# Dynamic Simulation of Optical MEM Switches

**Timothy P. Kurzweg, Jose A. Martinez, Steven P. Levitan**
*Department of Electrical Engineering, University of Pittsburgh, 348 Benedum Hall, Pittsburgh, PA 15261*
*tim@ee.pitt.edu, jmarti@ee.pitt.edu, steve@ee.pitt.edu*

**Philippe J. Marchand**
*Optical Micro Machines, 9645 Scranton Rd, Suite 140, San Diego, CA 92121*
*marchand@omminc.com*

**Donald M. Chiarulli**
*Department of Computer Science, University of Pittsburgh, 212 Mineral Industries Building, Pittsburgh, PA 15260*
*don@cs.pitt.edu*

**Abstract:** We have extended our CAD tool Chatoyant to support system-level optical MEM modeling. In this paper, we briefly describe our modeling techniques and we present dynamic simulations of a 2x2 optical MEM switch.
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## 1. Introduction

Recently, optical MEM (micro-electrical-mechanical) components have been used in a number of optical interconnect designs. Typically, these systems are based on micro-mirror components used to switch, steer, and direct optical beams through the system. Lucent Technologies and Optical Micro Machines (OMM) have commercialized small switching systems using these optical MEM mirrors and plan on scaling these designs to larger switching networks. For successful development of optical MEM systems, CAD tools are needed to simulate and reduce the high cost of prototyping and testing. CAD tools can greatly reduce the time it takes to develop a marketable product.

Currently, a complete mixed-technology CAD tool is not available, as simulations of these systems are commonly performed using a variety of single domain tools, such as SPICE for the electronics, Code V [1] for the optics, and ANSYS [2] for the mechanics, with very little or no interaction between the tools. We have developed a free-space opto-electronic CAD tool, called Chatoyant, for system-level modeling of optical interconnects [3]. With the addition of mechanical models and determining the appropriate optical propagation technique for micro-systems, we have extended Chatoyant to support the modeling and simulation of optical MEM systems. In this paper, we briefly describe our modeling methodology for micro-optics and mechanics, and present the dynamic simulation of a 2x2 optical MEM switch.

## 2. Models

For the quickest simulations, Chatoyant performs Gaussian propagation for its optical models. However, this propagation method does not support diffraction or propagation through diffractive components. At OC'99, we presented Chatoyant's addition of the Fresnel approximation to simulate diffractive effects in interconnect and switching systems. However, when system and component sizes shrink to the scale of microns, as found in optical MEM systems, the validity of the Fresnel approximation is questioned and a more rigorous technique must be performed. Chatoyant currently supports the Rayleigh-Sommerfeld formulation for optical propagation [4]. This technique is limited only by the requirement that the aperture sizes and propagation distances are greater than the light's wavelength, which is valid for most optical MEM systems.

Our mechanical models extend our piece-wise linear (PWL) technique that is used to model Chatoyant's electrical signals. We employ a modified nodal representation for the component, piece-wise linear modeling of non-linear devices, and piece-wise characterization of signals to accomplish the simulation of these mixed technology systems. The details can be found in [5]. This PWL technique results in a decrease in computational time and allows for a user-determined trade-off between accuracy and computation speed. The model for a mechanical device can be summarized in a set of differential equations that define its dynamics as a reaction to external forces and given to the PWL solver for evaluation. In Chatoyant, a MEM device is characterized by its basic components, such as beams, plate-masses, joints, and electrostatic gaps, and the local interactions between these components.

### 3. Simulations

In this paper, we concentrate on the modeling and simulation of a 2x2 optical MEM switch. 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. Systems built with these switches have numerous advantages over typical waveguide or fiber switching systems, including a reduction of coupling loss and crosstalk, as well as being independent of wavelength, polarization, and data format [6]. The switches have been reported to be 10 times smaller and faster than typical fiber-based switches, while requiring only 1/100th of the operating power [7]. We use RSoft's BeamPROP [8] to simulate the light through the fiber, and have developed an interface between the fiber propagation (BeamPROP) and free-space (Chatoyant) through a data file.

