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2D Laser Scanners for Automobile Applications

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1. Introduction

The most widely used optical scanners today are polygon mirrors and galvanometric mirrors. Although research is continuing in these fields nowadays[1], research on optical scanners made with MEMS technology started at the beginning of the 80's[2]. The applications for optical scanners are numerous and include display, barcode readers, printers, radar systems and optical communication systems. Because of this diversity of applications for optical scanners, designs and actuation mechanisms are also numerous. Electrostatic, thermal, piezoelectric, electromagnetic and magnetostrictive scanners have been reported in the literature. They also include one-dimensional (1D) and two-dimensional (2D) scanners. However, most MEMS optical scanners reported previously possess a small mirror (area is usually around 0.25 mm^2). This size of mirror is unsuitable if simple optical elements as well as cheap laser sources are to be used, the size of the spot being rather 5mm in diameter. It is only recently that MEMS optical scanners with a large mirror have been reported[3,4].

The devices presented in this article are included in this last category of devices where the size of the mirror is several mm^2. They were studied and realized in the frame of a cooperative project with the Nissan Motor Company. For the application, the requirements are:

- The scanner is a two-dimensional (2D) scanner.
- The mirror size is 6×8 mm^2.
- The peak-peak optical deflection angles are 40° and 10° in the two scanning directions respectively.
- The ratio between resonance frequencies is more than 5.
- The lowest resonance frequency is around 100Hz.

The size of the mirror is imposed by the desire to use a cheap laser source whose spot size is 5mm in diameter and simple optics. The deflection angles are specified by the application. The ratio between the resonance frequencies is to obtain a nice scanning pattern. Finally, the required value for the lowest resonance frequency is imposed by the electronic processing of the signal. Potential applications for such a device are related to objects detection in a given 3D space.

Previous studies conducted in LIMMS showed the possibility of using magnetic materials to excite the mechanical resonating modes of 2D optical scanners realized by MEMS technology[5,6]. More recent studies showed that this principle could be extended to make a 2D scanner with a large mirror, good optical performances and including piezoresistive gauges to perform real-time position detection[4]. However, the deflection angles of this scanner appeared to be too small for the application. In order to overcome this drawback, two new kinds of scanners were developped and are presented here: the frame scanner and the PDMS scanner.

2. Frame scanner

The first design is a silicon-only device with magnetic layer coating which allows an electromagnetic actuation. This project was initiated by T. Bourouina, a CNRS researcher belonging to LIMMS and working in the laboratory of Pr. Matsuzawa. The design, modelization and silicon processing has been done by A. Debray, a LIMMS researcher affiliated with the laboratory of Pr. Fujita. A scheme of the scanner with the used dimensions is presented in Fig. 1. It consists of a large mirror, a frame and four beams. The thickness of the mirror and of the frame is the same as the wafer (225 or 525μm) and therefore cannot be deformed during operation. The laser beam reflects directly on the polished silicon surface. The thickness of the beams is much smaller and therefore they can be easily deformed. Using ANSYS software, modal, harmonic and static anlaysis have been performed in order to design the shape and dimensions of the scanner fitting the requirements. As explained on Fig. 2, the actuation is made *via* the application of a magnetic field H perpendicularly to the mirror

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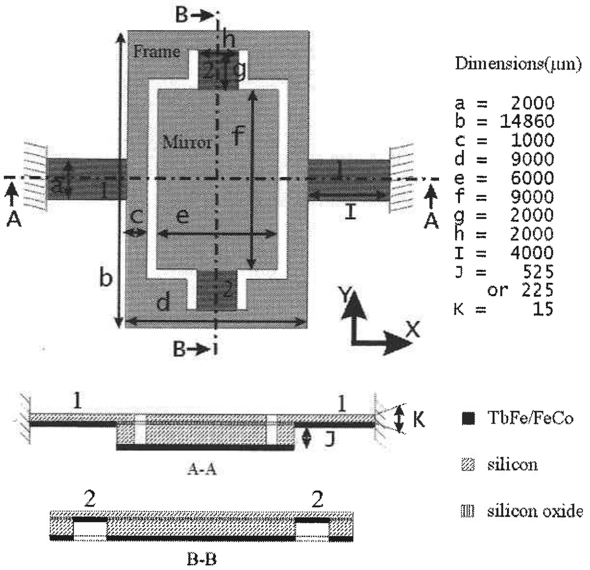

Fig 1　Scheme of the 2D «frame» scanner.

