Optical Coupling Analysis And Vibration Characterization For Packaging Of 2x2 MEMS Vertical Torsion Mirror Switches

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ABSTRACT

We report optical coupling loss and vibration characterization for packaging of 2x2 vertical torsion mirror switches. The coupling losses of fiber-to-fiber and fiber-lens-lens-fiber are examined in order to design 2x2 MEMS optical switches required for the performance specification. The results indicate that the fiber-lens-lens-fiber configuration provides a over 1 mm working distance of 2.5 dB loss between the lens centers. The fiber-to-fiber only allows 175 μm for the same loss. In addition, the mechanical frequency response of the vertical torsion mirror is experimentally examined by electrostatic excitation. The discrepancy between the calculated and the measured nature frequencies is investigated by the study of the effect of the in-house post processes.

Keywords: optical switch, MEMS packaging, optical coupling, torsion dynamics, nature frequency

INTRODUCTION

The importance of fiber-optics switches has been increasing due to the rapid growth of optical fiber network. Recently, there has been a growing interest in applying MEMS technology to make fiber-optics switches. The use of MEMS techniques to make fiber-optics switches offers advantages such as miniaturization, high performance and potentially low cost. For example, the FDDI (Fiber Data Distribution Interface) fiber-optics ring network employs optional 2x2 fiber-optics switches, called optical bypass switches, to bypass a failed node, thus maintaining the network reliability. Fig. 1 demonstrates a novel 2x2 MEMS free-space fiber-optics switches which consists of four vertical torsion mirror devices [1]. The principle of the switch operation is illustrated in Fig. 2. As seen in Fig. 2, the four vertical mirror are arranged such that in the reflection mode, the input beams are reflected by two 45° vertical torsion mirrors and coupled into the output fibers on the same side of the chip. In the through mode, the vertical torsion mirrors are rotated out of the optical paths, and the input beams are coupled into the opposite output fibers.

The purpose of packaging the MEMS fiber-optics switches is to integrate optical components, to achieve technical performance requirement and to preserve device reliability. The silicon-based hybrid packaging [2] for the 2x2 MEMS vertical torsion mirrors, as shown in Fig. 1, is employed to assemble all the necessary optical components such as fibers, lenses and mirrors. This scheme may offer effective assembly, passive alignment and flexibility to accommodate various kinds of free-space optical MEMS devices. The FDDI bypass switch specification requires 25 millisecond of maximal switching time and 2.5 dB of maximal optical attenuation [3]. The vertical torsion mirror has achieved sub-millisecond switching time, which is well below the requirement. Optical attenuation is associated with fiber alignment and the separation distance between the input and the output fibers. The distance inserted by the mirrors is required to meet the optical specification. In this paper, optical coupling loss is examined to realize the allowable distance between the input and output fibers with the inserted mirrors. Furthermore, the dynamic behavior of the vertical torsion mirrors is also examined to further understand the mechanical design during operation or under external vibration.

