Macro-Modeling of Systems Including Free-Space Optical MEMS

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ABSTRACT

One barrier to the integration of MEMS devices into optical systems is the lack of a system-level CAD tool allowing the optimization of MOEMS designs simultaneously with embedding control electronics. Our work addresses this issue by integrating extracted electro-mechanical macro-models for MEMS devices and optical macro-models based on Gaussian beam optics into a system-level simulation tool. Microcosm's *MEMCAD* includes *MEMSys*, a *Saber* based package used to simulate and analyze mixed electrical, mechanical, and fluidic systems. We have added an optical domain to this framework. In this paper, we introduce this optical system-level modeling concept in both theory and through the simulation of an optical MEMS noise suppression system.

Keywords: Optical MEMS, MOEMS, free-space optics, Gaussian beam propagation, system-level simulation.

1 INTRODUCTION

Telecommunications networks are evolving toward an all-optical network for broadband communications as electronic circuits have limitations towards data rates in excess of 10 GHz. Beyond the promise of added bandwidth, DWDM (dense wavelength division multiplexing) also promises to provide circuit-switching capability in the optical domain thus avoiding all contention on the channel and providing complete protocol transparency. To take advantage of this capability, flexible scalable low-cost elements routing optical wavelengths from fiber-to-fiber for large fiber counts are required. MEMS (micro-electrical-mechanical systems) are a promising technology to provide low-loss flexibility in optical circuits. Other applications for optical MEMS, or MOEMS (micro-optical-electrical-mechanical systems) are growing to include scanning, projection, display, printing, sensing, modulating, and data storage [9]. However, for these ideas to quickly become incorporated into marketable products, a CAD tool is needed for efficient system-level evaluation.

Commonly, separate CAD tools are used to simulate each domain in a mixed-domain system. For example, *Spice* is used for simulating the electrical domain, *COSMOS* is used for finite element mechanical simulations, and *Code V* is used to verify the optics through ray tracing. Either a "hand wave" or cumbersome manual data transfer is then used to model the interactions of all three domains. We strive to create an efficient system-level CAD environment where one tool can design and analyze mixed-domain systems.

We use our *MEMCAD* CAD framework [6], which provides MEMS component design, modeling, simulation and extraction. The system level tool, *MEMSys* [2], is a *Saber* based package used to simulate and analyze mixed electrical, mechanical, and fluidic systems. Our optical system-level modeling builds on research performed at the University of Pittsburgh [4][5].

The remainder of this paper presents the current optical MEMS system-level modeling, simulation, and analysis work being developed at Microcosm Technologies. We first introduce our system-level methodology, followed by an overview of our optical modeling approach. We then apply this to an optical noise suppression system and present simulation results.

2 SYSTEM-LEVEL MOEMS MODELING

The challenges of simulating systems operating in multiple physical domains lie in the accurate and efficient modeling of each domain and in the proper treatment of the interaction of different domains. For example, to simulate optical MEM systems, a CAD tool must not only model electrical, mechanical, and optical signals, but, of equal importance, also model the interaction between these signals. We chose to expand Microcosm's existing system-level CAD tool, *MEMSys*, to support optical models. By using this package, two of the three desired domains are already modeled, and our efforts can be concentrated on the inclusion of the optical domain. An additional advantage of using *MEMSys* is that the model parameters for the electrical and mechanical domains can be automatically extracted from physical MEMS models in *MEMCAD* and used in these mixed-domain simulations.

The new optical domain in *MEMSys* enables the propagation of light through free-space and optical components. The optical domain is written in MAST [1], Saber's analog hardware description language (AHDL). The optical propagation is based on Gaussian beam analysis, allowing coherent light to be modeled by the following eleven scalar parameters: x,y,z, the position of the Gaussian beam center; ρ, θ, γ, the orientation of the Gaussian beam; I_0, the peak intensity of the beam at waist; z_0, the Rayleigh range, or depth of focus; z_{w0}, the distance to the next minimum waist; λ, the wavelength of the light; and p, the phase of the central peak of the beam.

