

# Integrated Modeling of Optical MEMS Subsystems

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## ABSTRACT

This paper presents top-down holistic design and verification of a MEMS-based 3-D optical switching subsystem utilizing an integrated CAD environment. The subsystem design takes place in a nodal simulation environment that includes models for fibers, lenses, mirrors, control elements, general electronics, and detailed mechanics.

In this paper, we explore the design of an optical cross-connect using an optical circuit to evaluate the optical performance of the cross-connect and electromechanical models to assess the tuning limitation imposed by the MEMS mirrors. From the performance specifications, we are able to deduce an optimum cross-connect array size for any given mirror size.

**Keywords:** microelectromechanical systems (MEMS), MOEMS, behavioral model, microsystems, optical cross-connect.

## 1 INTRODUCTION

Optical MEMS subsystems are complex compositions of varied components that can include optical fibers, free-space and guided wave optics, drive electronics, control systems, MEMS chips, and packaging. Good engineering practice requires that each of these components be designed with the system application in mind. In general, there are two approaches to the design of complex integrated systems. The designer can start with abstract behavioral elements, work out the interactions, and then proceed to a detailed design of individual components. This process is known as top-down design. Alternatively, the designer can, with prior knowledge from other systems, focus on key component development and then integrate each into the overall system in a bottom-up approach. The first has the advantage of providing complete flexibility in the architectures used and should provide optimum system solutions. The second has the advantage of concreteness and should provide the fastest path to system realization.

Depending on the specific design and position in the design cycle, either or both of these approaches should be utilized. Conventional MEMS analysis tools are not able to completely support either approach as they only provide isolated physical simulation results that cannot be evaluated in terms of system tradeoffs. They also provide little to no optical simulation capabilities [1]. We have presented

previously the foundation for such an integrated design and analysis approach [2,3]. The examples presented there focused on the implications of individual component design from a bottom-up perspective. This paper presents the complementary top-down approach through the holistic design of a MEMS-based 3-D optical switching subsystem and verification utilizing an integrated CAD environment.

The subsystem design takes place in a nodal simulation environment that includes models for fibers, lenses, mirrors, control elements, general electronics, and detailed mechanics. These models are provided both as parametric analytical models for rapid device and system design as well as white- and black-box models extracted from physical analyses. Devices designed with parametric models can be automatically transferred into a layout and process for fabrication or for physical analysis. Physical analyses to determine electrical, mechanical, thermal, and optical characteristics of individual components are focused on the performance of individual components and can be extracted back to the system level when necessary, using order reduction techniques.

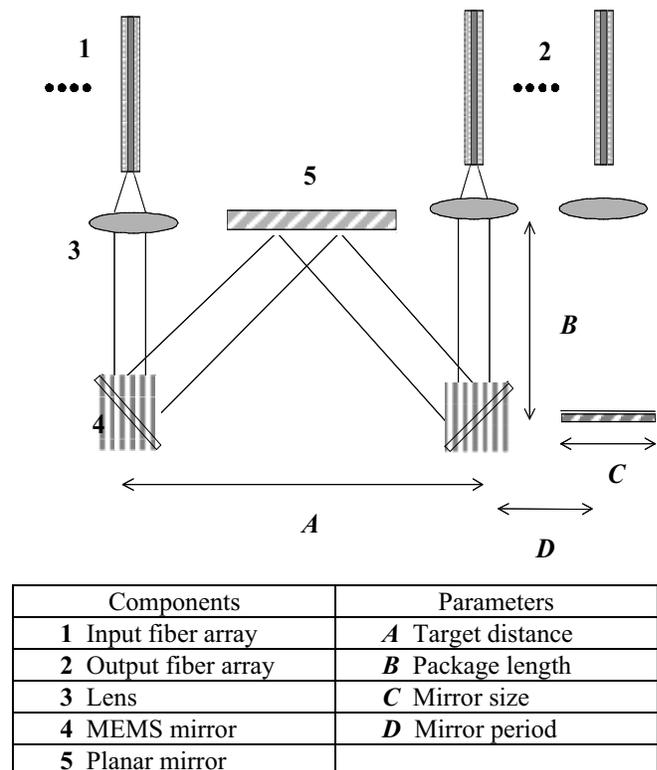


Figure 1: Schematic of NxN cross connect.