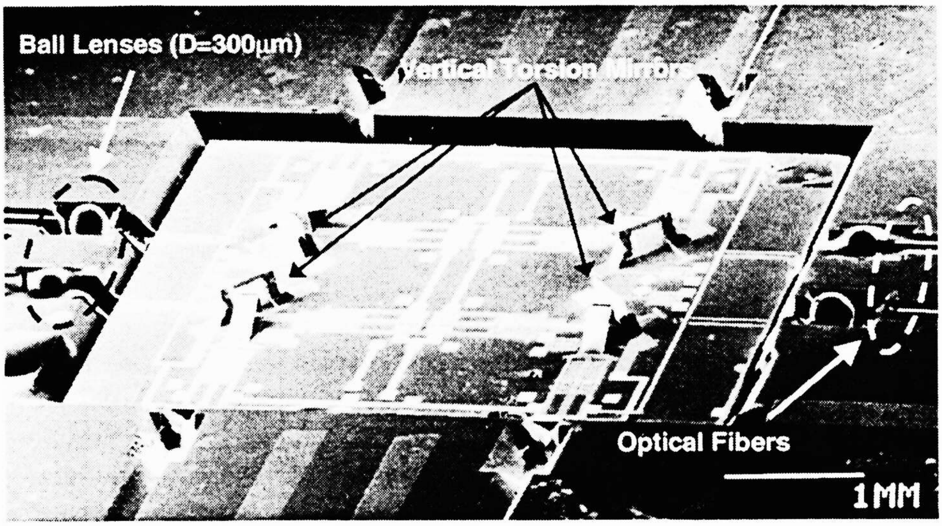

Figure 1. SEM picture of packaging of 2x2 FDDI vertical torsion mirror switch.

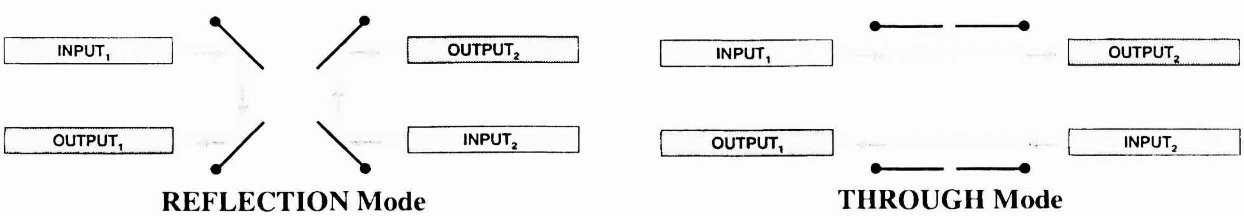

Figure 2. Illustration of switching operation between REFLECTION mode and THROUGH mode

OPTICAL COUPLING

Functionally, the switch has to meet the FDDI switch specification, which allows a maximal coupling loss of 2.5 dB, including connector loss. The distance between the input and the output fibers is needed for the installation of the vertical torsion mirror device. An effective design for packaging a 2x2 MEMS switch requires prior knowledge of the coupling loss with respect to the distance between fibers. However, the coupling loss is sensitive not only to the fiber separation along the common axis, but also to the lateral and the angular misalignment between the input and output fibers [4]. In this paper, V-grooves are used to exclude the lateral and angular misalignment. Two kinds of configuration, fiber-to-fiber and fiber-lens-lens-fiber, for the axial separation associated with the coupling loss are discussed. Ball lenses are used here to collimate the optical beam and to provide a large working distance. 62.5/125 μm cleaved step-index multimode fibers are used. The index of refraction and diameter of the lens are 1.517 and 300 μm, respectively.

(A) Fabrication of Silicon Substrate

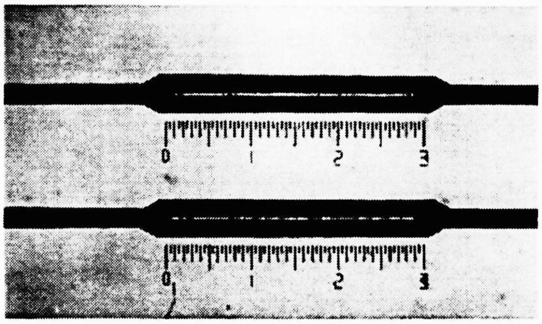

Figure 3. V-grooves of silicon substrate for optical coupling

In Figure 3, the high precision required for fiber-fiber and fiber-lens-lens-fiber alignment is easily achieved by using silicon micromachined V-grooves. 1000 Å thermally grown silicon dioxide and 1500 Å low-pressure chemical-vapor-deposition (LPCVD) silicon nitride layer are used as (100) silicon etch mask in KOH wet etching. Determination of true crystal direction has been employed for use in silicon optical bench [2]. The effect of silicon crystal lattice-to-mask misalignment during etching can be minimized to achieve high accuracy of 0.1° to the crystal direction instead of a typical wafer flat of within 0.5°. The process to reveal true crystal direction is made before the desired V-grooves with verniers are fabricated. The in-situ vernier is made of a series of V-grooves with 10 μm wide, 50 μm pitch and 3 mm of a measurable length.

