CAD for Opto-electronic Microsystems

Timothy P. Kurzweg*, Steven P. Levitan*, Philippe J. Marchand**, Kurt R. Prough*,
Donald M. Chiarulli***

*University of Pittsburgh, Dept. of Electrical Engineering, Pittsburgh, PA, USA, tim@ee.pitt.edu,
steve@ee.pitt.edu, krpst5@ee.pitt.edu
**University of California, San Diego, La Jolla, CA, USA, philippe@ece.ucsd.edu
***University of Pittsburgh, Dept. of Computer Science, Pittsburgh, PA, USA, don@cs.pitt.edu

ABSTRACT

The use of MEMs technology has enabled the fabrication of micro-optical and micro-electro-mechanical systems on a common substrate. This has led to new challenges in computer aided design of optical micro-electro-mechanical systems. We have extended our free-space opto-electronic system CAD tool, Chatoyant, to meet the needs of optical MEMS designers. This paper presents new analysis techniques which extend our tool to support optical MEM system design. We demonstrate these extensions with the analysis of a 1x2 micro-optical MEM interferometer switch.

Keywords: MEMS-CAD, optical MEMS, MOEMS, micro-optics

INTRODUCTION

Applications for optical MEMS (micro-electrical-mechanical systems) are growing to include scanning, projection, display, switching, printing, sensing, modulating, and data storage.[10] As these applications are quickly evolving from abstract ideas to marketable products, it is essential for designers to use CAD tools to model these optical MEM systems in order to save design time and avoid costly prototyping. In this growing field, technologies are constantly advancing and CAD tools must be flexible in their ability to model and simulate new multi-domain components and systems.

A complete optical MEMS CAD tool needs to model electrical and optical signals, mechanical positioning and tolerancing, thermal and vibration effects, fabrication, packaging, and, most importantly, the interaction of all these constraints. Currently, no single CAD tool completely models the complexity of optical MEM systems. Therefore, designers must use a collection of tools to model, simulate, and analyze each stage of this mixed signal design.

For conventional MEM design, a family of CAD tools is emerging, specializing in layout and simulation. Analogy, teamed with Microcosm Technologies, and Tanner have created CAD packages to design and simulate MEM systems through analog electronic (SPICE) simulation backbones, forcing all system models into electrical templates. Universities have also created specialized tools for MEM modeling and simulation,[8][9] and have bridged the gap between CAD and foundry facilities.[3] However, no tools have begun to address the additional constraints imposed by micro-optical systems. Many good commercial optical CAD tools exist, such as Code V and ASAP, but these tools do not have the simulation and analysis capability to model optical MEM systems. Therefore, optical MEMS designers are forced to use multiple tools in attempt to simulate a single system. The focus of our work is to provide the MEMS designer with a CAD tool that can model, simulate, and analyze system level optical signals as they interact with the mechanical and electrical signals found in an optical MEM system.

CHATOYANT

We have created Chatoyant, a mixed-signal opto-electronic simulation framework[5], built upon the simulation engine, Ptolemy[2]. Chatoyant, has been successfully used to design, simulate, and analyze free space opto-electronic interconnect systems by performing both static and dynamic simulations. Static simulations analyze mechanical tolerancing, power loss, insertion loss, and crosstalk, while dynamic simulations are used to analyze data streams with techniques such as noise analysis and bit error rate (BER) calculation. In Chatoyant, component models are written in C++ with sets of user defined parameters defining the characteristics of the component.

Until recently, Chatoyant has modeled light using only ray and Gaussian beam propagation methods. These high level abstractions provide sufficient accuracy for most refractive free-space opto-electronic systems. Chatoyant's optical library includes sources (vertical cavity surface emitting lasers, VCSELs, and multiple quantum well, MQW, modulators), optical components (lenses, lenslets, mirrors, apertures, etc.), as well as optical detectors. Opto-electronic signals are modeled using piece-wise linear discrete event techniques providing user control for accuracy and computation time.[6] Chatoyant possesses an advantage over other CAD tools by keeping all mixed-signal models and simulations within one internal framework.