Our optical propagation is a mixture of ray and Gaussian optics. We calculate the position and direction of the center of the Gaussian beam using ray propagation methods. The Gaussian beam is "superimposed" over the ray-traced beam to model the intensity, waist, and phase of the light beam. The advantage of using Gaussian beam analysis is the fast computational speed in which light is modeled and propagated, allowing for interactive system-level design. For many micro-systems, diffractive effects can dominate, and our Gaussian propagation will not always be accurate [8]. For these systems, other optical methods, such as scalar or vector diffraction propagation, must be used. This capability is also currently being investigated in a separate effort.

We have created two optical libraries. The first library contains strictly optical components, such as lenses, mirrors, and beam splitters, and the second contains opto-electronic sources and detectors. All components in these libraries are interconnected by the eleven light parameters, seen above, through separate data lines. Not only does the component model its own interaction with the light, the component also models the free-space propagation from the previous component.

An optical ABCD matrix [7], characterizing how the component interacts with the Gaussian light beam, models the optical elements. Using the ABCD matrix, explicit integration is not performed at each interface, drastically reducing the computation time. The beam's position and direction are calculated with the following equations (shown in only one of the three positions and directions):

$$x_2 = Ax_1 + Br_1 \qquad r_2 = Cx_1 + Dr_1$$

To calculate the remaining parameters of the Gaussian beam, we must first define a Gaussian beam's "*q*" parameter. This parameter is a complex number in which the real portion is the distance to the minimum waist and the imaginary portion is the Rayleigh range, as shown:

$$q = z_{w0} + j \cdot z_0$$

With a Gaussian beam of known amplitude and position, the q parameter is sufficient in describing the Gaussian beam. Using the ABCD law, a transmitted Gaussian beam from an optical component, q_2, can be described by the incident Gaussian, q_1, and the component's ABCD matrix:

$$q_2 = \frac{Aq_1 + B}{Cq_1 + D}$$

For example, in the case of a thin lens, A=1, B=0, C=-1/*f*, and D=1, where *f* is the focal length of the lens. Solving for q_2, and determining the real and imaginary parts, the new *z0'* and *zw0'* for the emerging Gaussian beam can be found:

$$z_0' = \frac{f^2 \cdot z_0}{(f - z_{w0})^2 + z_0^2} \qquad z_{w0}' = \frac{f\,(f \cdot z_{w0} - z_{w0}^2 - z_0^2)}{(f - z_{w0})^2 + z_0^2}$$

The second optical library contains opto-electronic sources and detectors. We currently have modeled a VCSEL (vertical cavity surface emitting laser) source. This model is based on electrical to optical power conversion [3]. The opto-electronic p-i-n detector integrates the Gaussian beam's intensity over the area of the receiver, calculating the optical power detected. The receiver's responsivity parameter is multiplied by the optical power to compute the output electrical current. Taking advantage of the electrical components available in *MEMSys*, transimpedance amplifiers are built, transforming the current into a voltage.

The optical simulator uses a data flow scheduler, where we assume the amount of time the light takes to travel between optical components is negligible. This results in each component receiving the incident Gaussian beam parameters, calculating the transmitted beam, and passing the light to the next optical component. *MEMSys*'s internal scheduler resolves the interaction between the "continuous" electrical and mechanical signals with the data flow optical signal.

In the next sections we present an example optical MEM system and show simulation results achieved by our simulation system.

3 EXAMPLE SYSTEM

As a composite example of our work, we have simulated an optical MEM noise suppression system. The system, shown in Figure 1, is composed of a VCSEL source, a *4f* optical interconnect system, and a detector plane composed of a three-detector linear array. The system is in "perfect" alignment when the beam strikes the center detector. In the center of the *4f* system, there is a 45-degree torsional mirror, controlled electrostatically by electrodes underneath the mirror. This mirror is constructed and simulated using *MEMCAD* to extract all electro-mechanical parameters into *MEMSys* for system level simulation. A *MEMCAD* solid model and simulation of the mirror is shown in Figure 2. The mirror is controlled by a PI (proportional-integral) electronic feedback control loop. The controller senses the optical power detected on each of the side detectors and applies the proper amount of voltage on the mirror's electrodes to tilt the mirror for reflection of the light beam onto the center detector. This general optical feedback technique can be used to achieve