(B) Optical coupling Experiment

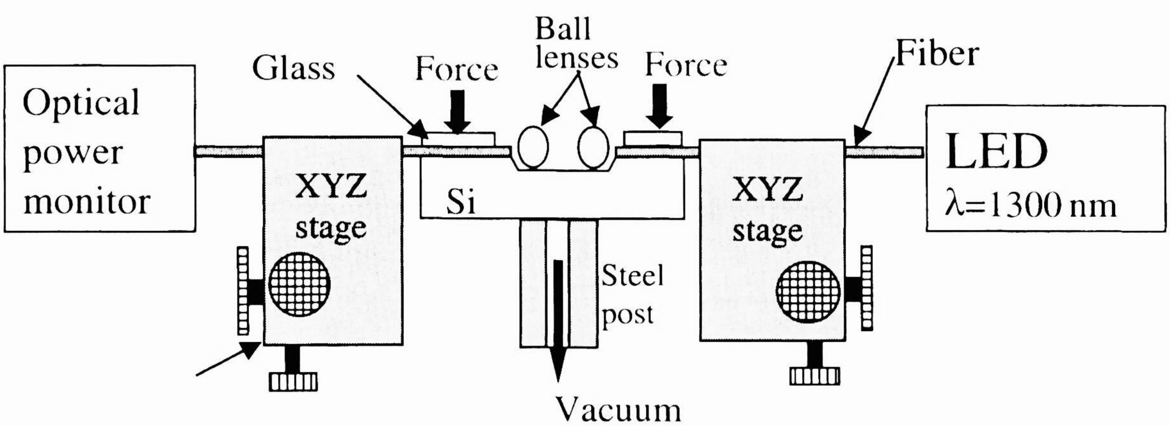

Figure 4. Experiment setup for measurement of optical coupling loss

The experimental setup used to measure optical coupling loss is shown in Fig. 4. The silicon substrate for the coupling test is secured on the hollow steel post vacuumed. Axial separation between fibers at the coupling site is adjusted using 3-axis micropositioners which keep fibers straight and aligned to the V-grooves of the silicon substrate. Measurement of the axial separation distance is made from observing the in-situ verniers through a microscope. A 1300 nm wavelength is used for measurement.

The coupling loss of the cleaved multimode fiber-to-fiber is shown in Fig. 5. The optical coupling loss increases as the fiber-to-fiber separation increases along the common axis. This corresponds to the result of the cleaved multimode 50/125 μm fiber-to-fiber coupling with active alignment [4]. To meet the FDDI specification of the 2.5 dB loss limit, the maximal separation distance is allowed to be around 175 μm. The separation distance within 175 μm between fibers is a practical challenge for the switch packaging to accommodate the inserted mirrors and associated parts.

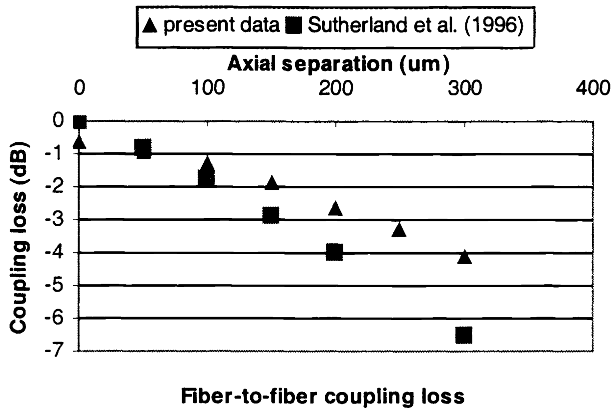

Figure 5. Fiber-to-fiber optical coupling loss

Fig. 6 demonstrates the coupling loss for the fiber-lens-lens-fiber configuration. The axial separation represents the distance between the centers of the ball lenses. The coupling results were obtained when the fiber-lens separations were adjusted at the minimal loss. The coupling loss is about 2 dB in the distance of 1 mm between ball lens. Therefore, the ball lenses apparently collimate the optical beam and provide a larger space. In other words, the fiber-lens-lens-fiber configuration demonstrates a more desirable than the fiber-to-fiber configuration. The results may be improved by applying an index matching gel in the gap between the fiber and the lens, and anti-reflective film on the lenses to eliminate Fresnel loss and spherical aberration loss [3,5].

