MULTICHANNEL MEMS SPECTROMETER

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Abstract

Utilizing optical MEMS, a novel apparatus that detects light waves emanating from a well-lit source has been designed. A MEMS spectrometer comprised of a set of actuable torsion mirrors, photodiodes and optical slits scans and records UV/Visible/IR light waves generating from specimen. This device is controlled by an electrostatic actuation method that simultaneously operates two electrodes to produce a smooth range of motion over small angles. Depending on the mirror's relative location to the slits, it only reflects a particular range of frequency. The light wave reflected by the mirror is focused through an optical lens and converted into electrical signals by a photodiode.

Introduction

As tool for collecting optical data, spectroscopy instruments have found useful niche in a wide variety of analytical and life sciences applications. A spectrometer that combines MEMS optical technology with spectroscopy has several distinct advantages over the conventional spectrometers. This paper will describe the design and fabrication of MEMS spectrometer that will be used to detect and record the frequency signature of various specimens.

Market Opportunity

In 2000, the spectroscopy instrument market generated approximately $4.5b in revenues.[1] The molecular spectroscopy segment, which accounts for nearly half of the entire spectroscopy market, is comprised of four competing technologies-UV/Visible/IR, Nuclear Magnetic Resonance (NMR), Fourier Transform-near-infrared (FT-NIR) and Raman. The sales of UV/Visible/IR spectroscopy products produced more than $500mm in revenues in 2000.

Product Comparison

Due to the unique size advantage and the operating characteristics of the MEMS spectrometer, its performance is superior to that of conventional spectroscopy instruments.

	Double Beam	**Multichannel Diode Array**	**MEMS Spectrometer**
Cost	$4,000 to $15,000	$7,000 to $9,000	<$1,000
Resolution	4 nm	2 nm	<0.5 nm
Spectrum	190 to 850 nm (UV/Visible)	Up to 850 nm (UV/Visible)	100 to 1100 nm (UV/Visible/IR)

Fig.1 Product comparison

As shown in figure 1, the MEMS spectrometer will deliver superior performance to the end user at a lower systems cost.[2]

Principles of Spectroscopy

Diffraction is an optical term that refers to the behavior of a wave front when it encounters a semi-permeable obstacle. When a wave front derived from a distant source encounters a semi-permeable barrier, each permeable area or gap behaves like a new light source and a radial wave front will be emanating from each one of these sources.[3] Due to the radial propagation of the wave an interference pattern will be projected on a distant screen placed parallel to the barrier. Given that different frequencies propagate with distinct wavelengths, each one of them will project a different interference pattern on the screen.

One common technique to differentiate each wavelength is to search for its first maximum. To get a sharper resolution, i.e., to clearly resolve the maximums of neighboring wavelengths, one needs to increase the number of wave front sources, thus adding up parallel wave fronts for each frequency. In fact, the resolution is inversely proportional to the number of sources:

$$\frac{1}{N} = \frac{\Delta\lambda}{\lambda} \qquad (1)$$

Using a diffraction grating as a barrier the number of sources is equal to the number of slits N.

The angle at which a maximum m of a particular wavelength λ is projected on a distant screen can be calculated using the equation for a multiple diffraction grating:

$$m\lambda = d\ SIN(\phi) \qquad (2)$$

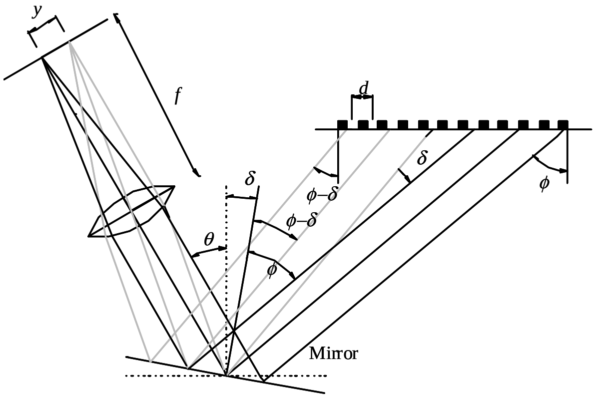

Fig.2 Schematic diagram of MEMS spectrometer

Setting m = 1, i.e., looking for the first maximum and for small angles one can approximate equation 2 with a linear relationship such that:

