Extensions to the Chatoyant O/E CAD Framework for Modeling Micro-Opto-Electronic Systems

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Chatoyant is a mixed signal CAD tool developed at the University of Pittsburgh and University of California, San Diego. The tool has been extensively used to design and simulate free space opto-electronic interconnect systems.[1] Chatoyant is capable of performing end-to-end system simulations, with analyses including bit error rate (BER), insertion loss, cross talk, and mechanical tolerancing. Chatoyant's optical library includes sources (VCSELs and 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. Until recently, Chatoyant has modeled light using only ray and Gaussian beam propagation methods. However, with the desire to analyze micro-optical systems, where the light's wavelengths and the system's physical dimensions are on the same scale, we have extended Chatoyant's capabilities in two ways. First, we introduced modeling techniques for diffractive optics. This allows the use of diffractive models in cases where Gaussian approximations are not valid. Fresnel propagation equations are used for the scalar modeling of light, since we desire to calculate the complex wave function in both the near and far field.[2] An additional requirement emphasized by these microsystems is support for automatic tolerancing on the precise alignment required for desired operation. Therefore, we have also implemented a Monte Carlo tolerancing package within Chatoyant to determine worst case mechanical tolerancing and sensitivity.

Figure 1 shows a high-speed FFT micro-opto-electronic project, being designed at USCD under the DARPA FSOIA program. The design is based on integrating a compact optical system, called OTIS (Optical Transpose Interconnect System)[3], together with two functional logic blocks. The logic blocks perform the necessary computations, and the optics perform a butterfly shuffle. The components are placed onto a substrate, and are held and aligned using conventional MEM technology.[4] Figure 1 is a rendering of the FFT system created by a VRML (Virtual Reality Modeling Language) interface that we are incorporating into Chatoyant.

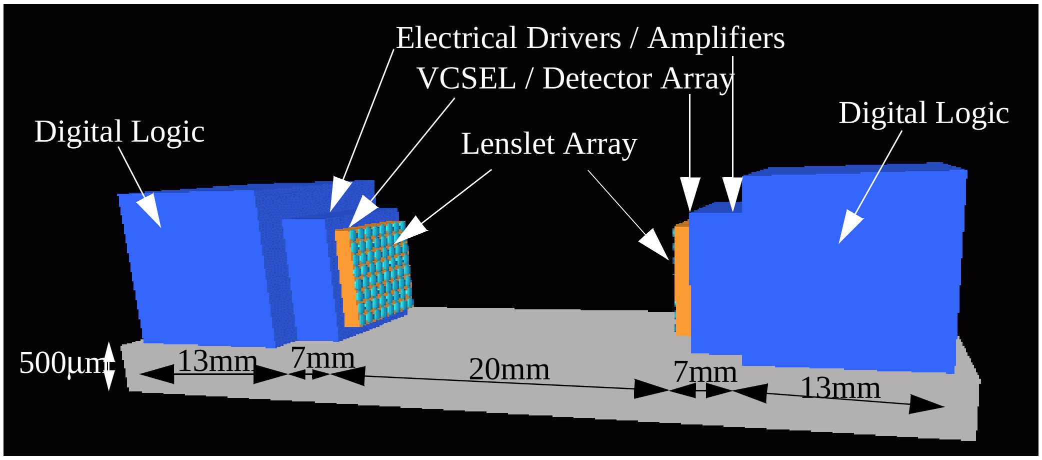
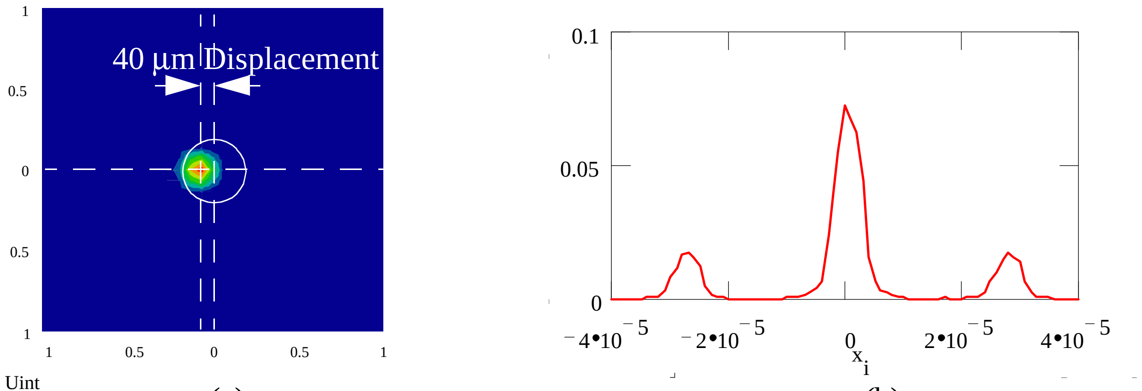