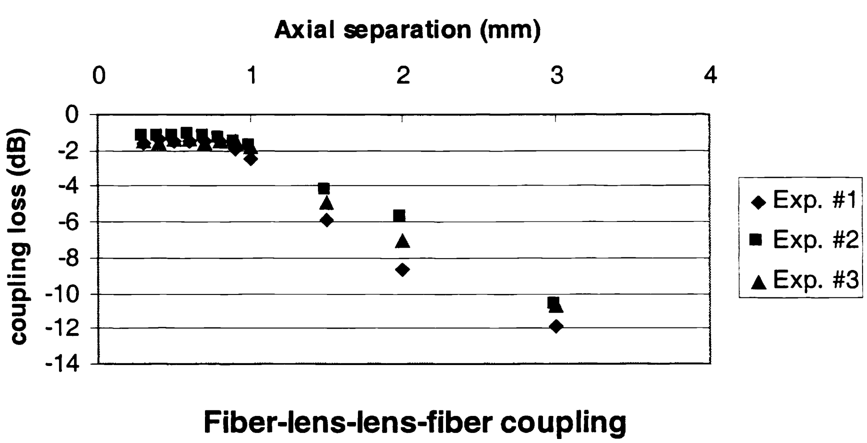

Figure 6. Fiber-lens-lens-fiber optical coupling loss

DYNAMIC BEHAVIOR OF A VERTICAL TORSION MIRROR

The 2x2 MEMS free-space fiber-optic switch consists of four vertical torsion mirrors. The schematic drawing of a vertical torsion mirror switch is shown in Fig. 7. The switch is composed of a vertical torsion mirror and a back electrode. Both the vertical torsion mirror and the back electrode are realized by the microhinge technology [6]. The angle between the vertical torsion mirror and the back electrode is designed to be 45°. Fig. 8 shows the SEM of the vertical torsion mirror. The mirror is attached to a beam which is fixed at a peripheral polysilicon frame. The input beam is redirected by the mirror to an orthogonal direction without biasing the electrodes. When a voltage is applied to the switch, the mirror is rotated toward the back electrode so that the input beam passes through the switch. The relation between the measured angles and the applied dc voltages was reported [1]. The pull-in voltage was measured around 80 volt. The switch time reached less than 1 ms. A dynamic behavior of the vertical torsion mirror is of importance to realize switch reliability. The dynamic response at nature frequency is resonant, resulting in large dynamic deflection undesired for the structure reliability. Calculation and experiment of the mirror mechanical structure were conducted to characterize the frequency response.

