A FAST, ROBUST AND SIMPLE 2-D MICRO-OPTICAL SCANNER BASED ON CONTACTLESS MAGNETOSTRICTIVE ACTUATION

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ABSTRACT

We have fabricated and successfully operated a new 2D Micro-Optical scanner based on contactless magnetostrictive (MS) actuation using only one coil. A Si cantilever coated with a sputter-deposited MS film is vibrated simultaneously in both bending and torsion modes at high frequencies (10-50 kHz). It exhibits the maximum optical deflection of +/- 12 degrees at an excitation filed of 4 mT; this is only 2% of the saturation field of the MS material. Moreover, the contactless magnetic actuation enabled an easy wireless vacuum encapsulation that gave Q-factors up to 1400 and improved the vibration amplitude four times more than that in air.

INTRODUCTION

One of the challenging problems in microsystems is supplying power without wires. Since the scaling law prohibits a microsystem from holding large amount of energy in it, remote power sources through some kind of field are an attractive alternative. Because of its magnetic nature, magnetostriction enables such a wireless actuation. Moreover, its maximum available strain is comparable or better than that of piezoelectric actuation [1] and its response time is in the 10^{-9}-10^{-13} second range that makes the main speed limitation depending mainly on the mechanical structure design.

Recent achievements in material science enables thin film deposition of a few magnetostrictive materials [1-5]. Some of them have been successfully used in MEMS [1,5]. For instance, static deflections up to 200 micrometers on millimeter-sized cantilevers have been reported [5].

In this paper we report on magnetostrictive actuators, which were obtained by thin film deposition of Terfenol-D (TbDyCoFe alloy) on silicon structures. Furthermore, since there is no need for electrical connections to the actuator, a cost-effective vacuum packaging (for enhancement of the quality factor) could be easily fabricated. It consists of a glass tube. As a demonstration of their actuation capabilities, these actuators were used as two-dimensional optical-scanners.

MAGNETOSTRICTIVELY ACTUATED 2D OPTICAL-SCANNER

The core of the prototype is a magneto-elastic bimorph resonator. It consists of a rectangular single-crystal-silicon cantilever beam coated with a thin film of sputter-deposited Terfenol-D doped with cobalt (TbDyCoFe alloy), which has giant-magnetostrictive properties [3]. The studied silicon cantilevers are 1 mm long, 400 μm-wide and are 5 or 15 μm–thick. The MS film is 2 μm–thick. The resonator is (optionally) encapsulated in vacuum, inside a homemade glass tube (fig.1,2), in order to obtain high Q-factors. External twin-coils mounted in Helmotz configuration are used to produce a nearly uniform magnetic field for the excitation of the resonator.

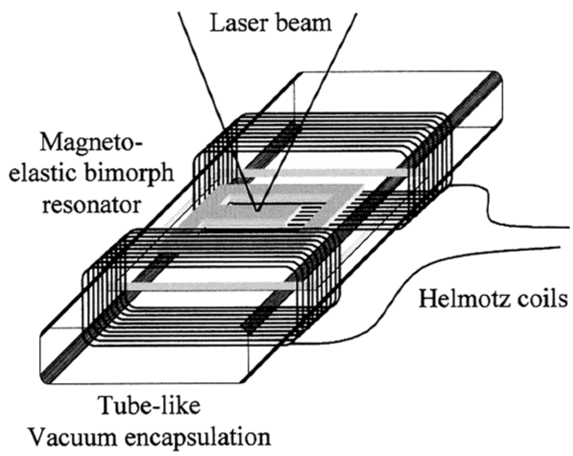
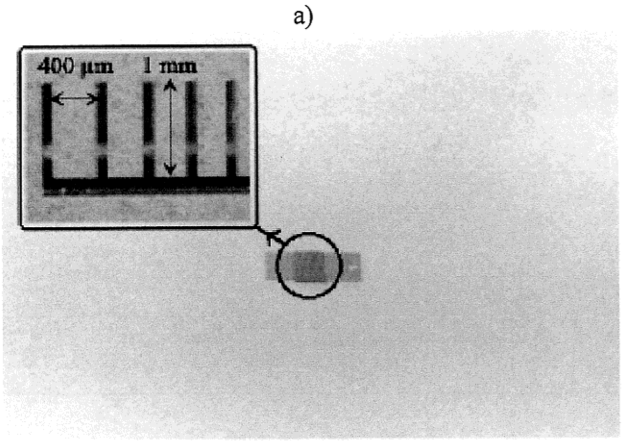