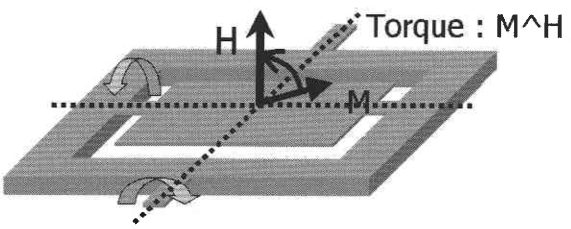

Fig 2　Principle of the 2D Electromagnetic Actuation.

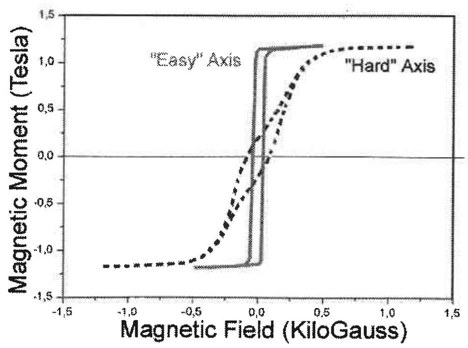

Fig 3　Magnetic characteristic (Magnetization loop) of the TbFe/FeCo multilayer.

plane. The chosen magnetic layer is an artificially nanostructured multilayer: such a structure, obtained by the sputtering technique, allows the combination of the magnetic properties of different alloys, in order to «tailor» the characteristics of the final layer. In our particular case, it is realized by stacking TbFe alloys with so-called «hard» magnetic properties, and FeCo with «soft» properties but high saturation magnetization.

The resulting layer magnetic properties are shown on Fig 3. This

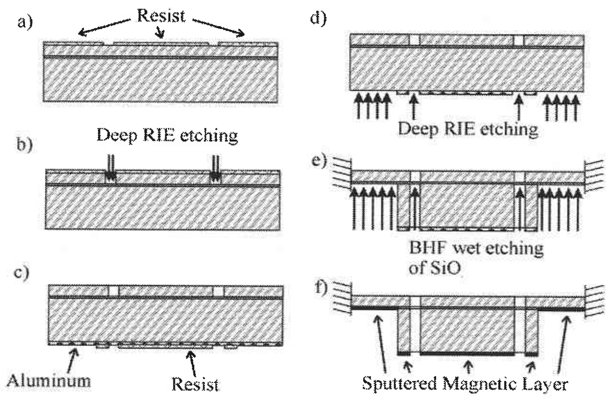

Fig 4　Process flow chart (Fig. 1 A-A view).

kind of magnetic behaviour is typical of «uni-axial» anisotropy. It means the magnetic layer magnetic moments exhibit a priviledged axis. Moreover, the coercive field required to switch the direction of the moments on this axis is high enough to avoid a continuous switching of the magnetic moments during an alternative excitation. This magnetic material layer has been developed by A. Ludwig and Pr. E. Quandt in the CAESAR institute and was deposited by them in their institute[7].

The technological process is summarized on Fig. 4. It starts with a 15μm-thick SOI wafer. The shape of the scanners is patterned on the front side using deep RIE with a photoresist mask. The backside is then etched using deep RIE with an aluminum mask. The structures are released using BHF. Finally, the magnetic material is sputtered everywhere on the backside. A magnetic field is applied during the deposition in order to generate the «easy axis» in the thin film. The mechanical stress in the torsional spring is small enough so that no further annealing is needed. Each layer has a thickness of about 10 nanometers and the total thickness of the film is around 4μm.