## 2 OPTICAL CROSS-CONNECT

There are many configurations of optical switches that can be modeled in this environment. For this paper, we assumed a folded optical system where the MEMS mirrors are all in one plane, and the fiber inputs and outputs are arranged to create a 3-D optical cross-connect [4]. Figure 1 shows an illustration of the system model with a single representative fiber input and output, collimating optics, and mirrors. The inputs to and outputs from the system are single-mode fibers (SMF).

### 2.1 Optical System Level Design

We assume the following performance specification for the optical switch:

Description	Specification
Nominal insertion loss	5dB
Power uniformity between channels	$\pm 1$ dB
Maximum cross-talk	-40dB

Table 1: Optical cross-connect performance specifications.

The first task is to design for insertion loss and uniformity between switching states. An optimal solution for any mirror size exists. Assuming a mirror size and simple electrostatic mirror actuation, there is a balance between package length and target distance that will give the optimum insertion loss and coupling uniformity. Considering the insertion loss of 5dB and uniformity of 1dB, Figure 2 displays the power coupled into the receive fiber of the output array as a function of these parameter scans. For a 400 $\mu$ m diameter mirror, a package length of

19mm and a target distance of 28.6mm satisfied the insertion loss and uniformity specifications.

If we instantiate a second output fiber with associated optics, the input and outputs can be placed in any spatial orientation to give primary and secondary targets for measuring the signal and crosstalk. Assuming a static cross-talk specification of -40dB for a single signal system, the requirements on the mirror parameters become more stringent than the insertion loss and uniformity specifications alone. The cross-talk simulations are shown in Figures 3a and 3b.

In Figure 3a, the mirror period is allowed to vary in 50 $\mu$ m increments and the cross-talk is measured on the adjacent fiber receiver for dynamic cross-talk MEMS mirror activity. The results of this parametric sweep enable the designer to deduce the minimum mirror period based upon the constraints imposed by the power loss and cross-talk specifications. Figure 3b demonstrates the intuitive phenomenon of increasing cross-talk on an adjacent receiver as the target distance increases. This arises directly from increased beam divergence as the beam propagation distance is increased.

The results of varying the mirror angle of the secondary MEMS mirror and scanning the mirror period between primary and secondary MEMS mirrors suggests that a mirror period of 650 $\mu$ m or greater satisfies the cross-talk specification; in this case, light from the primary MEMS input mirror is assumed to strike the secondary MEMS output mirror and focus into the secondary output fiber.

Therefore, a mirror size of 400 $\mu$ m with a mirror period of 650 $\mu$ m satisfies the loss, uniformity, and cross-talk specifications when the package distance is 19mm and the

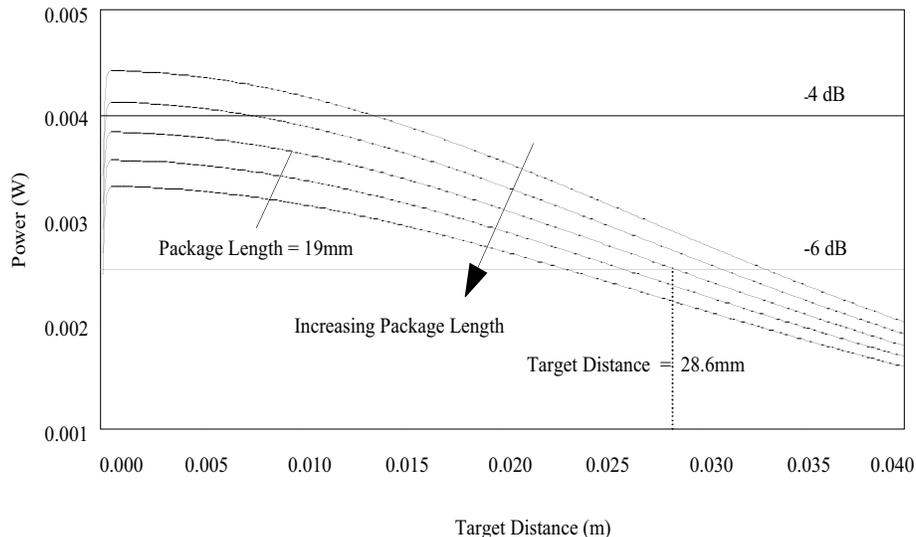


Figure 2: Power coupled into target receiver.