In order to support optical MEM components, we have extended Chatoyant in three ways. First, we introduced

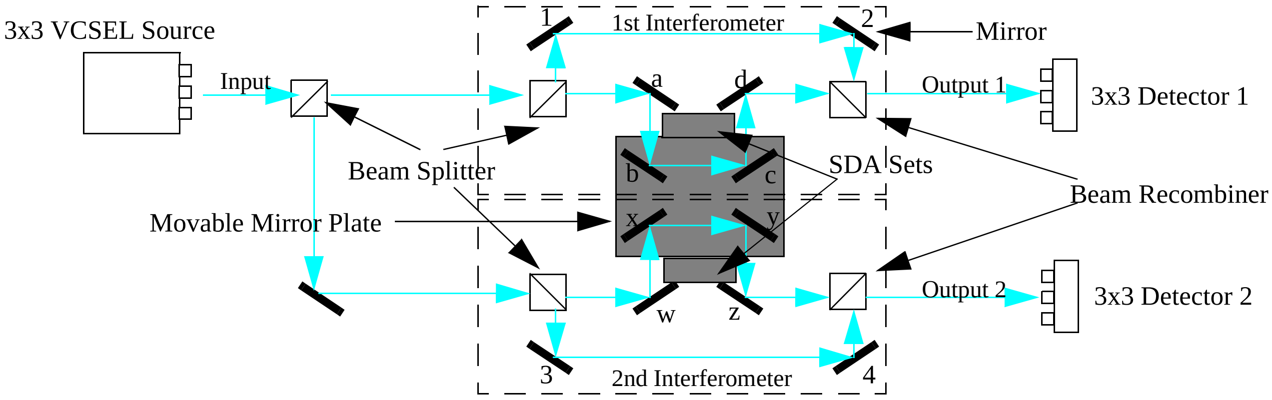


Figure 1: Two Interferometers and the Mirror Plate

modeling techniques for diffractive optics. This allows the use of diffractive models in cases where Gaussian approximations are not valid. Second, we have included models for micro-optical structures, including micro-Fresnel lenses, micro-mirrors, and phase masks, along with MEM models, such as micro-mechanical actuators. An additional requirement emphasized by these microsystems is support for tolerancing on the precise alignment required for desired operation. Therefore, our third extension is the implementation of a Monte Carlo tolerancing package within Chatoyant to determine worst case mechanical tolerancing and sensitivity. In this paper, we focus on this third extension.

SIMULATION RESULTS

To illustrate our model implementations and analysis techniques for optical MEM systems, we introduce the following example system, a 1x2 optical MEM switch. This design is based on the constructive and destructive interference of light in two interferometers.

The system design is shown in Figure 1. A 3x3 VCSEL array source is split into two beam arrays, providing inputs into the two interferometers. A movable plate on the substrate of the wafer holds two of the mirrors from each interferometer (b, c and x, y) in the shape of an “X”. The position of the plate is controlled by feedback circuitry in the system, and is moved by two scratch drive actuators (SDA) sets which move the mirror plate back and forth. Therefore, when the plate moves, the optical path length of one interferometer is shortened causing constructive interference on one detector, while the other optical path is lengthened, causing destructive interference. Two 3x3 detector arrays provide the outputs of the system.

The number of mirrors that steer the beams through the system affects the insertion loss of the output beams. We assume each gold plated mirror has an efficiency of 87%, and our beam splitters to be ideal (50%/50%). Initial VCSEL spot sizes of 80μm are required such that no lenses have to be added to the system to keep the beams from significantly diverging and becoming unfocused.

The SDAs are modeled in Chatoyant by the actuator’s “step” size (determined by the height and length of the actuator) and the voltage pulse train, which drives the actuator.[1] In this simulation, the SDAs are powered by a 50kHz pulse with an amplitude of ±70 V, and a height and width resulting in a 11nm “step” size. Since we are using a 3x3 array of VCSEL sources, one beam is used as a reference and is always “on”, as shown in the upper left corner of Figure 2. The other 8 beams are used for data transfer. The feedback circuitry is a basic comparator, which compares the converted voltage from the reference “on” beam with a threshold voltage, specified by the user. If the received voltage is not at the desired level, the actuator keeps moving the mirror plate to a position that produces the desired interference, resulting in the correct optical power at the desired detector.