Fig.1: Schematic view of the MS 2D-Optical-Scanner. The magneto-elastic resonator is encapsulated in a vacuum-sealed glass tube. External twin-coils are used to produce the magnetic field needed for actuation in both bending and torsion. The translucent glass packaging allows the deflection of a laser beam.

a)



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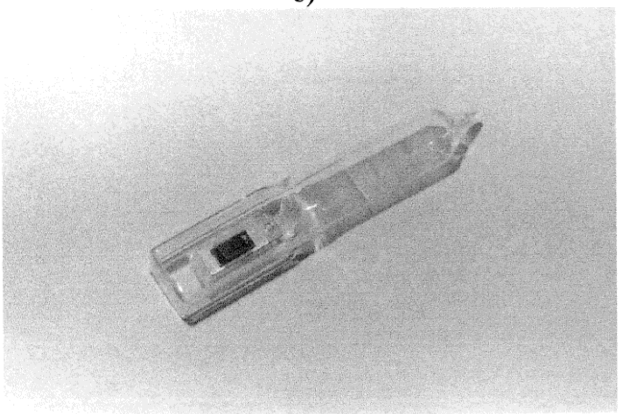

c)

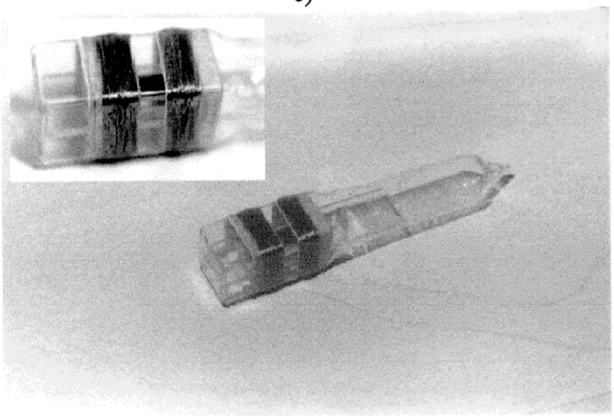

Fig.2: Picture of the device: a) silicon die only glued on a holder, b) with the glass vacuum packaging and c) also including excitation coils.

The MS material is uniaxial; that is, there is an easy axis of magnetization (fig.3.a). Its orientation (22° for our sample) is chosen by applying a strong magnetic field during thin film deposition. Because the MS material is uniaxial, both bending and torsion vibrations are simultaneously generated (fig.3.b) when an AC magnetic field is applied perpendicularly to the easy axis [6]. The effects of a DC bias field applied perpendicularly to the easy axis are [6]: i) a rotation of the magnetic moment and ii) static bending and torsion deformations (fig.3.c). In addition, if this DC field is superimposed to the AC field, it will modify the bending/torsion vibration amplitude ratio.

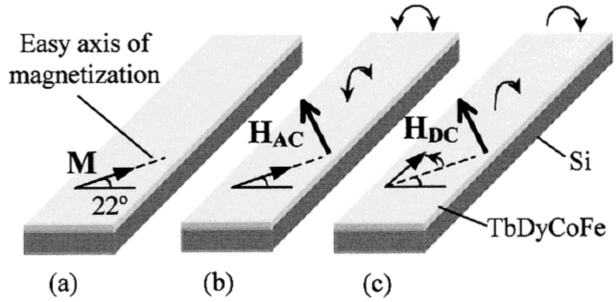

Fig.3: Schematic view of the bimorph magnetostrictive actuator. a) orientation of the easy axis of magnetization is fixed at 22° during thin film deposition, b) AC magnetic field applied perpendicularly to the easy axis produces both bending and torsional vibrations c) DC bias field produces a rotation of magnetization and static deformations. It also modifies the bending/torsion vibration amplitude ratio when it is superimposed to the AC field.