$$\lambda = \kappa\phi + b \qquad (3)$$

The minimum wavelength difference that can be resolved by the set up illustrated on fig 2 is:

$$\Delta\lambda = \kappa(\Delta\phi) + b = \kappa(\phi - \delta) + b \quad \rightarrow$$

$$\delta = \frac{\kappa\phi - \Delta\lambda + b}{\kappa} \qquad (4)$$

The distance between the two maximums of the closest wavelength at the focal plane of the lens will be:

$$y = f\ TAN(\delta) = f\ TAN\left(\frac{\kappa\phi - \Delta\lambda + b}{\kappa}\right) \qquad (5)$$

Where *f*, the focal distance of the lens is a function of the index of refraction *n* and the radius of the lens *R*,

$$\frac{1}{f} = (n-1)\left(\frac{1}{R}\right) \qquad (6)$$

To minimize the error due to our linear approximation (eqn. 3), our set-up consists of six mirrors, thus dividing the spectrum to be analyzed. By doing this, we are able to lower the average error. Figure 3 shows the parameters or each mirror.

Mirror	Frequency Range [hm]	k [10-9]	b [hm]	Avg. Error [%]	Incident Angles [DEG]	Mirror Actuation Range [DEG]	Angle [DEG]
1	120-298	34.7	0.7	0.034	3.4 - 8.6	-2.6 - +2.6	1.35
2	298-477	34.3	4.6	0.035	8.6 - 13.8	-2.6 - +2.6	1.35
3	477-659	33.5	15.3	0.041	13.8 - 19.2	-2.7 - +2.7	1.35
4	659-842	32.4	36.7	0.041	19.2 - 24.9	-2.8 - +2.8	1.41
5	842-1025	30.9	73.7	0.045	24.9 - 30.8	-3.0 - +3.0	1.47
6	1025-1200	29.0	132.3	0.046	30.8 - 36.8	-3.0 - +3.0	1.50

Fig.3. Operating parameters of torsion mirrors

Product Overview

Our spectroscopy device relies on a common diffraction grating along with 6 MEMS electrostatically actuated torsion mirrors. The diffraction grating separates impinging light by changing the propagation path by angle θ, depending on the wavelength, governed by the equation 2.

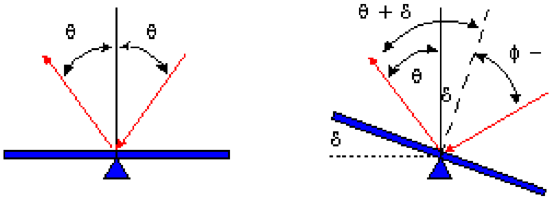

Fig.4 Incident light reflecting on torsion mirror

Since we know the incoming angle of each wavelength, we can scan the micro mirror to reflect each wavelength onto a photodiode which is able to measure the intensity. Relating the intensity to the rotation of the mirror (and hence the wavelength of light striking the diode), we are able to determine the spectral content of the light source.

To select a certain wavelength, we need to rotate the mirror by an angle, δ, to monitor it. When there is no rotation the angle reflected is θ, which is the angle the photodiode is aligned with.

However if we wish to observe a different wavelength, φ, we need to know the correct deflection of the mirror. Using the fact that the incident and reflected angle of a light beam are the same we can find δ.

$$\theta + \delta = \phi - \delta \Rightarrow \delta = \frac{\phi - \theta}{2} \qquad (7)$$

Note that we only need to move half the difference in incident angle, this double the effective scanning range of the mirror.

Torsion Mirror

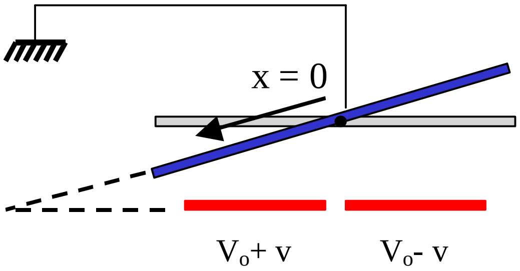

Fig.5 Schematic diagram of torsion mirror

We have decided to use a push-pull actuation method as shown in figure 5. This is a somewhat misleading name as there is no “push” force, the difference lies in the way the voltage is applied to the electrodes [4]. In the TI digital micro mirror, a voltage is applied to one electrode, pulling the mirror toward itself, in the push-pull both electrodes are turned on, one with voltage $V_o + v$ and one with $V_o - v$.