Static Simulations

We first present static simulations, useful for determining system insertion loss, efficiency, crosstalk, and mechanical tolerancing. Figure 2 shows a Chatoyant output image at one of the 3x3 detector arrays. For Detector Array 1, Chatoyant reports a worst case efficiency of approximately 56% for one of the beams in the array. 23% of the power is lost due to the efficiency of the mirrors, and an additional 21% of the power is lost is due to the beams’ divergence and the detector sizes. With a longer optical propagation and an extra mirror, Detector 2’s efficiency drops to approximately 41%. As shown in Figure 2, the detector’s size and spacing also generate optical system crosstalk. Worst case crosstalk between neighboring detectors is measured at -15.5 dB.

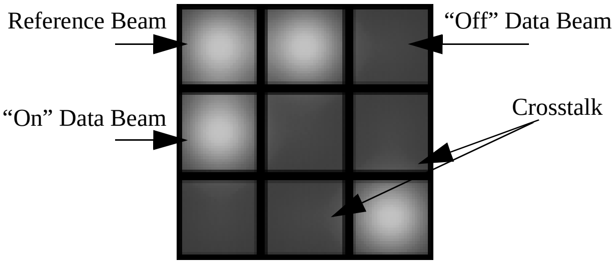
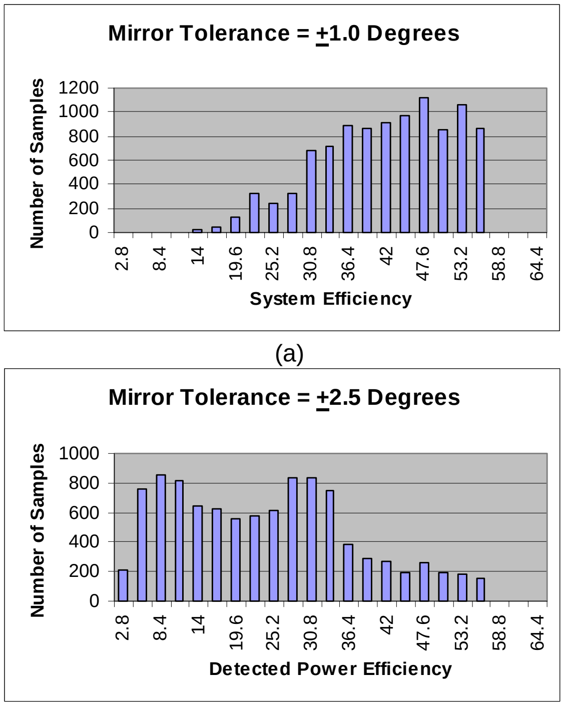


Figure 2: Detector Output Array

With MEM fabrication, the exact positions of the components can not be assured. Therefore, mechanical tolerancing analysis is essential for optical MEM system design. If a mirror angle is offset, the reflected beams could entirely miss the detector. In this switching system, this can occur with a single mirror offset by only 4 degrees. Mirror misalignment can also result in greater insertion loss and crosstalk. This can be seen when mirror “d”, from Figure 1, is moved only 1.0 degree. The system efficiency drops to 53.5%, and the crosstalk rises to -11.42 dB.

Granted, a 1.0 degree offset in a single mirror does not effect system performance substantially and is not difficult to simulate, however, if every mirror has an offset, or even more challenging, a tolerance range, prediction of system performance gets more complicated. Using Chatoyant’s Monte Carlo analysis, the Chatoyant user can simulate all possible mirror misalignment, and determine how these would effect the system performance.

Assuming, through standard MEM fabrication, that each mirror could be fabricated within a tolerance of ±1.0 degrees of its ideal position, we use Monte Carlo analysis of the system for 10,000 samples. The average system efficiency on Detector 1 is found to be approximately 40%, with no beams entirely missing the detector, compared to the maximum 56%. A histogram of the output data is given in Figure 3(a). This graph shows that even with 6 mirror tolerances in an interferometer, 7529 samples are detected with a system efficiency greater than 33%. However, when the tolerance is increased to ±2.5 degrees, the average detected power efficiency drops to 22.5%. We now measure in terms of detected power efficiency, the ratio of detected power to input power. This is due to the fact that in some runs we are detecting power from optical crosstalk between neighboring detectors. The output histogram for this second analysis is given in Figure 3(b). As expected, most samples have a low detected power efficiency, with only 1535 samples greater than 33%. Notice the two peaks in this histogram. The first peak of samples, in the range 28-34%, is a result of the interferometer’s beams not recombining and only one hitting the detector. Since either beam can be steered off the detector, this value is roughly double of the expected value. Optical crosstalk causes the second increase in samples, between 5 and 10%. Instead of receiving no power on a detector when both beams miss the detector, crosstalk from another beam registers small amounts of detected power.



