Optical Propagation Methodologies for Optical MEM Systems

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ABSTRACT

In this paper, we examine optical propagation techniques for modeling and simulating optical MEM systems. We determine an appropriate technique through studying two criteria: the requirements established by the physical properties of these systems and the goal of having an interactive CAD tool. After examining several classical methods, we conclude with the choice of an optical propagation method and the implementation of this method in our free-space opto-electro-mechanical CAD tool, Chatoyant.

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

1 INTRODUCTION

Optical MEMS (micro-electrical-mechanical systems) have the potential of drastically reducing the size and cost of digital communications and computation systems. For example, optical free-space MEM switching systems have numerous advantages over typical waveguide or fiber switching systems, including the reduction of coupling loss and crosstalk, while being independent of wavelength, polarization, and data format [11]. These scalable MEM free-space switches have been reported as 10 times smaller and faster than typical fiber-based switches, while requiring only 1/100th of the operating power [9]. These systems also have increased system reliability and reduced system costs. However, for this technology to continue to grow and be profitable, a CAD framework for modeling, simulating, and analyzing optical MEMS is required to reduce the time and cost of prototyping these systems.

CAD tools for conventional MEMS are being designed in both academia and industry, including those by CMU [8], Microcosm [7], and MEMScap [6]. These tools typically perform a finite element (FE) simulation of MEM components, and many have extensions to a system-level evaluation of electronics and mechanics. One of the greatest difficulties of adding an optical domain into system-level MEM CAD tools is determining the appropriate abstraction model for light propagation. This determination is the focus of this paper.

Optical propagation techniques range from simple ray tracing to the complete vector solution of Maxwell's equations. Two factors in determining the appropriate propagation technique for our CAD tool are the physical parameters of the optical MEM, or MOEM (micro-optical-electrical-mechanical), systems and the goals of the CAD software. We want an interactive system-level tool that accurately simulates optical MEM systems. Therefore, the optical propagation technique is required to be computationally "reasonable", such that the system designer does not have to wait hours for a system simulation.

This paper examines optical propagation techniques, with respect to optical MEM modeling. We first define the requirements for a system-level optical MEM CAD tool and introduce our tool, Chatoyant. Next, we examine typical MOEM systems, determining the requirements established by the physical properties of these components and systems. We then examine the possible free-space techniques that can be used for optical propagation in MOEM systems. These different techniques are compared in terms of validity and their effectiveness in achieving our goals for the system-level CAD tool. We conclude by presenting preliminary results of this optical propagation technique as used in Chatoyant.

2 SYSTEM CONCERNS

As stated above, our goal is to create a system-level CAD tool for the interactive design of optical MEM systems. Therefore, we are not only striving for accuracy, but we also require fast computation algorithms, producing results in a reasonable time. Additionally, a system level tool needs to evaluate such system concerns as BER (bit error rate), insertion loss, and crosstalk. Therefore, the light model must support optical power information, such as intensity, scattering, phase, and frequency (wavelength) dependence, along with an ability to model diffractive effects.

Chatoyant, is our multi-level, multi-domain CAD tool that has been successfully used to design and simulate free space optoelectronic interconnect systems [5] and continues to be extended to simulate optical microsystems [4]. 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 BER calculation.

To further identify the appropriate optical modeling technique, we must examine typical optical MEM systems and evaluate the available optical propagation techniques which satisfy the requirements imposed by these systems.

Optical MEM systems are created with both refractive and diffractive components, therefore, diffractive optical models are required for system modeling. Further, current optical MEM systems have component sizes and propagation distances of roughly ten to hundreds of microns. For example, typical micro-Fresnel lenses, found on such “system-on-a-chip” demonstrations as an optical-disc pick-up head, have a diameter of approximately 200 μm [11]; and the diameter of the mirrors on Texas Instruments’s DMD (digital micromirror device) chips, found in their digital video projectors, are only 16 μm [3]. Since MOEMS are fabricated with the same techniques as electronic VLSI design, the size of a MOEMS chip does not exceed a couple of millimeters, therefore, typical distances between components (i.e., propagation distances) are approximately 100-300 μm. With these sizes and distances on the order of only ten to a thousand times the wavelength of light, optical diffractive models are required even for applications composed of purely refractive components.

An additional requirement of the optical propagation method is that the optical models must easily interface with fiber-based CAD tools. Many commercial MOEM systems have light sources off-chip, coming on-chip through fiber, performing free-space computation (e.g. switching), and leaving the chip again through fiber.