For simplicity, we simulate only a single input switching to either the cross or bar state throughout this paper. Both output states are seen in Figure 1, represented by the solid and dashed arrows, respectively. The mirror fabrication and positioning can be achieved in a variety of ways. For example, in a Bell-labs design [9], a "see-saw" pivoting mirror is inserted into the optical path. UCLA [6] and AT&T [10] both have systems using scratch drive actuators (SDA) to assemble and position the mirror between the fibers, and the University of Neuchael, Switzerland [11] uses a combdrive actuator design to slide the mirror into the free-space gap. However, for the simulations presented in this paper, we use a system loosely based on an experimental system designed and tested at UCLA [12]. Similar to that system, a mirror is placed on top of a long anchored cantilever beam. In our system, the bar state is achieved in the steady-state of the system, with the mirror positioned between the fibers in the free-space gap. The cross state is achieved by the cantilever beam bending towards the substrate, moving the attached mirror out of the optical path. The beam movement is a result of electrostatic attraction between a voltage applied below the cantilever and the beam itself. This attraction results in a force being applied to the beam. The simulated system is also represented by Figure 1. The mirror is 100 x 100 μm, and is positioned at the end of a 700 μm cantilever beam. Both beam and mirror are fabricated with polysilicon, with the ideal mirror having a 100% reflectivity. The beam is 2 μm wide and 100 μm thick, while the mirror is 4 μm thick, to ensure the mirror remains rigid. The collimating lenses ($f = 50$ μm) are placed 50 μm from the fiber ends, and there is a free-space gap of 100 μm between the lenses.
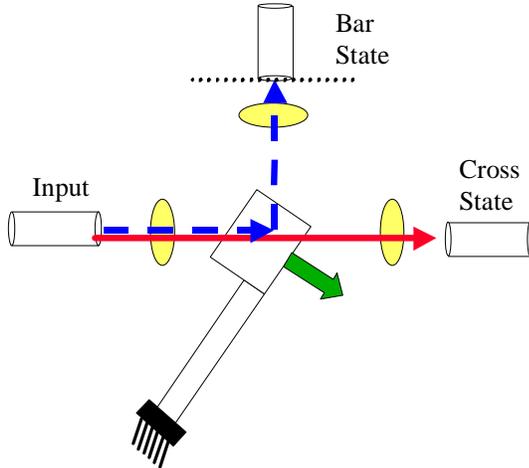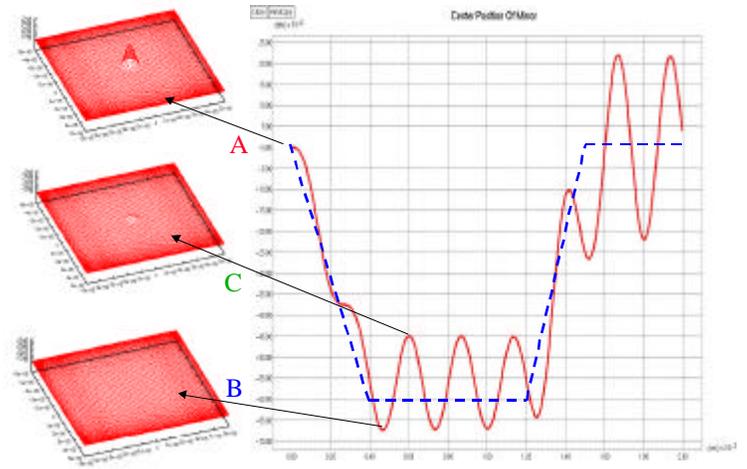


Figure 1: Switching System



Figure 2: Mirror Response

We first use Chatoyant to analyze the mechanical movement of the beam and mirror. The more significant mode frequencies of the beam, including the mirror mass, are determined to be 3.7 and 27.1 kHz, resulting in a period of about 270 μsec. These results have been verified through the finite element (FE) solver, ANSYS, with the results within 5% of each other. For a switching speed of 400 μsec, the response of the beam, in terms of the center position of the mirror from the original steady-state value, is shown in Figure 2. The switching force applied to the cantilever beam is also included in Figure 2, represented by the dashed line. We next examine the optical power that is detected on the bar state's fiber end (10 μm diameter) for the same 400 μm switching case. Chatoyant intensity distributions at an observation plane on the bar fiber end are included for three points on the response curve, labeled A, B, and C. A is when the mirror is inserted in the optical path, achieving the bar state in the system. B is at the