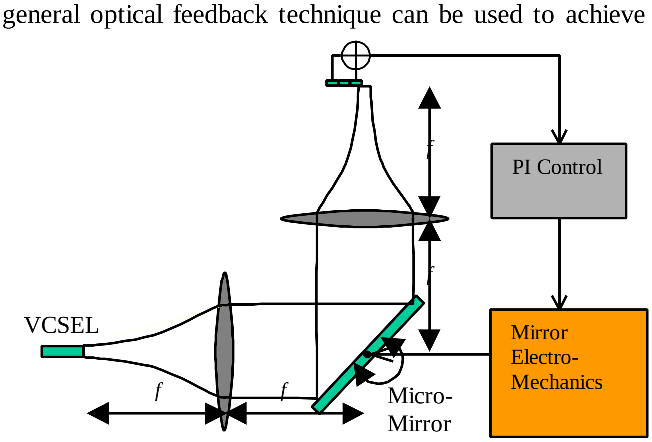

Figure 1: Optical MEM Noise Suppression System

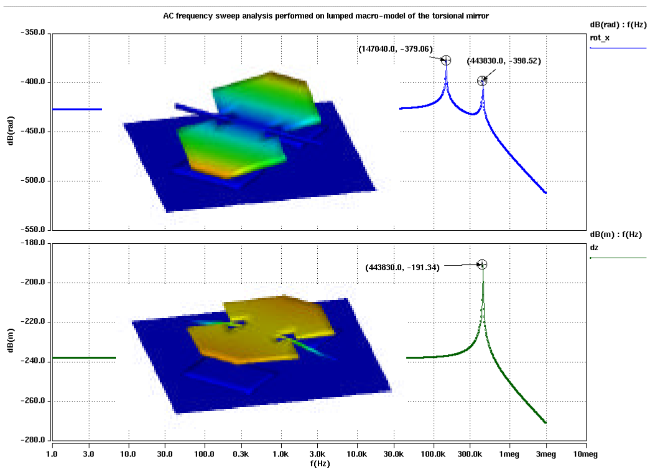

Figure 2: MEMCAD Torsion Mirror Modeling

perfect alignment in other MEM systems by compensating for noise sources such as physical vibration and thermal expansion or the mechanical misalignment caused by the packaging of a MEMS device.

The system as displayed in *MEMSys* is shown in Figure 3. On the far left is the VCSEL source, which emits a Gaussian beam through the first lens of the *4f* system. The torsion mirror then reflects the beam. The mirror component is broken into 2 segments, the optical and mechanical portions. The optical part, in-line with the optical path, reflects the optical beam through the remainder of the system. The mechanical part supplies the mirror's rotational and positional offsets to the optical portion through the vertical connections between the two. The MEMS mirror mechanical component is a hierarchical representation of the extracted torsional mirror, which is expanded and also shown in Figure 3. It is composed of dampers, mass, torsion bars, and electrostatic forces.

As light propagates off the mirror, it refracts through the second lens and is "wired" to each of the three detectors. Each detector intercepts a fraction of the beam and generates proportional currents. The difference of the resultant voltages from the transimpedance amplifiers of the two side detectors is fed into the PI control loop. A switch is placed in front of the PI controller, turning the feedback mechanism on or off. As the feedback loop is closed, the feedback voltage is placed on the electrodes underneath the mirror.

To test the system, we add a "noise" source by vibrating the second lens. This small movement in the second lens results in a large positional movement of the light beam at the detector plane. With the feedback loop, the system compensates for this noise source, remaining in perfect alignment.

4 SIMULATIONS AND RESULTS

We first simulate the system in an open-loop mode to observe the movement of the light beam and the corresponding power detected on each of the detectors by stimulating an electrode underneath the mirror with a ramped voltage from 0-20 V. The results from *MEMSys* are seen in Figure 4, where the center detector corresponds to 'det "0"', and the side detectors are labeled 'det "-"' and 'det "+"'. The center position of the Gaussian beam is also shown, as the beam sweeps over all three detectors. Notice that even when the beam is in perfect alignment with the center detector, the side receivers still detect the tails of the Gaussian beam.