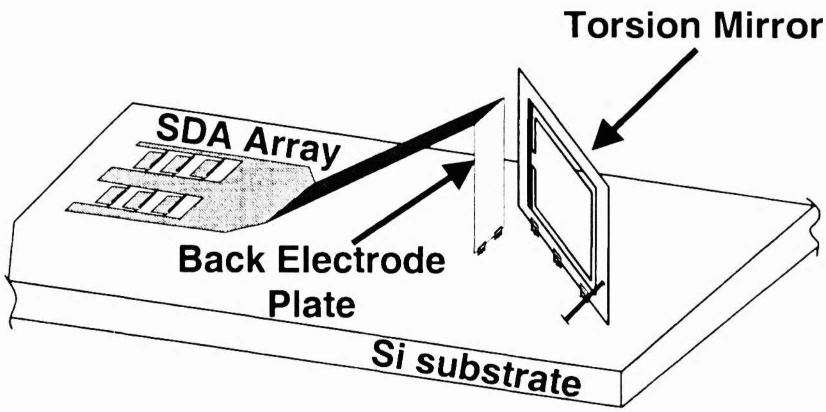

Figure 7. A schematic figure of a vertical torsion mirror

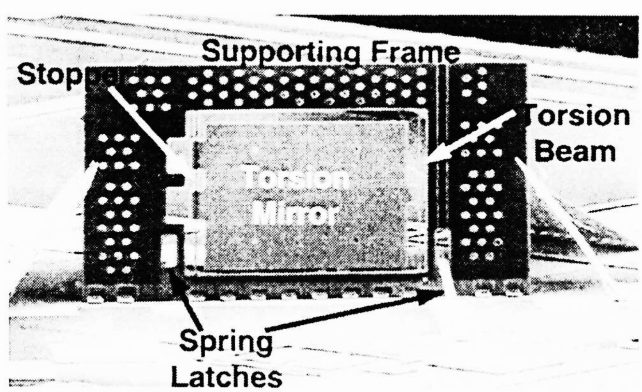

Figure 8. SEM of a vertical torsion mirror

(A) Calculation

The dynamic behavior of a vertical torsion mirror can be modeled by analyzing the dynamic response of the mechanical structure. In an angular system, the angular oscillator is described by

$$J\ddot{\theta} + c_\theta \dot{\theta} + K_\theta \theta = T(t) \qquad (1)$$

with angular moment of inertia J, angular damping c_θ, angular stiffness K_θ, angle θ, and driving torque T. The angular moment of inertia (J) dominated by the mirror plate J_{mirror}, is expressed as

$$J = J_{beam} + J_{mirror} \approx J_{mirror} = \int r^2 dm \tag{2}$$

Since the mirror is composed of a polysilicon plate and a gold coating, the angular moment of inertia can be extensively expressed as

$$J = \int r^2 dm = \int \rho w_m t r^2 dr = \frac{1}{3}(\rho_{poly} t_{poly} + \rho_{Au} t_{Au}) w_m (r_2^3 - r_1^3) \tag{3}$$

where w_m is the width of the mirror; ρ is the material density; r is the distance from the torsion beam, and $t_{poly,Au}$ is the thickness of the polysilicon and the gold, respectively. The angular stiffness can be expressed as

$$K_\theta = 2\frac{GS}{L} \tag{4}$$

where G represents shear modulus ($\frac{E}{2(1+\nu)}$); E is Young's modulus, and ν is poisson ratio. L is a half of a beam length and multiple 2 accounts for a total length of beams twisted. For a beam with a rectangular cross section, the torsion beam rectangular shape factor [7] is

$$S = (\frac{h_b}{2})^3 (\frac{w_b}{2})[\frac{16}{3} - 3.36\frac{h_b}{w_b}(1 - \frac{h_b^4}{12 w_b^4})] \tag{5}$$

where h_b and w_b are the height and the width of a torsion beam, respectively.
The nature frequency is

