Dynamic Simulation of Optical MEM Switches

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Abstract: Micro-optical-electrical-mechanical systems (MOEMS) present a new set of challenges for mixed technology systems on a chip (SoC) designers including the need for mixed-signal multi-domain simulation. We present new modeling techniques for optical and mechanical MEM components and apply these models for improved system-level simulation accuracy of MOEMS switches.

1. Introduction

New fabrication techniques permit micro- electro-mechanical systems (MEMS) to use the same fabrication process as CMOS integrated circuits. In fact, they can be designed using many of the standard CAD lay-out packages. Analysis and even synthesis of both electrical and mechanical components have been the topic of recent research. However, one deficiency in the MEMS design process is the need for a system level simulation tool that crosses the domains of electronic, mechanical and optical micro-systems. In order for a system simulation tool to be useful, it must be capable of modeling not only "first order" but also second order effects in each of the domains. This means that for the electrical domain, we must model both digital and analog components, for the mechanical domain we need to capture both linear and non-linear stress/strain relationships, and for the optical domain we must support diffractive (scalar) models of optical propagation.

One application area where the need for this level of modeling and simulation is apparent is in the design of all-optical cross-connect switches for fiber based telecommunications networks. All-optical switches are becoming increasingly popular due to the many advantages that they possess over typical fiber optic switches. No longer is a costly conversion between the optical and electrical domain needed to switch data signals, as all-optical switches also reduce the insertion loss and crosstalk found in conventional fiber switches. The switching is achieved through the mechanical movement of mirrors steering the data path to the desired output. With the advancement of micro-electro-mechanical systems (MEMS) technology, theses switches have become a reality, as the switches are small, fast, reliable, and eventually, will be very cheap to produce.

In earlier work, we introduced Chatoyant [1]. In this paper, we expand this work with new modeling techniques for increased simulation accuracy of MOEM systems. We first discuss the modeling of non-ideal component models, such as the modeling of the surface roughness and inherent curvature of micro-mirrors. We expand our mechanical library by including models for stress-induced cantilever beams. Using these improved component models, we simulate optical MEM systems with increased accuracy. We conclude with a summary and a plan for future work.

2. Models

In this section, we introduce the non-ideal component models for both micro-mirrors and cantilever beams. The micro-mirror models are enhanced with the addition of modeling the surface roughness, leading to light scattering, and the inherent curvature of the mirror, resulting in the focusing or defocusing of the light. The mechanical simulations are improved by the modeling of beam curvature due to induced stress on the beam.

2.1. Micro-Mirror: Surface Roughness

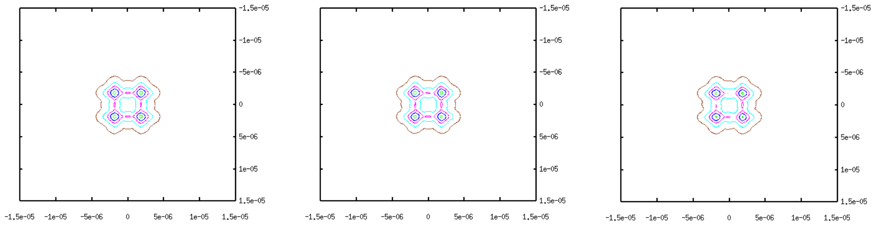
Scattering is a common optical effect when light strikes non-smooth surfaces. In optical MEM systems, the smoothness of the surface is determined by the material and techniques used to fabricate the component. Since we are typically interested in light reflection from a mirrored surface, in this discussion, we examine the surface roughness on an optical MEM mirror.

Commonly, surface roughness measurements are given by a root mean squared (rms) value, σ, which is the standard deviation of the height of the surface. In our modeling, we use the square of this value as the variance in a normal or Gaussian distribution with a mean of zero. This is used to simulate the roughness on the surface. Therefore, for each mesh point of the complex wavefront in the simulation, there is a variance on the distance, r, that each wavefront propagates to strike the surface.