Figure 1: FFT Optical MEM System



(a)

(b)

Figure 2: Intensity distributions of a 1µm Offset VCSEL (a) Propagated to the Second Lenslet (b) Propagated to the 80µm Detector

In the following example, Chatoyant is used to simulate this system to determine the mechanical tolerancing of the VCSEL position versus the system's optical insertion loss. This simulation demonstrates the sensitivity of micro-optic systems to minor offsets in components' positioning and fabrication. To simulate the positional tolerancing of 15°, 850nm VCSELs, the sources are offset in the *x* direction by 1µm, causing off-axis clipping between the beam and the first lenslet. Scalar diffractive models are required since there are no simple Gaussian approximation models for asymmetric beam clipping. The clipping at the first lenslet results in a power loss of 4.53%. As the light propagates 20mm to the second lenslet, the positional displacement of the 1µm offset beam grows to approximately 40µm. This is shown in Figure 2(a), along with the approximate size and position of the second lenslet. Most of the beam passes through the second lenslet, although, 22.6% of the remaining power is lost, resulting in a total system insertion loss of 26.1%. Figure 2(b) shows the *x*-axis intensity distribution at the 80µm detector. The shape of the beam is no longer Gaussian, as visible side lobes are present. Note that the second lenslet has steered the beam back onto the detector, with the center of the beam shifted off-axis only 1µm. Also, note that the side lobes are almost at the full radius of the detector, therefore, for some cases, these lobes will miss the detector, resulting in even a greater insertion loss. With a VCSEL offset of only 5µm, the beam will be displaced at the second lenslet by almost 200µm, resulting in the beam entirely missing the lenslet.

As demonstrated above, a slight mechanical change in a single component can have a large adverse effect on a micro-opto-electronic system. In general, it is hard to predict within a complex system the mechanical tolerances that result in the worst case system behavior. A standard technique is to use Monte Carlo analysis, which varies the mechanical properties (position and orientation) of each of the components according to a probability distribution based on manufacturing tolerances, mechanical vibration, and thermal expansion. We now include Monte Carlo analysis within Chatoyant. During this analysis, Chatoyant simulates the system thousands of times, using random values from the corresponding probability distributions (e.g., linear, Gaussian, or Poisson) for parameter values and returns the system parameters of the best and worst performing cases.

As an example, the same system is simulated using Chatoyant's Monte Carlo analysis. The sources are 15°, 850nm VCSELs and the detectors are 80µm squares. Each lenslet has a diameter of 250µm, with a radius of curvature of 0.145mm The VCSEL positions are held constant as a reference geometry for the system, and the parameter ranges for the other components are given in the first row of Table 1. There are ten tolerancing parameters in the system, making sensitivity analysis of the individual parameters to the system performance difficult. After running the Monte Carlo analysis for 10,000 random simulations, we analyze which cases have the largest deviation in parameters, but detect full optical power, and the cases where the parameters deviate the least, but result in the beam entirely missing the desired detector. We examine the runs in which full power is detected (1790 out of 10,000 runs), sort them by maximum parameter deviation, and report the top two cases in Table 1 (Full Power #1 and #2). Similarly, we examine the runs in which at least one beam completely missed its desired detector (6777 out of 10,000 runs), sort these in terms of minimum parameter deviation, and report the top two (No Power #1 and #2). When the beam completely misses the detector, we conclude the most common cause is the tilts (ρ or θ) of the lenses. This is shown in Table 1 by the largest normalized parameter in each run, typed in bold, being a lens tilt. Notice, for most parameters, the offsets of the runs Full Power #1 and #2 are larger than the parameter offsets for No Power #1 and #2. This is due to the system parameters compensating for each other. That is, if one parameter steers the beam out of the optical path, another parameter compensates by steering the beam back in line.