$$f_n = \frac{1}{2\pi}\sqrt{\frac{K_\theta}{J}} \tag{6}$$

(B) Experiment

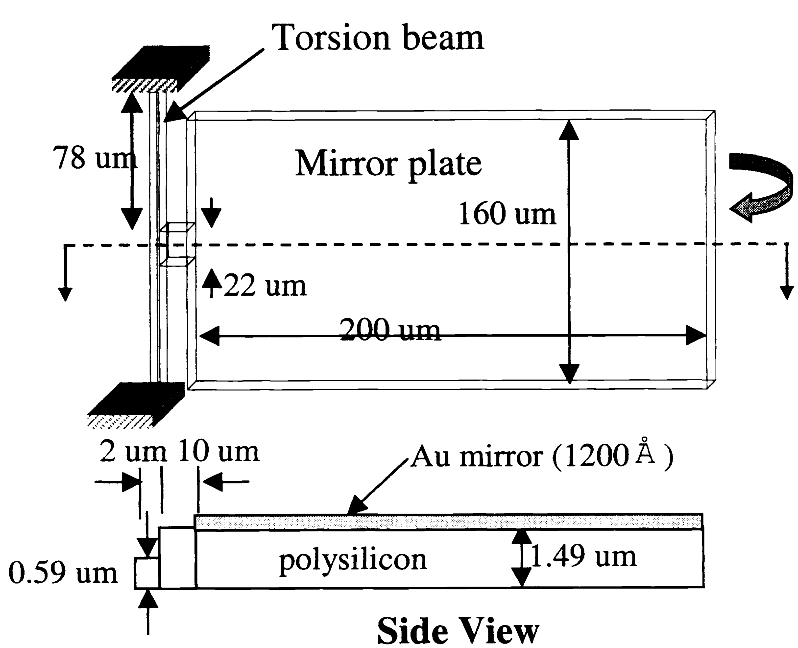

Figure 9. Dimension of a front and a side view of a vertical torsion mirror

The basic microstructures of the mirror chip were fabricated by the three-layer polysilicon surface-micromachining process at MEMS Technology Application Center at North Carolina (MCNC) under the Multi-User MEMS Process (MUMPs) service. The thickness of each layer is specified in the well-defined standard process. Since the restoring torque is proportional to the third power of the torsion beam thickness, reducing the thickness is the most effective way to reduce the operating voltage. The switch is designed to have a voltage less than 100 V. Two post processes have been done in order to improve both mechanical and optical characteristics of the switch. SF_6 Reactive ion etching (RIE) is used to reduce the thickness of the torsion beams from 1.49 μm to 0.59 μm. The surface of the mirror is coated with 0.12 μm of the gold layer to improve optical reflectivity. The detail dimension of the mirror refers to Fig. 9.

Five switches of mirror #1 to mirror #5 were experimentally examined for the mechanical frequency response. In order to prevent run-by-run in-house process variation, all the mirrors went through all the same runs. In practice, the thickness of the vertical torsion beam was referred to the measurable dummy chip and the thickness of the deposited gold for the mirror was referred to the gauge provided in the equipment.

The vertical torsion mirror was twisted around 8° by the applied dc voltage, then oscillated by small ac voltage.

(C) Result

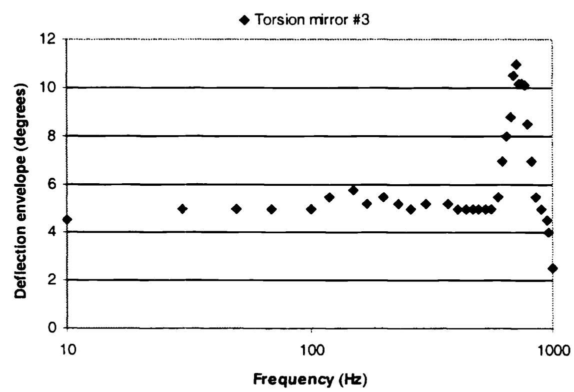

Figure 10. Deflection envelope (Δθ) response to excited frequency of the mirror #3.

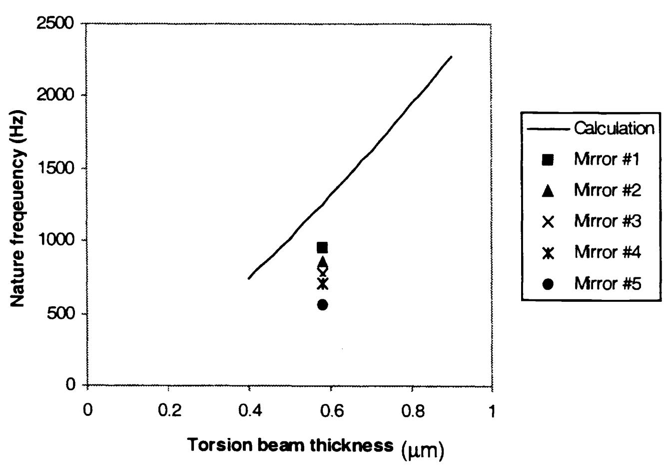

Figure 11. The calculated and the measured nature frequencies of vertical torsion mirrors

Fig. 10 illustrates the dynamic behavior of the vertical torsion mirror #3. As mentioned earlier, the mirror was tilted around 8°, and then was oscillated in the deflection envelope of 5° - 6° with the increase of excited frequency. The deflection of mirror #3 was resonant at nature frequency of 780 Hz. The nature frequency, based on the equation (6), is a function of angular stiffness (K_θ) and polar moment of inertia (J). S and thus K_θ are proportional to the cube of the height of the beam. The calculated nature frequency with respect to the beam thickness from 0.4 – 0.9 μm is plotted in Fig. 11, according to the dimension provided in Fig. 9. In this case, 0.1 μm reduction in beam thickness results in 300 Hz decrease of nature frequency. The measured results of mirror #1 to #5 are 960, 860, 780, 710, 560 Hz, respectively, which are lower than the calculated value.