This device has been characterized using the experimental setup shown on Fig 5. The magnetic driving field is applied on the entire sample and is perpendicular to the thin film. A 7cm diameter coil, fed with a sinusoidal current, produces this magnetic field. The two first modes of the mechanical structure can be excited. For a magnetic field of 0.3 mT, the first mode, that is the frame with the mirror in tortional vibration, is at 52 Hz, the total optical deflection being 32°. For the same magnetic field of 0.3 mT, the second mode, that is only the mirror in torsional vibration, is at 235Hz, the total optical deflection being 11°. The frequency responses for these first two modes for a magnetic field of 0.5 mT are presented in Fig. 6. The behavior of these scanners is seen to be non-linear with a hard spring effect[8]. When the coil is driven by the superposition of two sinusoidal currents at 50Hz and 230Hz respectively, and that the magnetic field produced is 0.8mT, the two first modes of the structure are excited simultaneously. The

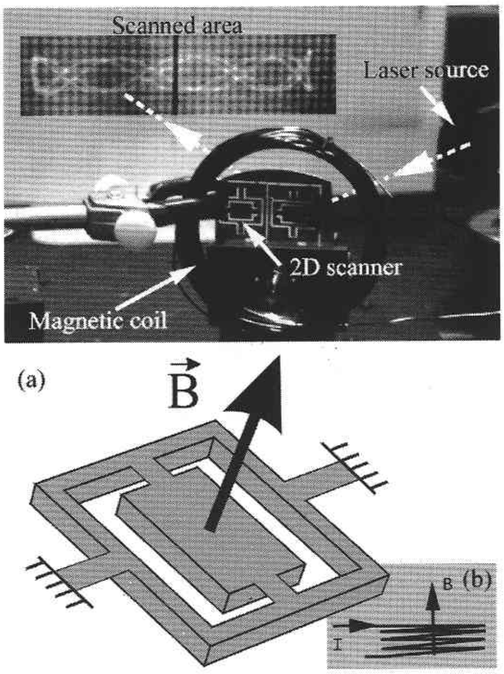

Fig 5 Characterization setup for the «frame» scanner.

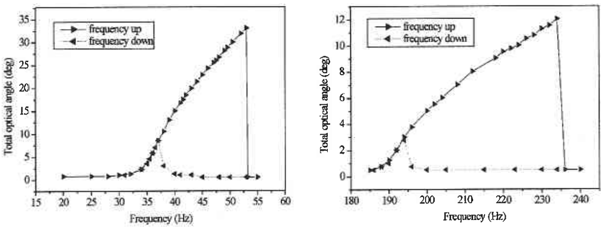

Fig 6 Total optical deflection angle frequency response for a magnetic field of 0.5 mT: left: the outer beams being deformed in torsion—right: the inner beams being deformed in torsion.

total optical deflection produced by the first mode is of 35°, and the total optical deflection produced by the second mode is of 6°.

The requirements concerning the resonant frequencies, frequencies ratio and deflection angles have been almost met. When compared to the previous prototype of the same project[4], it appears that the mechanical-magnetic sensitivity of the device has been improved by a factor from 60 to 80, depending on the scanning direction. The characterisations have been made independantly by the three collaborative groups on several samples made in different process runs. They all confirmed these improvements. These improvements are due to the mechanical and magnetic design optimizations as well as modifications in the process.

Further information on the work can be found in the paper accepted in the Journal of Micro-Electro-Mechanical Systems[9]and the presentation at the International Conference on Optical MEMS[10]. Two pattents have been submitted by our industrial partner[11,12].

3. PDMS scanner

Although the precedent device almost fulfills the requirements, it is expected that this device will be too fragile for several applications. When trying to find a new solution for this project, our attention turned to a polymer widely used in micro fluidics to realize micro channels for liquids, the Poly-Di-Methyl-Siloxane, also known as the PDMS. Due to its extremely low elasticity and high resistance, this polymer seemed to be suitable to the hinges of the scanner and large deflection angles of the mirror were expected.