(a)

(b)

Figure 3: Mirror Tolerance Histograms

Dynamic Simulations

The second type of simulations performed are dynamic simulations, where streams of data pass though the switch to the specified detectors. Figure 4 shows five outputs from a single simulation of the switch in Chatoyant. Figure 4(a) shows a 1.6 kHz square wave, which selects the switch’s output. When the value is positive, Detector 1 is selected, and when the value is negative, Detector 2 is selected. Figure 4(b) shows the detected voltage output of the reference bit. The optical detectors are composed of p-i-n photo diodes, which convert optical power into current, and transimpedance amplifiers, which convert the current to voltage. Figure 4(c), shows the output of the comparator circuity, which controls the SDAs. If the output is positive, the SDAs move the mirror plate reducing the optical path of the first interferometer, while increasing the optical path of the second interferometer. If the output is negative, the other SDA moves the mirror plane in the opposite direction. If the output is zero, neither of the SDAs move, resulting in no mirror movement.

Optical feedback allows us to compensate for mechanical tolerancing and noise. The noise sources from the detector changes the reference output voltage, occasionally causing the feedback circuity to signal the SDA to move another step. This accounts for the “spikes” that are found in Figure 4(c).

Figure 4(d) shows the movement of the mirror plate. Recall the mirror plate moves up and down by the step size of the actuators. The spikes seen in Figure 4(c) do not move the SDAs since a 50 kHz voltage pulse can not be completed in such a short time.

The final graph, Figure 4(e), shows one stream of data that is passed from one VCSEL source, through the interferometers, to the desired switch output. Both outputs from the switch are shown in the same graph, the first output by a dashed line, and the second output with a solid line. In this example, the optical data stream is passing at only 125 kbits/sec. In a practical application, the optical signal would actually be at a much higher bit rate (300 MHz - 3 GHz), but is kept slow here for illustration purposes. In this example, for