We next close the feedback loop and determine the proportional constant for the feedback controller. We run the system until stabilized, and determine that an electrode voltage of 14.47 V is required to center the beam on the

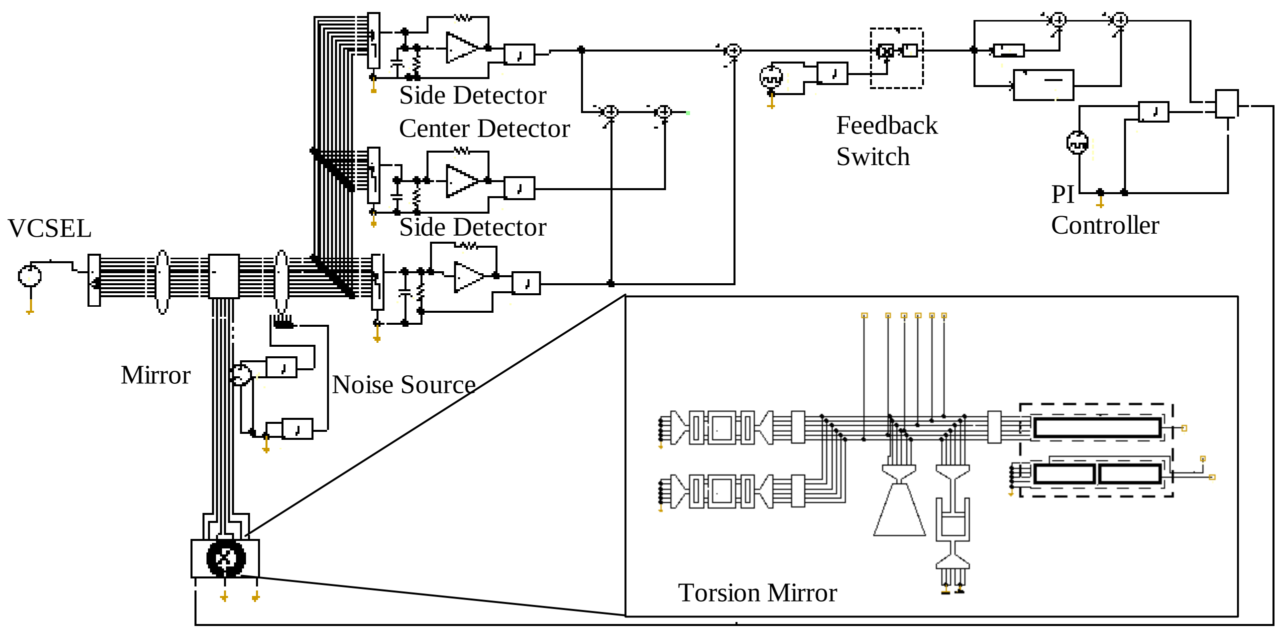

Figure 3: MEMSys Schematic of Noise Suppression System

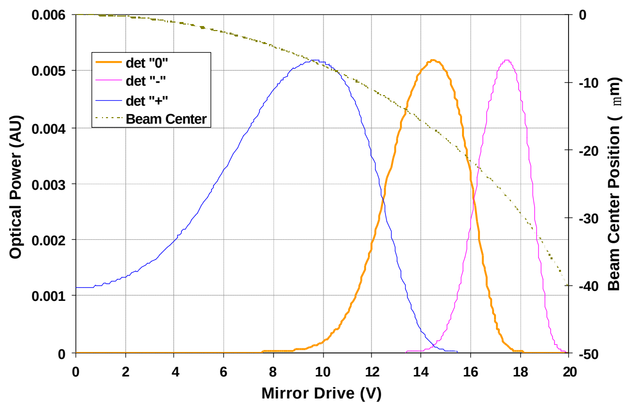

Figure 4: Detector Voltages from a Beam Sweep

center detector. We alter the integration constant to reduce the overshoot, while consciously not sacrificing too much of the settling time [8]. We found that adding a derivative to the PI controller did not give us any significant advantage. After setting our feedback loop constants, we are ready to simulate and evaluate our noise suppression system.