The mechanical structure of the PDMS scanner has been designed and fabricated by A. Debray and E. Leclerc, both belonging to LIMMS; the former was affiliated with the laboratory of Pr. Fujita for the silicon micromachining research and the latter with the laboratory of Pr. Fujii for the PDMS micromachining research. N. Tiercelin, specialized in magnetic materials, was in charge of the actuation part and supervised the magnetic film deposition at the CAESAR laboratory with A. Ludwig. He also conducted the characterization of the device in the laboratory of Pr. Fujita.

A schematic of the scanner is shown in Fig. 7. Two PDMS hinges support a silicon mirror and the whole system is held on a silicon support. As with the previous device, a magnetic layer is deposited on the backside of the mirror and insures the actuation *via* electromagnetic interaction. Before using the magnetic layer, a series of experiments with a permanent magnet attached to the mirror showed that scanning in two directions is possible. Therefore, the direction of the magnetic moments in the layer is set at a 45° direction in the mirror plane in order to generate the electromagnetic torque along two axes.

The fabrication is done using MEMS facilities. By photolithography, an SU-8 negative mold structure of the scanner is fabricated on a glass substrate and covered by a Teflon layer. Then, a sandwich molding of the PDMS is performed to get a thin membrane between the glass substrate and a silicon wafer[13]. The PDMS layer is then carefully peeled off with the silicon wafer from the SU-8 mold master. The obtained membrane thickness is around $135\mu m$. The mirror is then released by a deep ICP-RIE etching through the wafer performed from the backside using an aluminum mask. Finally, the magnetic multilayer is deposited by magnetron sputtering, combined with the shadow mask technique to avoid deposition on the polymer hinges. A magnetic field is applied in the chamber during the deposition in order to induce the privileged magnetization direction at 45° with the hinges direction. The total thickness of the layer is $4\mu m$.

The experimental setup used for the characterization of the

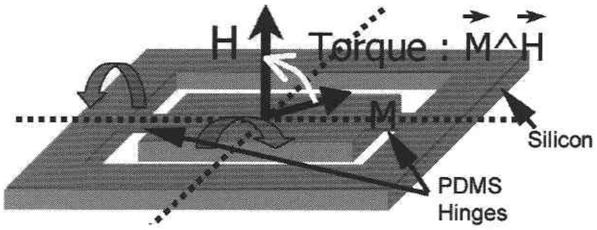

Fig 7　PDMS scanner principle.

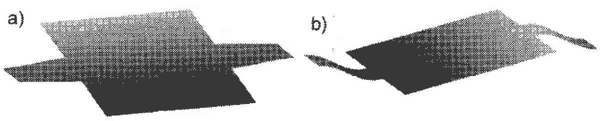

Fig 8　Simulated Resonance modes : (a)hinge torsion, (b)hinge bending mode.

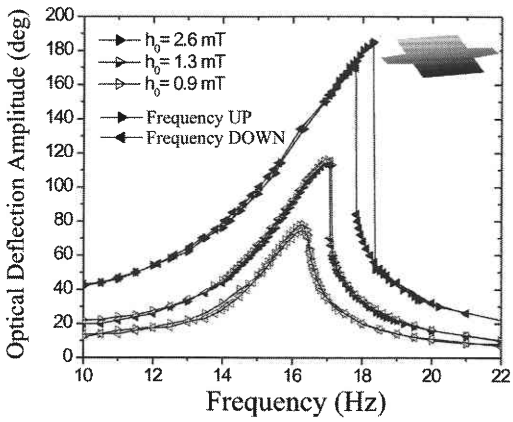

Fig 9　First vibration resonance of the scanner in "hinge torsion" mode.

device is similar to the previous one. The mirror has been excited by an alternative magnetic field $h(t) = h_0cos(2\pi f.t)$. When sweeping the excitation frequency from low to higher values, scanning of the laser in two perpendicular directions occurs for different frequencies. Modal analysis performed by N. Tiercelin using the FEMLAB software (Fig 8) confirmed that the 2 first resonance modes are a "hinge torsion" mode and a "hinge bending" mode. These allow the 2D scanning function with only one pair of hinges.