The simultaneous generation of bending and torsional vibrations is achieved with the same input port (coils current input) and this is a unique feature of MS actuation as compared to other actuation principles. Indeed, in the case of the electrostatic and the piezoelectric counterparts for instance, two input ports with out-of-phase excitation signals are needed for the generation of torsional vibrations. When using a uniaxial MS material, in most situations, we produce simultaneously bending and torsion. Thus, bending or torsional vibrations can be selectively amplified at the corresponding resonance frequencies so that only one kind of vibration can dominate.

When a laser beam is focused on the surface of the vibrating resonator, it can be deflected in two perpendicular directions, depending on the mode shape: for instance, horizontal for torsion mode and vertical for bending mode. Thus, light scanning is produced. The experimental setup is depicted in fig.4. For an input current applied to the excitation coils at 10kHz, corresponding to the bending resonance frequency of the cantilever, 1D vertical scanning is obtained as shown in fig.5.a. 2D scanning is obtained by superimposing two signals at 10kHz and 43kHz, corresponding to the resonance frequencies of the first bending and torsion modes. Such a 2D scanning is shown in fig.5.b. It is noteworthy that both bending and torsion vibrations can be produced without DC bias field in the sample under consideration (fig.6). This is because this sample has an easy axis of magnetization, which is at 22 degrees from the axis of the cantilever width [6].

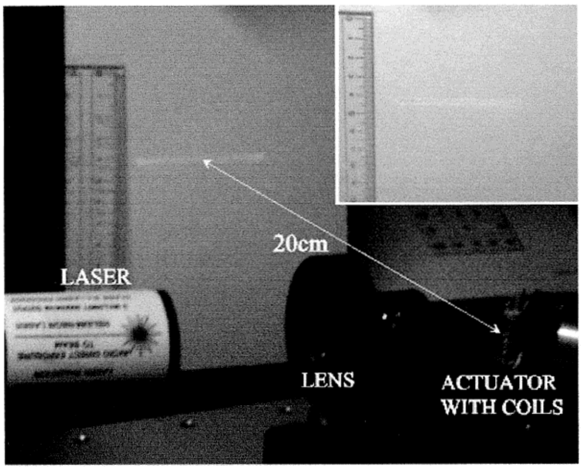

Fig.4: experimental setup for optical scanning by magnetostrictive actuation. An illustration is given of a 7cm-wide horizontal scanning at a distance of 20 cm.

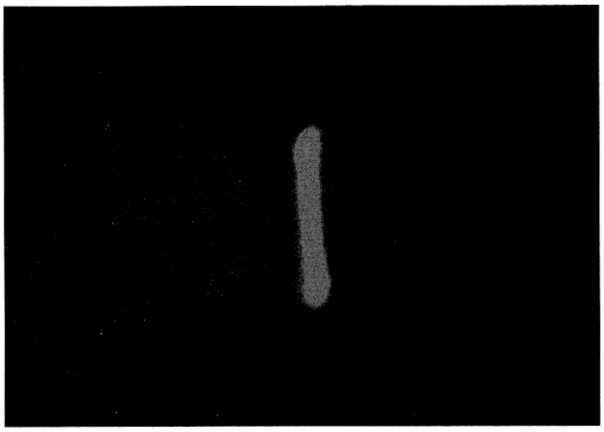

Fig.5.a: 1D vertical scanning at 10 kHz (bending mode). Recorded on a 15µm-thick, 400-µm-wide, 1000-µm-long resonator.

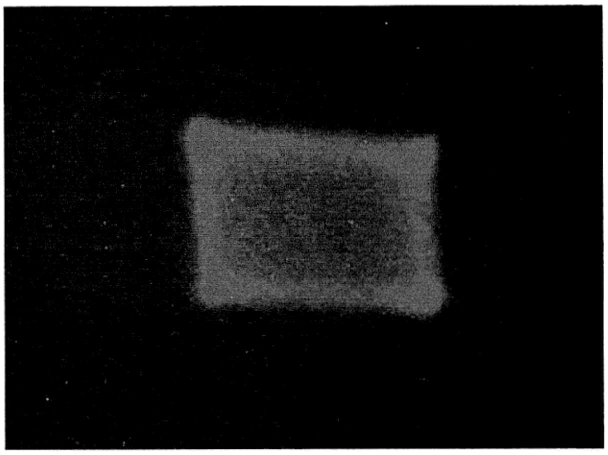

Fig.5.b: 2D scanning, at 43 kHz in horizontal direction (torsion mode) and 10 kHz in vertical direction (bending mode), recorded on a 15µm-thick, 400-µm-wide, 1000-µm-long resonator.

