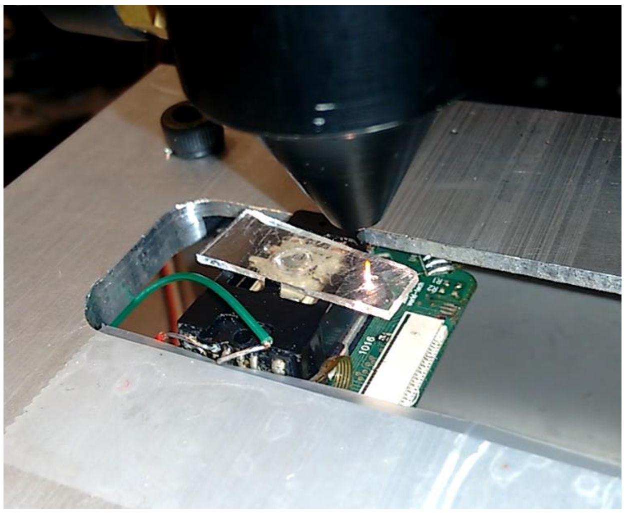

Figure 5 Laser processing of a substrate with the optomechatronics developed
Source: Self Made

The man-machine interface was developed using LabVIEW software, whose front panel is shown in Figure 6. The initial position field controls the linear displacement of the read head. Knowing that the maximum displacement is approximately 2000μm, the start of the processing can be done along those 2000μm. Due to the sampling frequency of the NI USB6008 card (10KS / s), there is a minimum allowed exposure time (time it takes to manufacture the guide) which is a function of the length of the waveguide to be manufactured (0 to 2000μm). If you want to respect the theoretical resolution provided by the DAC of the card, you must select a time greater than or equal to the minimum exposure time.

POSICIO INICAL (um) 500

Tiempo de Exposicion [s] 1.8

Tamaño de guia (usuario) [μm] 2000

Tiempo minimo de exposicion permitido [s] 1.7094

SELECCION DE POTENCIA PROMEDIO 0.5

PERIODO SELECCIONADO 1500

ANCHO DE PULSO NECESARIO 22

Figure 6 Man machine interface developed in LabVIEW
Source: Self Made

Manufacturing of guides

For the writing of the waveguides, a 150K DIMOND laser was used by Coherent Inc. This laser emits an electromagnetic transverse mode with Gaussian profile (TEM00) and a maximum optical power of 150W in quasi continuous operation.

The manufacturer indicates a beam diameter of approximately 7mm. The power used in the laser writing was 0.6W that corresponds to an optical density DO≈15mW / mm2 during the process. Below are two of the results obtained from engraving the waveguides. The first one was made on polymethylmethacrylate substrate (Figure 7) and the second on a glass substrate (Figure 8). These images were taken with a commercial optical microscope. The diameter measurement of the guide was made by means of a reference standard, obtaining for the acrylic an approximate diameter of 320μm and for the glass an approximate diameter of 270μm. It can be highlighted from these photographs that in the direction of movement (vertical) the steps of movement are imperceptible even at this scale.

Acknowledgement

Ing. Xavier Eduardo García Sánchez for his collaboration in the development of mechatronics.

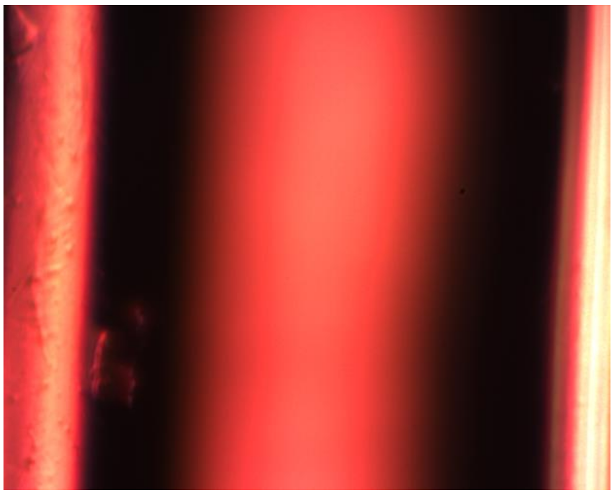

Figure 7 Wave guide written in polymethyl methacrylate
Source: Self Made

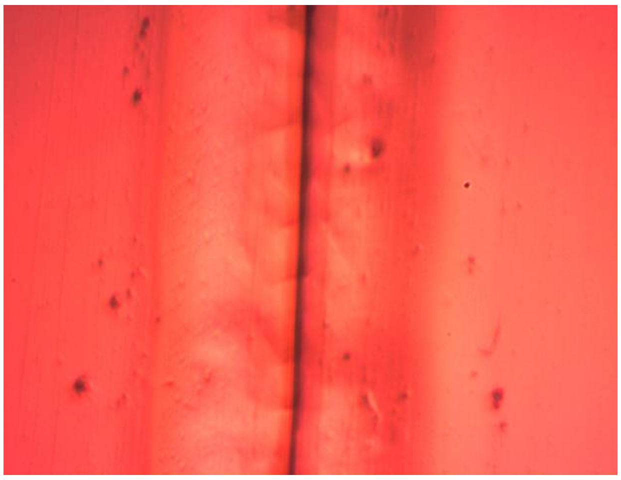

Figure 8 Wave guide written in glass
Source: Self Made

Conclusions

This work has shown a practical and innovative use based on the sophisticated technology but at the same time underestimated by the optical disc units. The galvanometric system provided a linear displacement of 2mm by varying the voltage at its terminals in a range of ± 10V with an 8-bit analog digital converter. For an optical power density of ~ 7.5W / mm2, the results showed an average waveguide width of ~ 320µm on polymethylmethacrylate substrates and ~ 270µm for glass substrates. These preliminary results will allow the optimization of waveguide writing processes in different substrates that may be used in the development of integrated photonic biosensors.

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