Table 1: Monte Carlo Analysis Results

Parameter	Lens1_x (μm)	Lens1_y (μm)	Lens1_ρ (°)	Lens1_θ (°)	Lens2_x (μm)	Lens2_y (μm)	Lens2_ρ (°)	Lens2_θ (°)	Detect_x (μm)	Detect_y (μm)
Range	±1	±1	±0.05	±0.05	±1	±1	±0.05	±0.05	±1	±1
Full Power #1	.483923	.795798	.029097	.044562	.792757	-.625983	-.037319	.036576	-.655080	-.432245
Full Power #2	.792841	.596940	.042626	.042072	-.644088	.938024	.049612	.020996	.427233	-.938518
No Power #1	.422470	.080384	**-.023795**	.023149	-.431848	.403542	-.012593	.000738	.009119	.028665
No Power #2	.045314	-.411032	-.019199	.024634	.128980	.208934	-.016890	**-.027808**	-.168906	-.031077

Finally, to compare our scalar diffraction models with experimental results, we simulate a *4f* system using a 15°, 850nm VCSEL source, two 250μm micro Fresnel lenses, shown in Figure 3(a), and a 30μm detector. The beam's radius intensity distribution at the detector is shown in Figure 3(b). Our scalar results match Wu's[4] experimental results in terms of the lens efficiency, 10%, and Gaussian shape, 95% Gaussian.

As opto-electrical systems grow smaller, Chatoyant must continue to adapt to the specific needs of these microsystems. With the addition of the scalar propagation models and the mechanical tolerancing analysis, Chatoyant can now accurately model O/E systems on the micron level and perform optical, electrical, and mechanical trade-offs, making our system valuable to micro-opto-electrical designers. Results from system simulations show that Chatoyant is a useful, practical alternative to costly prototyping micro-opto-electrical systems.

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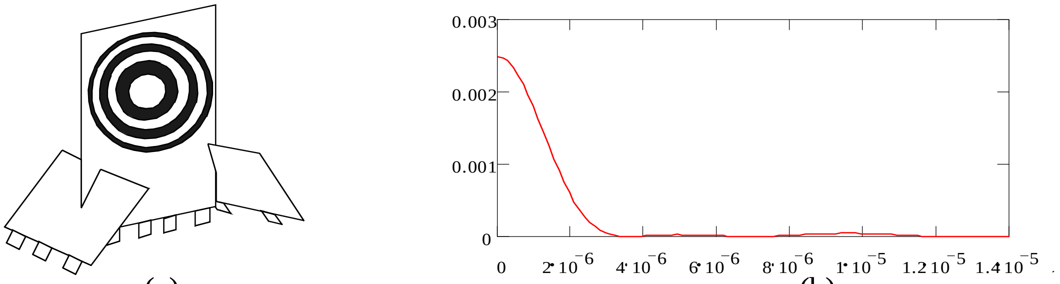
[1] Applied Optics, Vol. 37, No. 26, (September, 1998) pp. 6078-6092.
[2] Goodman, J.W., Introduction to Fourier Optics, Second Edition (The McGraw-Hill Companies, Inc., 1996).
[3] OSA Topical Meeting on Optics in Computing, Lake Tahoe, NV, (March 1997), OThD16, pp 233-235..
[4] Proceedings of the IEEE, Vol. 85, No. 11, (November 1997), pp. 1833-1856.



(a) (b)

Figure 3: (a) Micro Fresnel Lens (b) Radius Intensity Distribution of 4f System at the Detector