This method of actuation is preferred for our application in that it provides a more linear relationship between voltage and deflection angle. The general torque due to electrostatic attraction is:

$$\tau_{elec} = \frac{1}{2}\frac{\varepsilon_o W a V^2}{g^2} \qquad (8)$$

where voltage is:

$$V^2 = (V_o + v)^2 - (V_o - v)^2 = 4 \cdot V_o v \qquad (9)$$

the gap varies as:

$$\frac{1}{g^2} = \int_0^L \frac{1}{((\frac{d}{\sin\theta} - x)\cdot\theta)^2} dx \qquad (10)$$

For the gap we use circular electric field lines instead straight ones to be more accurate.[5]

$$g = R \cdot \theta = (\frac{d}{\sin\theta} - x)\cdot\theta \qquad (11)$$

combining all elements,

$$\tau_{elec} = 2 \cdot \varepsilon_o V_o W v \int_0^L \frac{x}{((\frac{d}{\sin\theta} - x)\cdot\theta)^2} dx \qquad (12)$$

We see that the torque is now related linearly to voltage, v. Unfortunately, the relationship between θ and v is not totally linear due to the nonlinear nature of the gap.

To find the over all position of the mirror we need to consider the opposing torque of the torsion bar given by:

$$\tau_{mech} = \frac{G \cdot J}{L}\theta = \frac{1}{C_M}\theta \qquad (13)$$

Setting T_{mech} equal to T_{elec} we find the over all relationship:

$$v = \frac{\theta}{2 \cdot \varepsilon_o V_o W C_M \int_0^L \frac{x}{((\frac{d}{\sin\theta} - x)\cdot\theta)^2} dx} \qquad (14)$$

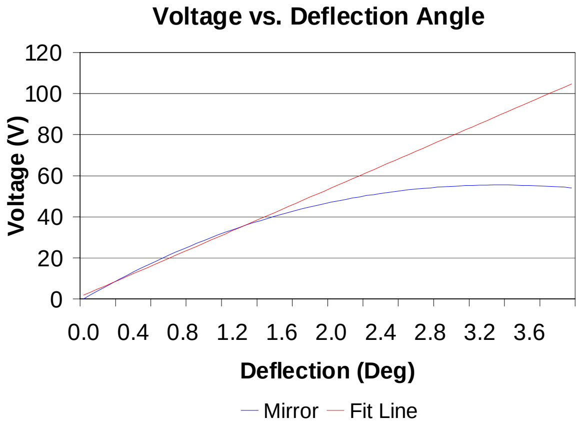

Fig.6 Voltage vs. deflection curve

Setting V_o = 10V and a C_M = 1 x 10^9 Nm we get a nearly linear relationship from 0 to 1.5 degrees with v ranging from 0 to 39 V. Figure 6 compares the linear equation V = 1490 θ + 1.866 to the nonlinear voltage-deflection relationship.

The pull in voltage is difficult to calculate empirically, using the result for the TI digital mirror,

$$V_{pull-in} = \sqrt{\frac{2 \cdot d^3}{\varepsilon_o W L^3 C_M}} \qquad (15)$$

We find that the pull in voltage is 47.5 V or 2°.

Lumped Element Model

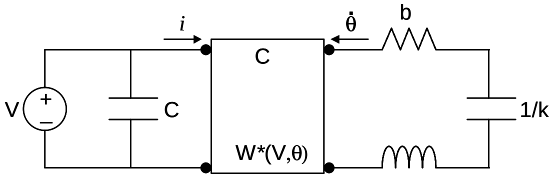

Fig.7 Lumped element model

As shown by the derivations in the previous section, it is evident that the physical equations are solvable. Figure 7 shows the lumped element model representing the torsion mirror.