3 OPTICAL TECHNIQUES

Ray, or geometric, optics are the simplest of the optical propagation methods. This method traces rays of light through refractive elements, however has no inherent support for the optical characteristics of light. This is improved by using Gaussian optics, which satisfies the paraxial Helmhotz equation in solving for optical parameters such as waist size, depth of focus, intensity, and phase. An additional benefit of using Gaussian analysis is that we can approximate the behavior of the lasers used in these systems as sources of Gaussian shaped beams. The greatest advantage of both these methods is fast computational speed, as computational complexity for both Gaussian and ray optic models is on the order of the number of beams that are being propagated. Many software packages use these techniques for macro-scale optics. Limited diffraction modeling is supported for both these methods, however, a large propagation distance and on-axis symmetry are required, which eliminates these optical techniques from consideration.

Realizing that more stringent diffractive optical propagation models are required, we continue our search for the appropriate optical propagation method with scalar diffraction models. These approximations are developed by recasting Maxwell’s equations into a scalar form, where all components in the electric and magnetic field can be summarized by a single scalar wave equation. The scalar methods calculate a complex wave function at an observation plane. This observation plane can be placed anywhere in the system and captures the optical properties of intensity and phase, meeting a requirement of the optical software.

Figure 1 is a tree that begins at the top with Maxwell’s equations and branches downward through the different abstraction levels of scalar modeling techniques. Along the arrows, notes are added stating the limitations and approximations that are made to get to the next, less accurate model.

All scalar diffraction solutions are limited by two assumptions; the diffracting structures must be “large” compared with the wavelength of the light and the observation screen can not be “too close” to the diffracting structure. The concept of “too close” is defined for each approximation model in Figure 2. The figure shows where the diffractive models are valid with respect to the distance z propagated past the aperture.

Working from the bottom to top of Figure 1 and from right to left of Figure 2, we investigate the least accurate of these scalar approximations, the Fraunhofer approximation. The advantage of this technique is the ability to implement a Fourier transform to solve the complex wave function. Most diffractive software tools perform Fraunhofer propagation, using a common FFT routine for quick evaluation. As shown in Figure 2, the Fraunhofer approximation is valid in the “far-field”, where the light has propagated to a distance far from the aperture, and the diffraction pattern is essentially the same as that at infinity. To illustrate the problem of this method with respect to typical

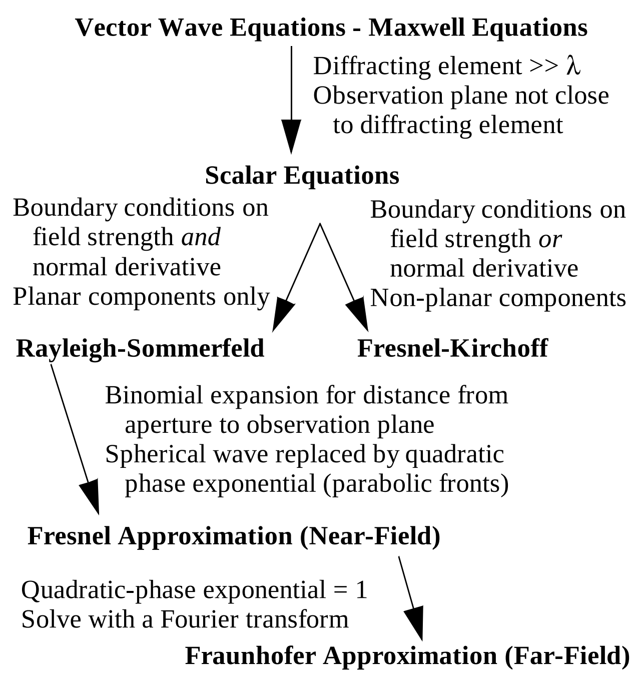


Figure 1: Diffractive Modeling Techniques

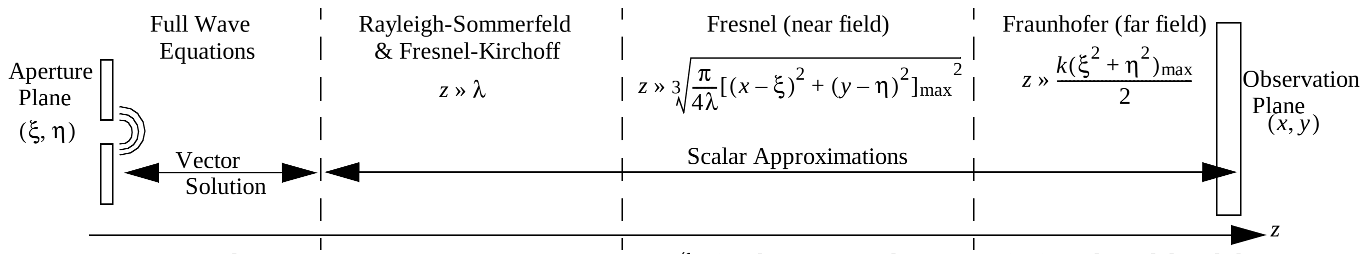


Figure 2: Optical Propagation Distance, z, Aperture Size, (ξ,η), Observation Plane Size, (x,y), and Model Validity

MOEM systems, we consider a system with an aperture of 50 µm and an observation plane of 200µm, using a 850 nm source. Using the equation found in Figure 2, the minimum propagation distance for the Fraunhofer approximation to be valid is 4.6 mm, far too large for typical MOEM systems.