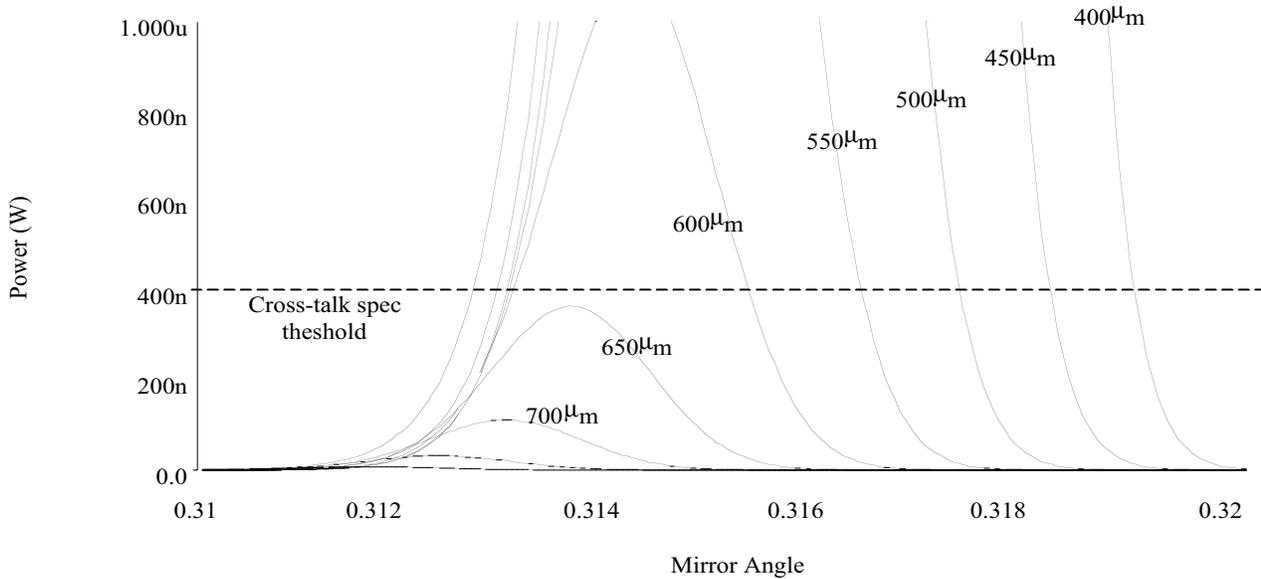


Figure 3a: Cross-talk on adjacent fiber receiver that is located one mirror period farther from the input fiber. Plot shows cross-talk as a function of mirror period (curves) and MEMS mirror tilt angle.

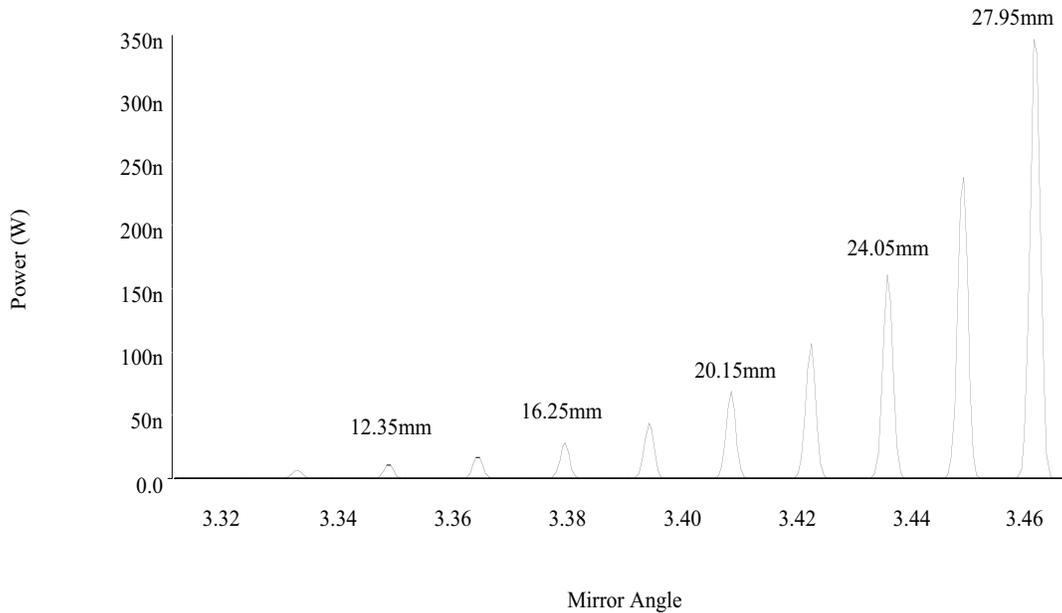


Figure 3b: Cross-talk on adjacent fiber receiver as a function of target distance and MEMS mirror tilt angle.

maximum target distance is 28.6mm. In this case, a square array of 32x32 MEMS mirrors can be realized if the MEMS technology exists to tune such a mirror over a range of 18 degrees. The tuning range is determined primarily by the mirror-electrode gap and the pull-in effect, which is the topic of the next section.