The "hinge torsion" and "hinge bending" modes have been observed and are shown on Fig. 9 and 10. The magneto-mechanical sensitivity of the torsion mode is greater that the bending one. This is due to the geometry of the device. Figure 9 shows the optical deflection amplitude obtained when sweeping the frequency up and down over the resonance area, for different excitation amplitudes. Optical amplitude of more than 180 degrees with an excitation field of only $3.2mT$ of amplitude was obtained at $18Hz$. These are typical characteristics caused by a nonlinear elas-

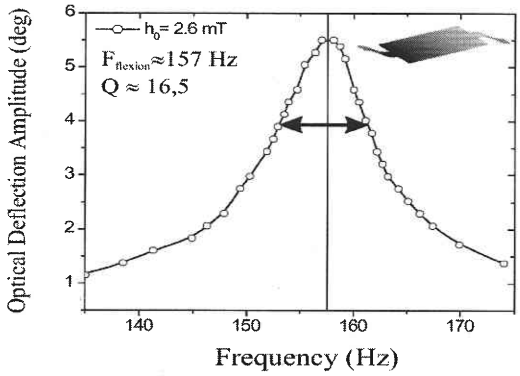

Fig 10　Second vibration resonance of the scanner in "hinge bending" mode.

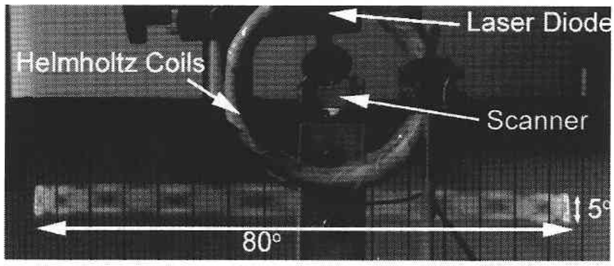

Fig 11　2D-laser scanning with the PDMS scanner.

ticity effect, so called "hard spring" effect[8].

2D-scanning has also been achieved by applying two frequencies simultaneously. Two sinusoidal signals of $18Hz$ and $164Hz$ with equal amplitude were mixed resulting in a magnetic field of $2.5mT$ AC amplitude. The obtained deflection pattern is shown in Fig. 11. An 80° wide and 5° high laser scanning area was obtained. To compensate the fact that the bending mode is harder to actuate, it is possible to change the "easy axis" direction to increase the torque in the needed direction. Further works in this direction are in progress.

This work has been presented at the International Conference on Optical MEMS[14].

4. Conclusion

This paper presented here two kinds of actuators devoted to 2D laser scanning for automobile applications. Because of this industrial perspective, special requirements have to be met such as large deflection angles, large mirrors, integration of position sensors and of course a sufficient robustness to be integrated into an automobile. The first proposed design or "frame scanner" satisfies to most of the requirements including, thanks to the silicon technology, the embedding of piezo-resistive position sensors, although it is not presented here. The major drawback of the structure is its poor robustness because of the thin silicon hinges. The second design, however, showed an outstanding resistance and impressive scanning angles because of the PDMS based hinges. This technology is nevertheless very new, and the behavior of PDMS over a long period of time is not known yet. Also, hybrid structures with PDMS and silicon have to be used to integrate the position sensors. New scanning applications using this material are currently under investigation.

This paper also showed some interesting features of the LIMMS. First, with these two projects, we can see that LIMMS projects can involve several generations of LIMMS researchers. Although the French researchers stay in IIS during 2 or 3 years, the roots of these projects, optical scanners using magnetic materials, have started 5 years ago. Secondly, with the second project, we can see that the LIMMS could help combining technologies and know-how from different laboratories in IIS in order to lead to new projects and new technological solutions.

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