To remove the limitation of the far-field, our study moves up the tree, towards more rigorous optical models. We next examine the Fresnel approximation, valid in both the far and near field. The "near field" is defined as the region closer to an aperture where the diffraction pattern differs from that observed at an infinite distance. No longer can a fast Fourier transform be used for this calculation, as an explicit integration must be calculated. When solving the minimum distance needed to propagate with the same example system from before, we find the propagated distance must be larger than 966 µm, making this method also invalid for optical MEM systems. Therefore, our search for an appropriate optical propagation method continues in order to support the propagation region smaller than the near field.

We next examine even more rigorous scalar diffraction models, the Fresnel-Kirchoff and Rayleigh-Sommerfeld scalar formulations. Both of these methods produce similar, accurate results, again with the use of an explicit integration. The difference between the two lie in their boundary conditions. Fresnel-Kirchoff has boundary conditions on both the field strength and normal derivative, whereas the Rayleigh-Sommerfeld removes this inconsistency and imposes boundary conditions on either the field strength or the normal derivative, since they are related. Unlike the Fresnel-Kirchoff formulation, the Rayleigh-Sommerfeld is limited to planar components. However, for small angles, these methods are identical. These formulations are only limited by the propagation distance being "greater" than the wavelength of light. We believe that these are the appropriate optical propagation methods to use for the modeling and simulation of current optical MEM systems. However, we must also evaluate their computation efficiency to ensure our system-level CAD requirements are also satisfied.

Examining the Rayleigh-Sommerfeld equation, which we choose to model over the Fresnel-Kirchoff due to simplicity in the equation form [2], we see that an explicit integration is required:

$$U(x,y) = \frac{z}{j\lambda}\iint_{\Sigma} U(\xi,\eta)\frac{e^{jkr}}{r}d\xi d\eta \quad ,$$

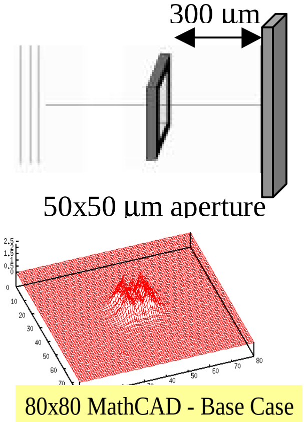
where, k is $2\pi/\lambda$, r is the distance from the source point (ξ,η) to the observation point (x,y), z is the distance propagated, Σ is the area of the aperture, and U is the complex optical wave function. The computation time of this scalar technique is based on the gridding of both the aperture and observation plane. For each grid point in the observation plane, $U(x,y)$, a double integration is performed over every grid point in the aperture plane, $U(\xi,\eta)$. This is very costly in computation time, however, reductions can be made. First, computation time can be saved by decreasing the number of grid points used to represent the complex wave function, however, at a cost to accuracy. Second, in systems with radial symmetry, polar coordinates can be used which reduces the integration to a single integral. Finally, the integration algorithm performed factors largely in the computation time. These factors are discussed in the simulation and results section below.

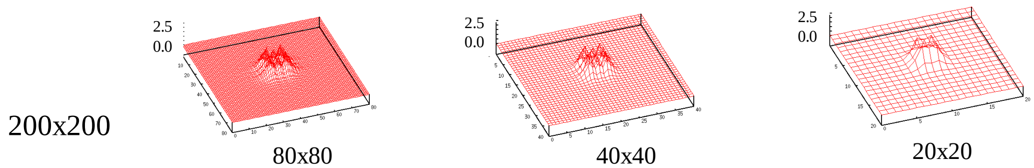
For completeness, we must mention Maxwell's equations, the vector solution for light propagation. Although the most accurate and valid at all propagation distances, solving Maxwell's equations is exceedingly slow since complex vector operations are required. Therefore this model is not conducive for interactive system design.

4 SIMULATION RESULTS

In Figure 3, we show Chatoyant's Rayleigh-Sommerfeld simulation results of the same 850 nm plane wave, 50 µm aperture, and 200 µm observation plane example, as we saw previously. We compare our simulations with a 80x80 grid-point "base case" from MathCAD, which uses a Romberg integration technique. The table in Figure 3 shows the computation time and relative error of the system (compared with the base case) for different grid spacing. Using a 96-point Gaussian quadrature integration technique [1] we can decrease the computation time an order of magnitude and still remain within 2% accuracy.