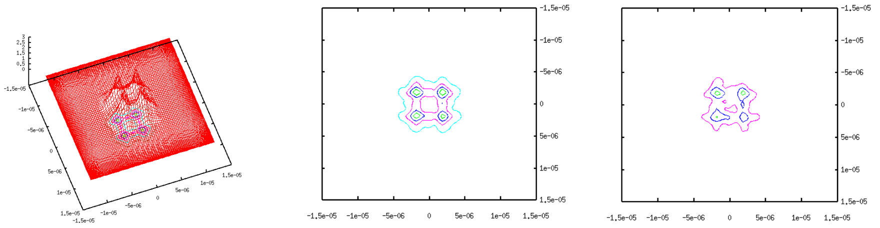
Our optical propagation modeling technique is based on the Rayleigh-Sommerfeld formulation for scalar diffractive propagation, which is necessary for near field effects [2]. As an example of this technique applied to a rough surface, we simulate a plane wave striking a 10x10 µm MEM mirror and reflecting straight back towards the source. The light is detected on a 25x25 µm observation plane at a distance of 10 µm from the mirror.

In Figure 1, surface intensity contours are shown from these simulations. At the left side of the figure (contour A), we show the result of reflection from a smooth, ideal surface. The intensity distribution of the reflection off the ideal mirror is given below the contour. As expected with such a small propagation distance, the intensity distribution shadows the size of the mirror, that is the small square shape with peaks at the corners of the aperture.

Figure 1 also presents the results of the same simulation with surface roughness rms values of 10 nm, 25 nm, 50 nm, and 100 nm, shown as contours B, C, D, and E, respectively. When compared to the flat case, (A), it is very noticeable how the shape of the beam deteriorates as the level of surface roughness increases. Of course, this also leads to light being scattered off of the optical path, resulting in a loss of power at the 25x25 um observation plane.



A) 0 nm rms - 0% Loss B) 10 nm rms - 0.5% Loss C) 25 nm rms - 3.3% Loss



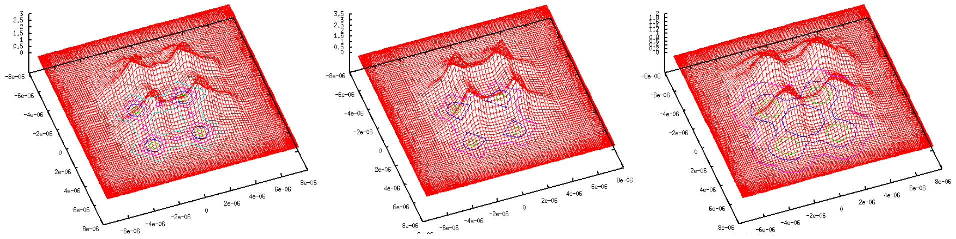
D) 50 nm rms - 12.6% Loss E) 100 nm rms - 41.5% Loss

Figure 1: Intensity contours of propagation off a rough mirror

2.2. Micro-Mirror: Curvature

Curved surfaces are common in optical MEM systems, since many thin components experience an inherent curvature due to factors including the fabrication material, the fabrication processes, and internal residual stress. Optical MEM mirrors are usually covered with layers of metal to increase the reflectiveness of the mirror as well as strengthen the mirror, reducing the final curvature.

We present simulations that show the effect of using curved optical components in a micro-optical system. In these simulations, we again model reflection off of a 10x10 µm mirror, however, we now simulate a slight curvature (R=1mm) in the mirror. For these examples, we assume a surface roughness of zero. In Figure 2, we show intensity surface and contour distributions of light reflecting from the mirror and being detected on a 15x15 µm observation plane. The simulation result at the left of the Figure 2, (A), shows the result of reflection from an ideally flat mirror, as a basis for comparison. In the intensity distribution in the center, (B), the curvature is in a concave, so the beam starts to converge towards the focus point of the mirror (f=R/2). In the third distribution, (C), the light strikes a convex mirror, with the same degree of curvature, resulting in the divergence or spreading of the light. The simulated power detected on each of these observation planes is essentially the same, although the shape and direction (i.e., convergent or divergent) of the reflected beam is different. These effects can cause insertion loss and crosstalk as the beam propagates further down the optical path.