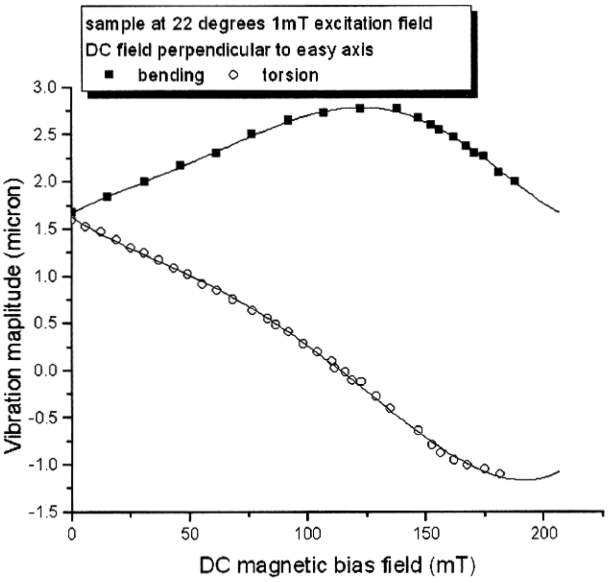

Fig.6: Vibration amplitudes versus a bias field perpendicular to the easy axis of magnetization. Both bending and torsion vibrations are generated at 0 bias.

Moreover, the aspect ratio of the 2D-scanning window is tunable (fig.7). Indeed, according to the curves shown in fig.6, the ratio of bending/torsion vibration amplitudes is adjustable within a very wide range, by means of a DC magnetic field biasing. Otherwise, we have also shown with other samples, that we obtain (without biasing) only torsion for a 0-degree orientation and only bending for a 45 degrees orientation. Nevertheless, both vibrations can be produced in all these samples by superimposing a bias field to the excitation field. The hysteresis loops of fig.8 (due to coercitivity) show that the devices can be operated without steady application of a bias field.

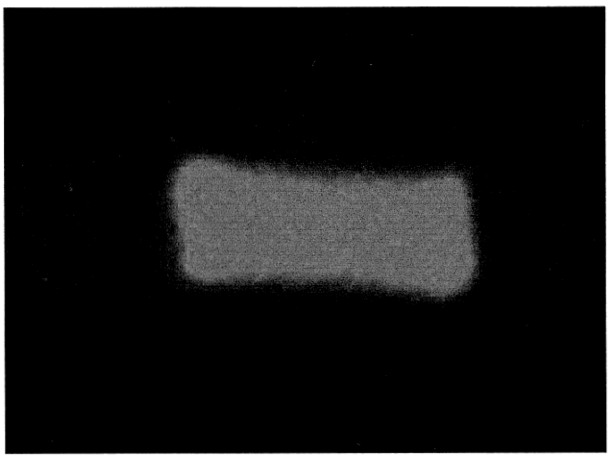

Fig.7: 2D scanning while tuning the aspect ratio of the scanning window by means of a DC magnetic field. Recorded on a 15µm-thick, 400-µm-wide, 1000-µm-long resonator.

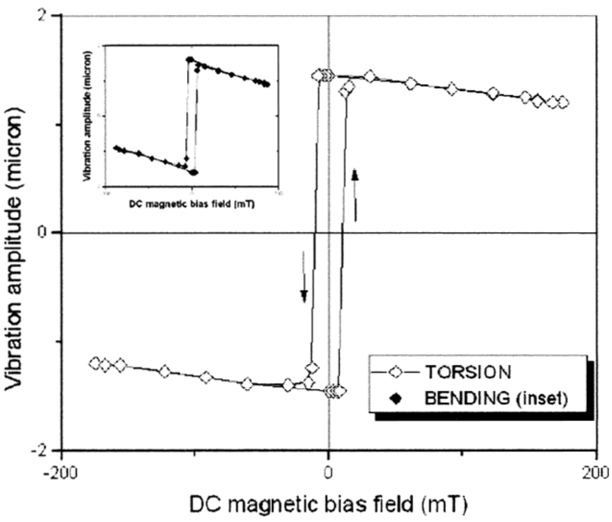

Fig.8: Vibration amplitudes in torsion mode (and bending mode for the inset figure) versus a bias field parallel to the easy axis of magnetization. Evidence of hysteresis loops showing that operation of the device does not require steady application of a bias field.