To simplify the lumped element model, following derivations are calculated:

$$W = \frac{Q^2}{2C} = \frac{Q^2}{2C_o}\left(\frac{1}{a_1\theta + a_2\theta^2 + a_3\theta^3}\right) = \frac{Q^2}{2C_o P(\theta)}$$

$$\tau = \left.\frac{\partial W}{\partial \theta}\right|_Q ; \quad V = \frac{Q}{C_o P(\theta)}$$

$$\begin{bmatrix} \delta V \\ \delta \tau \end{bmatrix} = \begin{bmatrix} Z_{EB} & T_{EM} \\ T_{ME} & Z_{MO} \end{bmatrix} \begin{bmatrix} \delta I \\ \delta \dot{\theta} \end{bmatrix} = \begin{bmatrix} Z_{EB} & \Phi Z_{EB} \\ \Phi Z_{EB} & Z_{MO} \end{bmatrix} \begin{bmatrix} \delta I \\ \delta \dot{\theta} \end{bmatrix}$$

$$Z_{EB} = \frac{2}{sC_o P(\theta)} ; \qquad T_{EM} = T_{ME} = \frac{-\Delta Q P'(\theta)}{sC_o P^2(\theta)}$$

$$Z_{MO} = \frac{\left(Q_1^2 - Q_2^2\right)}{2sC_o}\left(\frac{P'^2(\theta)}{P^3(\theta)} - \frac{P''(\theta)}{P^2(\theta)}\right) + k$$

$$\Phi = \frac{T_{EM}}{Z_{EB}}$$

$$Z_{MS} = Z_{MO} - \frac{T_{ME}^2}{Z_{EB}}$$

which leads to a simplified lumped element circuit shown in figure 8.

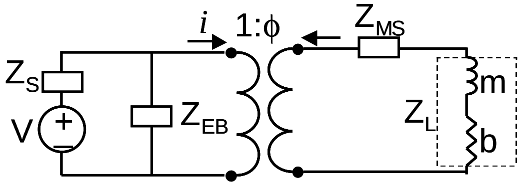

Fig.8 Equivalent circuit of lumped element model

Figure 9 represents the final circuit. Compared with the lumped element circuit, the final electrical equivalent circuit is easier to solve. From the circuit, the dynamics of the system can be readily obtained.

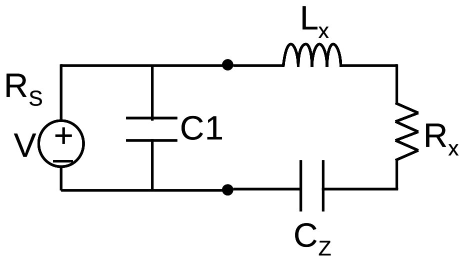

Fig.9 Final equivalent circuit

Mirror Fabrication

The SUMMiT process, which offers the benefit of CMP planarized surface, is used to build the torsion mirror. Only the key steps will be discussed in this paper. The torsion mirror is fabricated using the first two poly layers (mmpoly0, mmpoly1) and the sacrificial layer (sacox1) between the two poly layers.

First, the ground layers, permanent oxide (0.63 µm) and nitride (0.80 µm), are deposited. Then the first poly layer (mmpoly0-0.3 µm) is deposited and patterned to create the landing pads and the electrodes. The electrodes are separated by 1 µm gap. The pads are isolated from the electrodes. The nitride layer underneath the mmpoly0 layer provides the electrical insulation. Second, the first sacrificial oxide layer (sacox1-2 µm) is deposited and etched, exposing the anchor areas. Third, the final poly layer (mmpoly2-1 µm) is introduced and patterned to form the mirror surface and the torsion beams. Following the SUMMiT process, a metal deposition and liftoff take place to create the reflective property of the mirror.

Conclusion

A novel spectrometer utilizing MEMS optical mirrors has been successfully demonstrated. The torsion mirrors are electrostatically rotated to scan for the optical signals emanating from a well-lit source. Initial calculations have shown that the MEMS spectrometer provides dramatic performance improvement as well as a reduction in the overall systems cost.

References

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