The next simulation compensates for a 10 kHz noise source. To simulate the noise, we placed a y-axis vibration with a 10 μm amplitude and with a frequency of 10 kHz, on the second lens. The results of this simulation are seen in Figure 5. Initially the feedback is turned off and the light can be seen moving over the three detectors in the system. However, when the switch is closed at 80 μsec, the feedback quickly compensates for the noise, and the system remains aligned with only approximately 4% variation in the power on the center detector, even though the second lens continues to move. The voltage applied by the control system to keep the alignment is also shown in Figure 5. We next simulate the same system, except using a 50 kHz noise source. It is seen in Figure 6 that the simple PI controller and this torsion mirror can not totally compensate for this higher noise rate. By performing *Memsys*'s AC frequency analysis, we determine that with this system's feedback parameters, the frequency response rolls off at roughly 10 kHz. Noise frequencies beyond this limit will not be compensated.

5 CONCLUSIONS

In the past, there has been no single CAD tool to simulate optical MEM systems due to the challenge of mixed-signal interaction of three separate and distinct domains. This paper has shown Microcosm Technologies' capability to fill this void. Gaussian beam optics were used to model optical MEM systems in a computationally fast, interactive working environment. Diffractive effects may require more rigorous optical propagation methods.

MEMSys' ability to simultaneously simulate and analyze electrical, mechanical, and now optical signals make our CAD framework valuable to optical systems designers. Keeping all of the simulations within a single framework allows for accurate, rapid and efficient analysis throughout multiple domains. We have shown through simulation results that our tool is a useful, practical alternative to costly cycles of prototyping optical MEM systems.

REFERENCES

[1] Analogy, Inc. *MAST Reference Manual*, 1987-96.

[2] *Analogy Press Release*, Raleigh, North Carolina, June 15, 1998.

[3] Fan, et al., *Applied Optics*, 34(7), 3103-3115, 10 June, 1995.

[4] Levitan, et al., *Applied Optics*, 37(26), 6078-6092, 10 September 1998.

[5] Levitan, et al., *DAC*, 768-773, June 1997.

[6] Microcosm Technologies, http://www.memcad.com

[7] Saleh and Teich, Fundamentals of Photonics (New York: Wiley-Interscience, 1991).

[8] Walker and Nagel, "Optics & MEMS," Naval Research Lab, NRL/MR/6336—99-7975.

[9] Wu, M.C., *Proc. of the IEEE*, 85(11), 1833-1856, Nov 1997.

[10] Shinskey, The Measurement, Instumentation, and Sensors Handbook, Chap. 97, (CRC Press LLC, 1999).

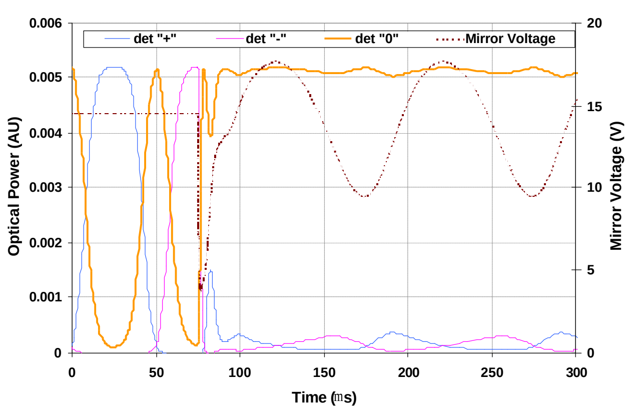

Figure 5: Successful 10 kHz Noise Suppression

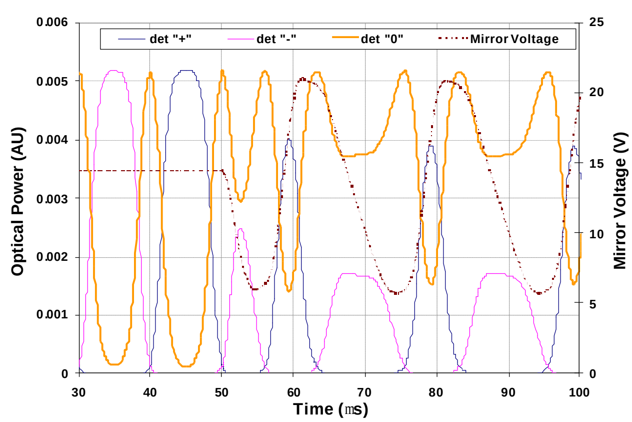

Figure 6: Failed 50 kHz Noise Suppression