MEASUREMENTS IN AIR

Our most compliant cantilevers are 5μm-thick. We have made a precise evaluation of their performance through vibration measurements by using a laser Doppler vibrometer. The frequency response to the magnetostrictive actuation was measured near resonance. The results for the torsion mode are shown in fig.9. Because of large deflections, typical nonlinear behavior of anharmonic oscillators is observed. This behavior is also known as the hard spring effect or the Duffin oscillator. The shape of the resonance curves are deflected (towards high frequencies because the cubic elastic constant is positive for our resonator). The curve shapes are more and more distorted when increasing the excitation field. There is also a hysteresis behavior in these curves, that is, different paths are described when sweeping up or sweeping down the frequency. The maximum vibration amplitudes (quasi-resonance) are plotted in fig.10 as a function of excitation field. The corresponding quasi-resonance frequencies are plotted in fig.11.

One can see in fig.10 that a deflection of 20 μm has been attained for an excitation field of 4mT. The corresponding optical deflection angle, which is calculated from these measurement data, is 24 degrees (+/-12 degrees) as shown in fig.12. We can also see from fig.10 that we have also operated the resonator at excitation fields up to 7 mT. However, we reached the overload limit of the laser Doppler system in the range 4-7mT. Thus, we could not measure precisely the deflection at these magnitudes. By extrapolating the linear behavior shown in fig.10, one can expect deflection angles of about 43 degrees at 7 mT as indicated by the hollow circles in fig.12.

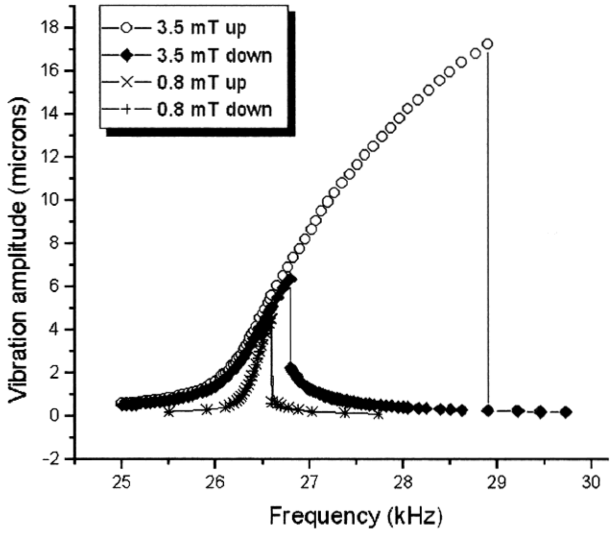

Fig.9: Vibration response near resonance for torsion mode, measured on the 5-μm-thick, 400-μm-wide, 1000-μm-long structure. Nonlinear behavior of anharmonic oscillators is observed because of large deflections.