We have also been able to interface our Rayleigh-Sommerfeld scalar results into the fiber based software package, BeamPROP [10]. As an example showing this interface, Figure 4 shows a fiber coming on-chip, propagating through free space, and returning off-chip through a fiber. The fibers are both 10 µm core, single mode fibers with an index difference of .006, length of 1000 µm, and support 1550 nm light. There is a 100 µm gap of free-space between the fibers. A 1550nm Gaussian beam with a 10 µm waist is





	Chatoyant		MathCAD	
	Time (min)	Error (%)*	Time (min)	Error (%)*
160x160	17.75	X	X	X
80x80	4.45	0.637	120	0
40x40	1.1	1.67	20	1.54
20x20	0.29	3.37	7	4.32

* RMS error of grid cells with respect to 80x80 MathCAD

Figure 3: Rayleigh-Sommerfeld Scalar Diffraction Performance

used to source the first fiber.

Using Snell's law, the acceptance angle of this fiber is 6.3 degrees. To illustrate the relationship of the acceptance angle to the mechanical tolerancing for the system, we show how tilting the end of the fiber effects the propagation of light down the second fiber. This tilt could occur by physical vibration, thermal expansion, or the mechanical misalignment caused by the packaging of a MEMS device. Figure 4 shows results as the beam propagates down both fibers for three cases of tilt in the second fiber; 0, 2, and 6 degrees. Chatoyant models the tilt of the fiber by tilting the observation plane and solving the complex wave function that is placed on the surface edge of the second fiber. Figure 4 also contains Chatoyant outputs at the exit of the first fiber and the entrance to the second, as the waist grows from approximately 7 to 10 µm. For the perfectly aligned case, the beam is quickly accepted into the fiber. However, as the mechanical rotation is applied, the beam enters the fiber at a tilt, resulting in the beam bouncing back and forth on the core/cladding interface. As we approach the maximum acceptance angle of the fiber, most of the beam's intensity is lost through the cladding and little of the beam is left to propagate down the fiber, as seen in the last case of the figure.

5 CONCLUSION AND SUMMARY

We have shown that determining the appropriate optical propagation technique for optical MEM systems is non-trivial. The common propagation methods, Ray, Gauss, and Fraunhofer (far field), used in standard optical CAD tools are not appropriate. We have shown that for MOEM systems, the optical method must be more rigorous, to accurately model the small sizes and distances of propagation used in these systems. Even with our current modeling efforts, we acknowledge that as these systems continue to decrease in size, the evaluation of appropriate optical propagation methods must continue.

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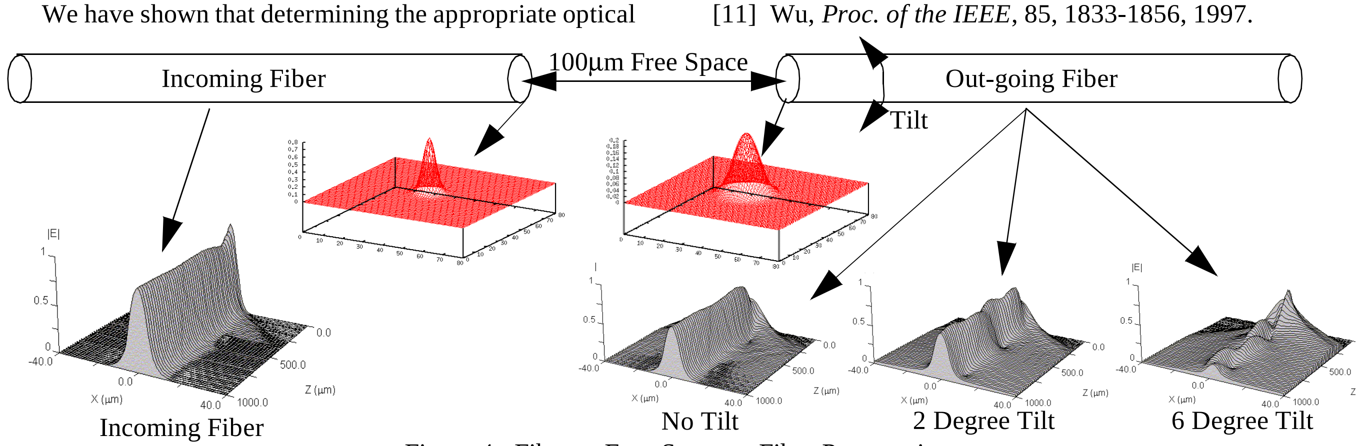

Figure 4: Fiber to Free-Space to Fiber Propagation