point where the mirror is totally out of the optical path, achieving the cross state. As seen in the intensity distribution, no power hits the bar detector,. *C* is somewhere in the middle, as the response of the mirror has caused some power to be detected at the bar state. The power on the bar fiber is shown in Figure 3 in terms of dB lost. Notice that the power detected corresponds to the mirror position movement in Figure 2. Therefore, as the mirror bounces, like at point *C*, optical power is detected in the bar fiber, even though the input force is trying to drive the light into the cross state. This allows for the possibility of crosstalk or the detection of a false "1". Also included in Figure 3, is the optical power detected with a slower switching speed (600 μsec). With this mirror response, the power detected in the bar state, while the mirror is switched to the cross state is always less than -45 dB.

We next further examine the mirror position, where the light strikes it, and the effect that this has on the power detected on the observation plane at the bar state fiber end. To help us in our explanations, we look at the intensity contour for each of the three cases we previously examined. The three intensity contours are seen in Figure 4, along with a circle drawn to representing the fiber. For case *A*, the light strikes the mirror in the center and reflects directly into the bar fiber. As seen in the figure, the contour for *A* is directly on the fiber, and we consider this full detected power (0 dB loss). For case *B*, the mirror is moved totally out of the optical path, resulting in virtually no power being detected on the fiber (123 dB of loss). However, it is interesting to note that even though almost all the power is missing the detector plane, there is still a diffractive effect, with very low power, striking the observation plane, approximately 28 μm away from the fiber center. In this system, it is not destructive, however, an effect like this could introduce crosstalk in larger scaled systems. With case *C*, the mirror is positioned such that half of the light is reflected off the mirror to the bar detector, and the other half propagates through to the cross detector. With the light striking the edge, the power is still concentrated, however, it is centered 3 μm from the fiber center. For *C*, a 6 dB loss in power is experienced on the bar fiber.
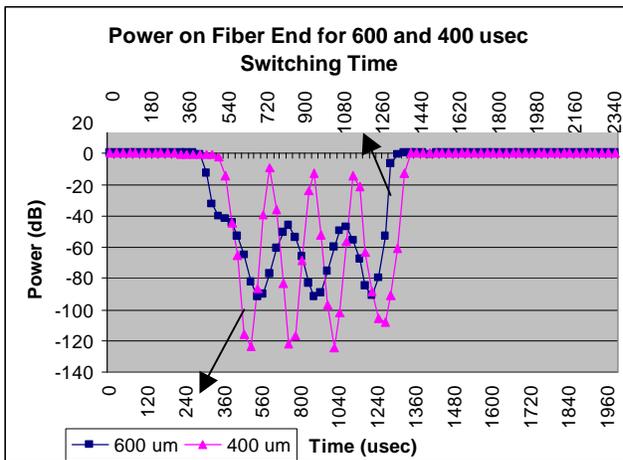


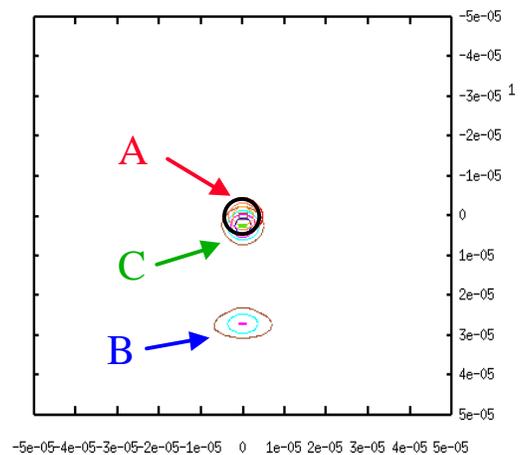Figure 3: Power Received on Bar Fiber End



Figure 4: Contour Distributions

## 4. Summary

As seen, Chatoyant is a useful tool that can model, simulate, and analyze optical MEM systems and interconnects, with mixed support for optical, electrical and mechanical domains. CAD simulations are viable solution to reduce the high cost of prototyping optical MEM systems. In this paper, we have shown simulations of a 2x2 optical MEM switch. We are able to analyze systems like these in terms of insertion loss, crosstalk, and BER.

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