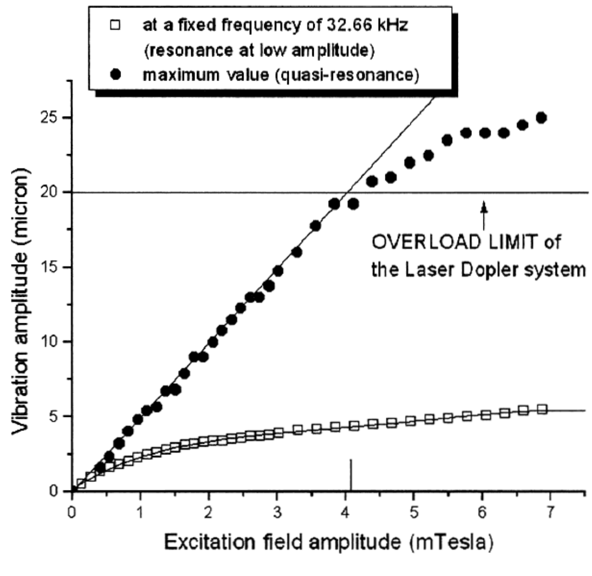

Fig.10: Vibration amplitude versus excitation field, measured on the 5-μm-thick, 400-μm-wide, 1000-μm-long structure. When following the maximum value of quasi-resonance, this load-deflection characteristic is linear up to 20 μm (solid circles). Then; we have an overload limitation in the laser Doppler measurement system.

It is noteworthy that the load-deflection characteristic of fig.10 is linear, provided that frequency is adjusted to the quasi-resonance value. This is in agreement with a theoretical model of anharmonic oscillator [7]. For the performance point of view, this linear relationship seems to indicate that performance is not affected by the anharmonic behavior. Indeed, according to fig.10, vibration amplitudes remain proportional to the applied magnetic field, when increasing its magnitude, until limitations of other nature will occur. The quasi-resonance frequency of the anharmonic oscillator versus excitation field follows a parabolic law as indicated in fig.11.

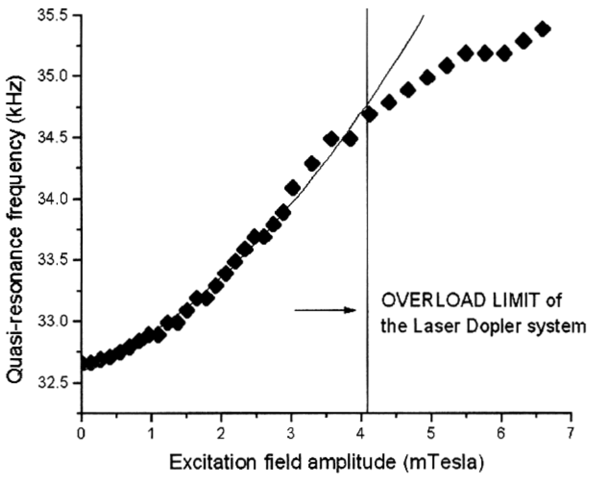

Fig.11: Quasi-resonance frequency versus excitation magnetic field, measured on a 5-µm-thick, 400-µm-wide, 1000-µm-long structure. These frequencies correspond to maximum vibration amplitudes in the deformed resonance characteristics.

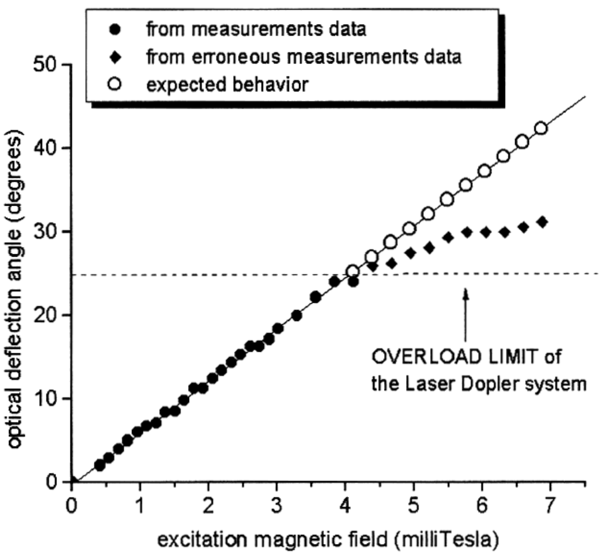

Fig.12: Optical deflection angles determined from vibration amplitude measurements with a laser Doppler vibrometer (solid circles). Same data as in fig.10. Hollow circles show the expected behavior.

The nonlinear behavior that was observed for torsion mode was not observed for bending mode at equivalent deflection levels. Normal resonance shape was obtained for bending vibrations. This difference is ascribed to the fact that higher strain is needed for torsion than for bending to produce the same deflection.