Angular moment of inertia (J) also contributes the effect to the nature frequency. With the length and width of the mirror plate given in Fig. 9, the angular moment of inertia is thus dependent on the coated material density and thickness. Fig. 12 demonstrates that as the gold-coated thickness increases, the nature frequency decreases. Despite the 0.12 μm thin coating of gold on the 1.49 μm thick polysilicon plate of the mirror, the gold coating still plays a certain role in nature frequency due to high density of gold (19.32 g/cm^3) compared to the polysilicon density (2.33 g/cm^3). As the thickness of the torsion beam decreases, the effect of gold coating in nature frequency decreases. This is because the influence of the cube of beam thickness in K_θ on the nature frequency is stronger than the linear proportion of gold thickness in J.

All the mirrors went through the same processes and additional in-house post processes were conducted at the same runs. However, there is still 180 Hz difference in nature frequency between the mirror #3, #4 and #5 made on the same chip. Uniformity of each process is hard to identify on the small area of the mirror structures, which causes the variation of the results on the chip. Since many processes such as the polysilicon deposition, the torsion beam- and the mirror-patterned etching, the torsion beam thin-down etching, and the mirror gold coating were involved in fabricating the mirrors, each of them may contribute to the deviation from the calculated value.

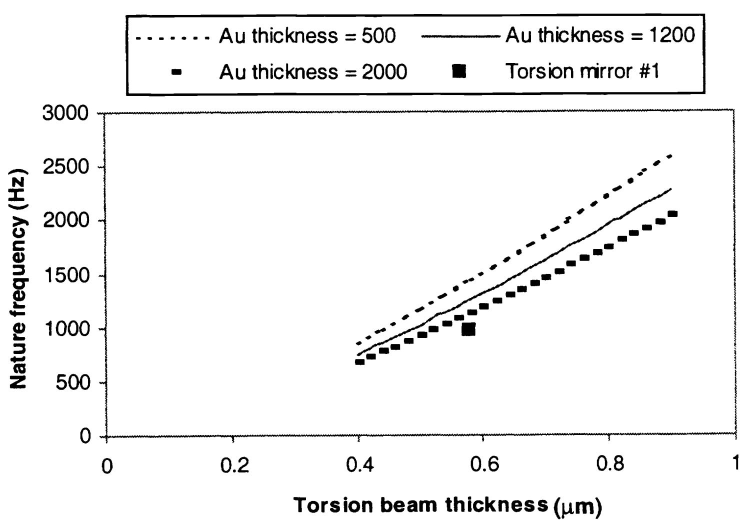

Figure 12. Effect of coated gold thickness on nature frequencies

SUMMARY

We have examined the optical coupling loss with respect to the separation distance between fiber-to-fiber and fiber-lens-lens-fiber for packaging 2x2 FDDI vertical torsion mirror switch. Based on the silicon-based passive alignment, the fiber-lens-lens-fiber coupling loss which includes Fresnel loss and spherical aberration loss allows about 1mm between the lens centers to insert the mirror devices within the specification. Compared to the fiber-lens-lens-fiber configuration, the distance is around 175 μm for fiber-to-fiber coupling at the same loss. The mechanical frequency response for the vertical torsion mirror was experimentally examined. The nature frequencies of the vertical torsion mirrors varied mirror by mirror through the same process. The nature frequency was sensitive to the torsion beam thickness and also varied with the gold-coated thickness of the mirror.

ACKNOWLEDGEMENT

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