A) Flat B) Concave C) Convex

Figure 2: Intensity distributions of propagation off a curved mirror

2.3. Stress-Induced Curvature of a Cantilever Beam

We have reported previously the use of nodal analysis and piecewise linear simulation for the modeling of mechanical structures [3]. In Chatoyant, we have implemented this methodology for the integration of mechanical elements to microsystems. In this methodology, the MEM device is modeled using a transformation of its general equation of motion into a set of first order differential equations:

$$[Mb]X' + [Mk]X = [E]F \text{ , where the state variable vector } X = \begin{bmatrix} U' \\ U \end{bmatrix}$$

U is the displacement vector, and U' is the velocity vector. The expression represents a set of linear ODEs assuming the characteristic matrices are static and independent of the dynamics in the body. Each mechanical element (beam, plate, etc.) is characterized by a template composed of characteristic stiffness, damping and mass matrices. The assembly of every element into the mechanical structure is achieved by merging together their individual templates, to create the general matrix representation (Mb, Mk, E).

We now expand our previous method to model one of the more promising optical switching MEM devices; a stress-induced curved cantilever used to move a mirror in and out of an optical path, shown in Figure 3. Our system simulation is based on the fabrication and testing of this switch at UCLA [4]. When the mirror is in the optical path, the bar state for the switch is enabled, when it is out, the switch is in the cross state.

Because of the curvature, the air gap between the substrate and beam surface is progressively decreased as the mirror moves from its initial position towards the fixed end of the structure. This introduces a strong electrostatic force over a section of the beam near the anchor, which in turn reduces the amount of applied voltage required to produce a specific degree of deflection on the entire structure.

A curved structure as described presents interesting modeling challenges. Because of the electrical field applied over the length of the beam, there is an effective section of the beam making contact with the substrate (oxide insulator) as measured from the anchor reference. This contact is mechanically a “collision” between both surfaces. The contact area increases as a function of the level of voltage applied. Collisions, in general, are difficult to characterize because of the necessity to quantify the interchange of energy, the momentum transformation, and the losses. An additional problem for this model is that the locations of nodes in this structure do not correspond to a simple linear arrangement. Consequently, in order to use our nodal modeling technique, the spatial location transformation for a curved structure must be defined.

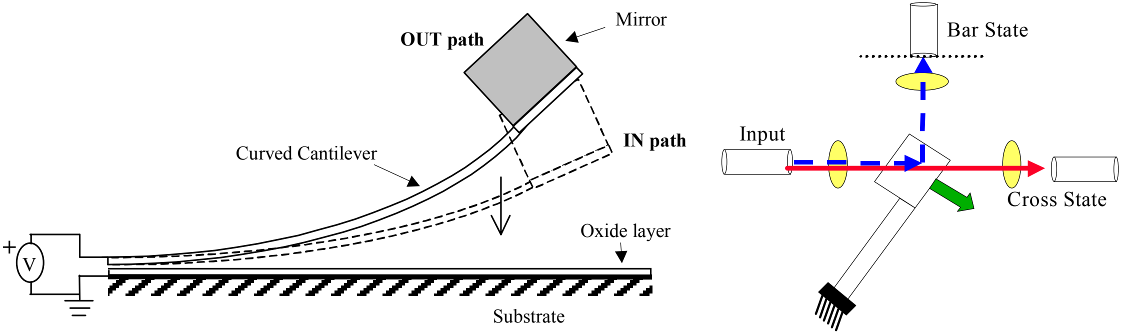


Figure 3: Stress-induced cantilever and Switching System

Surface Collision:

The structure is modeled as composed by a series of basic two-node beams. This has the advantage of offering a characterization for higher modes in the structure. When an electric field is applied between the substrate and cantilever surface, all the constituting elemental beams begin to displace toward the substrate.