VACUUM PACKAGING

It is well known that packaging is often the most expensive in microsystems. We propose a simple, cost-effective glass packaging (fig.1,2), which requires neither electrical nor optical feedthrough since magnetic actuation is used. The coil is outside the whole glass package, which can be easily closed as in vacuum tube technology. In fact, the coil must be in air and not in a vacuum. Indeed, the generated heat due to current flow can be more easily dissipated in air, preventing damage in the coil. In this way, the highest magnetic field will be more easily attained. A comparison between resonance characteristics measured in air and in vacuum is shown in fig.13.

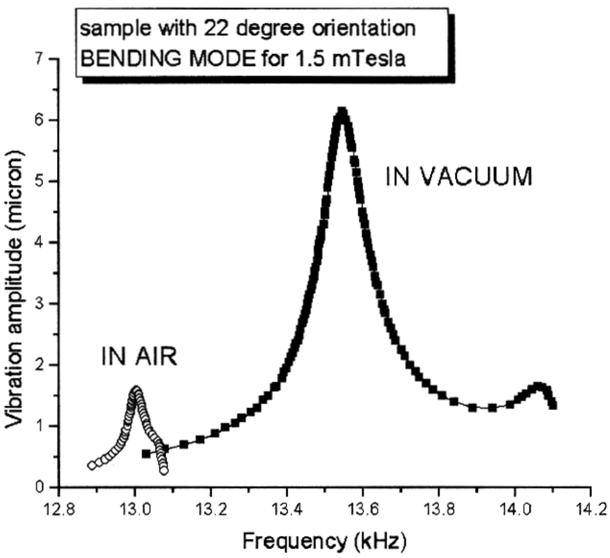

Fig.13: Comparison between operation in air and operation in vacuum. Vibration amplitude is increased 4 times more than in the air and a positive frequency shift is also observed. Measured at 1.5mTesla on a sample with a 22-degree orientation.

Vibration amplitudes are 4 times higher in vacuum. This is much smaller than the expected improvement. We have obtained the same improvement for vacuum levels ranging from 10^{-3} to 2.10^{-6} hPa. This seems to indicate that viscous losses are not the dominating phenomena. The saturation is ascribed to internal losses in the magnetostrictive material, which does not have a monocrystalline structure. A positive frequency shift is also observed in fig.13. This is a typical dependence of resonance frequency on the quality factor. These results are obtained for a sample with a 22-degree orientation, which is able to vibrate in both bending and torsion modes without biasing. Although the improvement was obtained by measurements at an excitation field of 1.5mT, one can expect a similar improvement at higher fields, according to the linear behavior observed in the load-deflection characteristics (cf. Fig. 10).

COMPLEMENTARY CHARACTERIZATION

We have built very simple 2D-scanners, for which we expect rather high deflection angles (50 degrees and more) or operation at moderate excitation fields with vacuum packaging. Because of limitations in our laser Doppler system, high vibration amplitudes could not be measured. The maximum angle, which could be measured, is 24 degrees. Thus, further evaluation at higher excitation fields and in vacuum is now underway through the direct measurement of deflection angles of a laser spot on a screen.

CONCLUSION

We have successfully demonstrated a new application of magnetostrictive actuation to 2D-optical scanners. 2 micron-thick sputter-deposited Terfenol-D doped with cobalt (TbDyCoFe alloy) on 5 micron-thick silicon cantilevers enabled light deflection with an angle of 24 degrees in air with an excitation field of only 4mT in the air. The deflection angle was not measured at 7mT, corresponding to the maximum dynamic field, which could be obtained with our hand-made coils. According to the linear behavior, which was shown in our devices, the expected deflection angle in air at 7mT is 43 degrees. Optical scanning was done at the resonance frequencies of the cantilevers, ranging from 10kHz to 50kHz. These performances are high enough for most applications of optical scanners. The fabrication process is very simple. It consists of double-side silicon etching on a SOI substrate followed by the sputtering of magnetostrictive material. It is noteworthy that no additional steps are needed, for instance those usually needed for electrical contact fabrication. Furthermore, the wireless actuation also enabled a very easy vacuum packaging in a glass tube, without electrical or optical feedthrough. This vacuum packaging leads to an increase of a factor 4 in deflection angles or operation at moderate excitation fields.

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