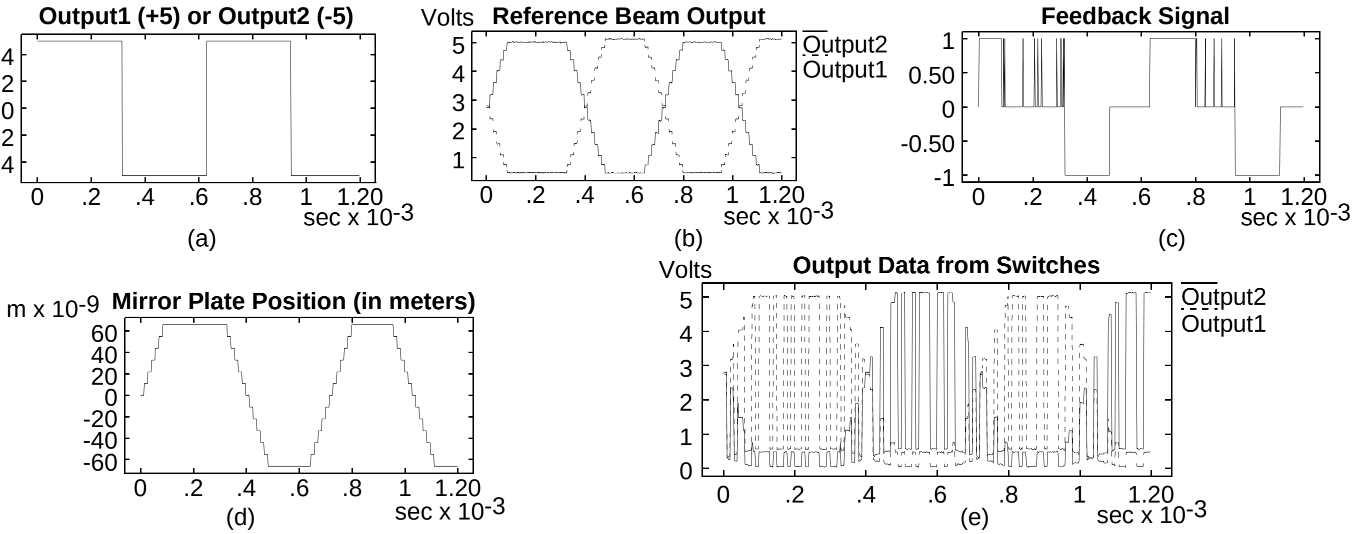


Figure 4: Dynamic Response of the 2x1 Optical MEM Switch

each switching pulse, approximately 50 bits are passed through to the receiver. In reality, we would switch packets of 10^3 - 10^5 bits. Similarly, we show data bits during the switch transition, while in real systems “guard bands” would be added to the data stream.

In theory, with a 50 kHz clock driving the SDAs, the actuators will take 10 μsec to move each of the 11nm steps. With a 850 nm laser source, the optical paths in the interferometer differ by 212.5 nm between complete constructive and destructive interference. For worst case switching time, the movable mirror plate, would have to move this entire distance. With a step size of 11nm, this would take approximately 20 steps, resulting in a switching time of 200 μsec.

However, in simulation, we find that with the detector parameters and the feedback circuity voltage reference specified, the maximum number of steps the SDA is moving is only 12, resulting in a switching time of 120 μsec. This is because neither total constructive nor destructive interference is achieved. This is visible in Figures 4(b) and (e), with the “off” switch output not completely reaching 0 volts. Total interference could be reached at the cost of increased switching time, by altering the feedback circuitry parameters. Using Chatoyant’s BER analysis[5], the designer could perform trade-offs between BER, switching time, and mechanical tolerancing to achieve the desired system performance.

Using parameters from the published literature, the free space interferometer switch that we have modeled here is comparable to optical fiber switches built by Lee and Marxer. Worst case switching time of Lee, et al.’s[4] surface-micromachined, moving plate mirror, fiber switch was found to be between 10 and 15 msec, and Marxer et al.[7], using bulk-micromachining and a comb-drive reports a switching time of 200 μsec.

CONCLUSION AND SUMMARY

Optical MEMS have the potential of drastically reducing the size and cost of digital communications and computation systems. However, due to the multiple technologies (optical, electrical, and mechanical) utilized in optical MEM systems, complete optical MEM CAD tools are difficult to create. This paper has shown how Chatoyant has been extended, in particular with Monte Carlo analysis tolerancing, to enable the modeling of micro-optical-electro-mechanical systems.

Chatoyant’s ability to perform and analyze optical, electrical, and mechanical trade-offs make our system valuable to optical MEM designers. Keeping all the simulations internal to the Chatoyant framework allows for quick and efficient analysis throughout multiple domains. Results from system simulations show that Chatoyant is a useful, practical alternative to costly prototyping optical MEM systems.

We would like to acknowledge the support of DARPA contract number F3602-97-2-0122 and NSF grant ECS-9616879.

REFERENCES

[1] Akiyama, et al., *J. of Microelectromechanical Systems*, 6, 10-17, March 1997.

[2] Buck, et al., *Int. J. Computer Simulation*, 4, 155-182, 1994.

[3] Karam, et al., *Design Automation Conf.*, 674-679, June 1997.

[4] Lee, et al., *TRANSDUCERS 97*, 1A4-07P, 1997.

[5] Levitan, et al., *Applied Optics*, 37, 6078-6092, September, 1998.

[6] Martinez, et al., *OSA Optics in Computing*, April 1999.

[7] Marxer, et al., *Proc. 10th Workshop of Micro Electro Mechanical Systems (MEMS)*, 49-54, 1997.

[8] Senturia, *TRANSDUCERS 95*, 232-A7, June 1995.

[9] Wilson, et al., *SISPAD 98*, 1998.

[10] Wu, M.C., *Proc. of the IEEE*, 85, 1833-1856, November 1997.