However, the first element, measured from the fixed end, will collide with the substrate at some time before any other in the structure, as shown in Figure 4. At this time, any further linear analysis will be erroneous because of the necessity to characterize the collision. Instead of characterizing the collision, we simplify the simulation by performing the simulation in discrete steps. After the collision of each section with the substrate, that section is considered virtually anchored to the substrate, resulting in its nodes unable to move. Consequently, further characterizations are carried on as a new simulation problem where the structure is composed of only the remaining sections with initial conditions equal to the ones at an instant previous to the time of the collision.

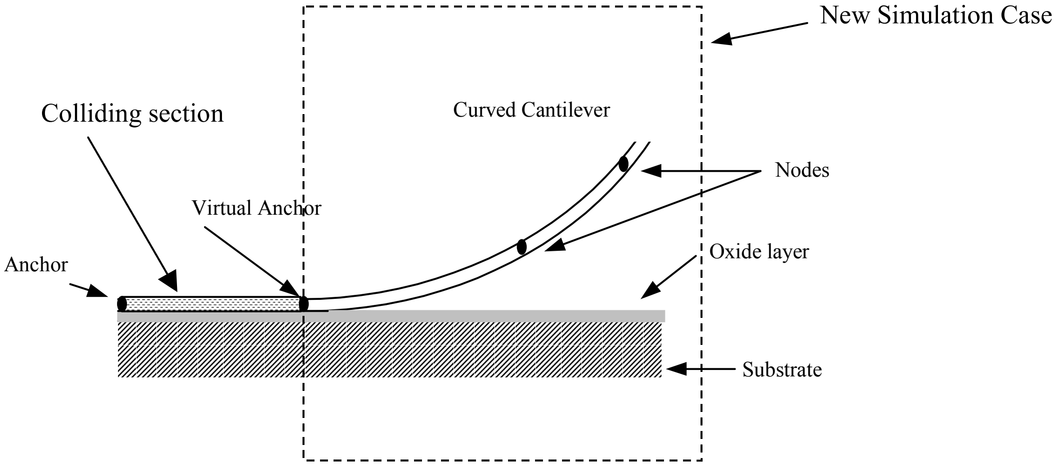


Figure 4: Step simulation in a colliding nodal characterization

Curvature:

In our methodology, a common coordinate reference frame is used for the characterization of mechanical structures, since every template, or element, is characterized in a local reference system. The process of translation of these local templates to the global reference system can be described by:

$$S = A^T \bar{S} A,$$

where, A represents the translation matrix from local displacements to global displacements (a function of the structure's geometry), $\bar{S}$ represents the local template, and S is the corresponding global representation.

For an element whose coordinate system is tilted in relation to the global reference system as in Figure 5 (a), the translation matrix will be according to the direction cosine of angles between the axis:

$$A = \begin{vmatrix} \begin{matrix} \cos\alpha & \sin\alpha & 0 \\ -\sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 1 \end{matrix} & \mathbf{0} \\ \mathbf{0} & \begin{matrix} \cos\alpha & \sin\alpha & 0 \\ -\sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 1 \end{matrix} \end{vmatrix}$$

In a curved structure, composed of an assembled group of elemental beams, the individual direction cosines will be given by:

$$\sin(\alpha_i) = \frac{n\rho}{s}\left(\cos(\frac{is}{n\rho}) - \cos(\frac{(i+1)s}{n\rho}) \right)$$

$$\cos(\alpha_i) = \frac{n\rho}{s}\left(\sin(\frac{is}{n\rho}) - \sin(\frac{(i+1)s}{n\rho}) \right)$$

where, n is the number of elemental beams, s is the curved length of the cantilever, ρ is the radius of curvature and i is the i^{th} elemental beam as shown in Figure 5 (b). With this transformation, the curved characteristic of the structure can be included in the nodal characterization and can be used in our existing piecewise linear simulator.

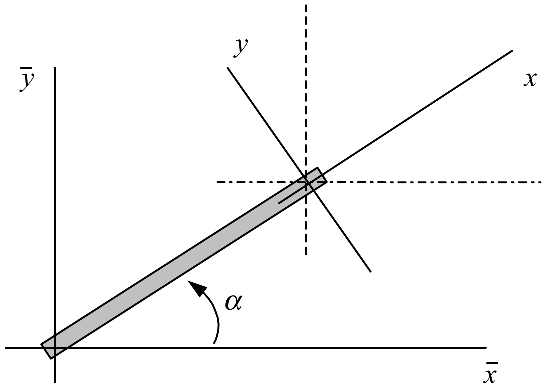


Figure 5: (a), Elemental tilted beam

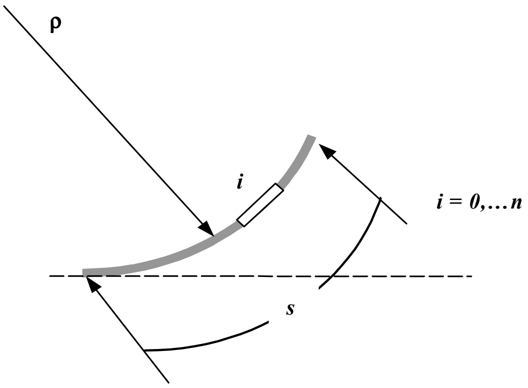


Figure 5 (b), Curved beam geometry

3. Simulations

We have previously performed dynamic simulations of a 2x2 optical MEM switch [5]. This architecture consists of a set of four optical fibers in the shape of a "+" sign, with the input and output fibers facing each other through a free-space gap. The switching system is in the "cross" state when the light is passed straight across the free-space gap. However, to switch to the "bar" state, a micro-mirror is inserted between the fibers at a 45-degree angle, and the light is reflected to the alternate output.

The micro-mirror switch simulation mentioned above was modeled as a straight beam with a uniform air gap. Instead, it is common to have a stressed induced beam with a mirror on the end act as the switching element of a system [4]. The effective progressive small air gap present in a curved beam switch systems offers a noticeable reduction in the required electrical voltage for operation. With the advanced models that we have presented in this paper, our new simulations represent a more realistic system, with the inclusion of a stress-induced beam and mirrors with curvature and surface roughness. System-level results from these simulations will be included in our paper and were removed for the space considerations of this abstract.

4. Summary

With the modeling of non-ideal components, we are able to perform simulations of systems that are more realistic to those currently being fabricated. We have presented the details of our modeling techniques and have shown the ability for these models to be easily placed in our simulation framework Chatoyant. With these new detailed models, the CAD tool can give more detailed and useful results to the user.

4. References

[1] Kurzweg, T. P., Levitan, S. P., Marchand, P. J., Martinez, J. A., Prough, K. R., Chiarulli, D. M., "CAD for Optical MEMS," Proceedings of the 36th IEEE/ACM Design Automation Conference (DAC'99), New Orleans, LA, June 20-25, 1999, pp. 879-884.

[2] Kurzweg, T.P., Levitan, S.P., Martinez, J.A., Marchand, P.J., Chiarulli, D.M., "Diffractive Optical Propagation Techniques for a Mixed-Signal CAD Tool," Optics in Computing (OC2000), Quebec City, CA, June 18-23, 2000.

[3] Levitan, S.P., Martinez, J.A., Kurzweg, T.P., Marchand, P.J., Chiarulli, D.M., "Mixed-Technology System-Level Simulation," Design, Test, Integration, and Packaging of MEMS/MOEMS, Paris, France, May 9 - 11, 2000.

[4] Chen, R.T., Nguyen, H., Wu, M.C., "A High-Speed Low-Voltage Stress-Induced Micromachined 2x2 Optical Switch," IEEE Photonics Technology Letters, Vol.11, No. 11, Nov. 1999, pp.1396-1398.

[5] Kurzweg, T.P., Levitan, S.P., Martinez, J.A., Marchand, P.J., Chiarulli, D.M., "Modeling and Simulating Optical MEM Switches," Optical MEMS, Kauai, HI, 21-24 August 2000.