## 2.2 Electromechanical Mirror Behavior

The next step is the design of a MEMS 2-axis mirror for this system. As an example, we implement a simple square mirror, 400µm on a side with purely torsional tethers. The mirror structure and the electrostatic actuation are rapidly modeled using mechanical and electro-static behavioral elements. Figure 4 shows the pull-in curves for the mirror

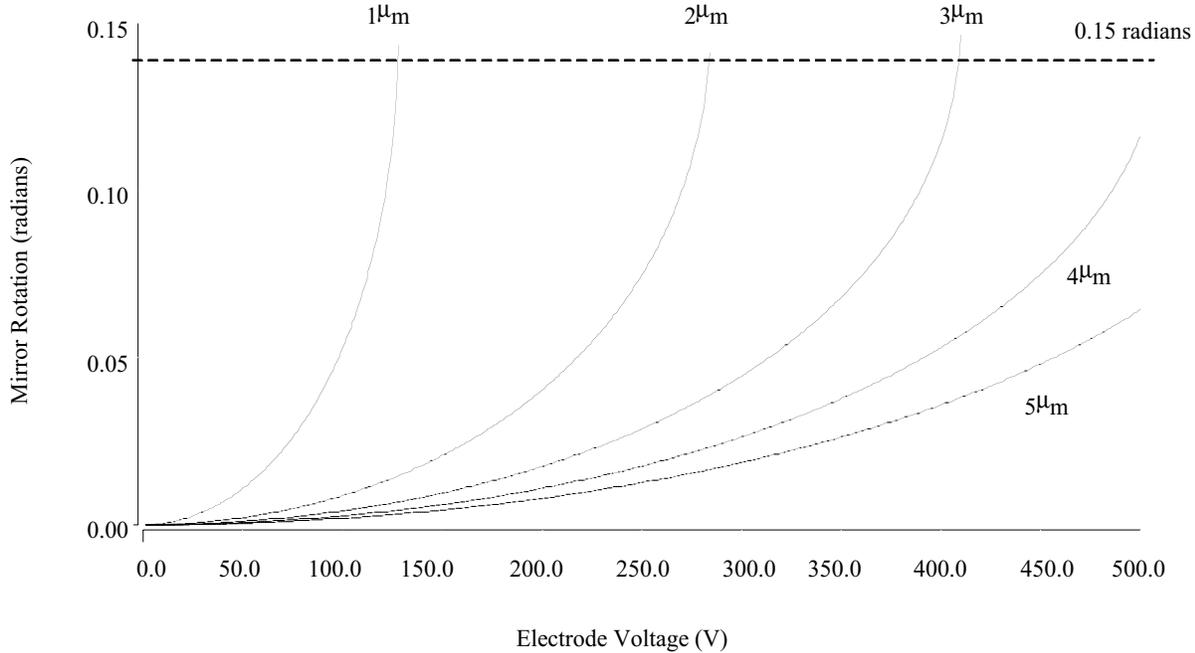


Figure 4: System level mirror pull-in analysis. Each curve indicates the tuning range for the given tether width.

design having a gap of  $50\mu\text{m}$  for a sequence of spring widths from  $1\text{-}5\mu\text{m}$  for a thickness of  $2\mu\text{m}$ .

The pull-in information is then used to determine the achievability of the  $32\times 32$  mirror array. Figure 4 reveals a maximum mirror rotation before pull-in of 0.15 radians (8.59 degrees), much smaller than the 18 degrees required for the maximum array size. If the mirror is tunable from 0 to 0.15 radians, then the maximum target distance is 11.7mm. This implies that the array size is limited to  $13\times 13$  for our assumed mirror size, leading to a switch with 84 inputs and 84 outputs.

If we require an array size that is larger than  $13\times 13$ , then we can quickly repeat the design process using lower power lenses. As Table 2 shows, the optical cross-connect array size can be scaled upward to accommodate more ports by decreasing the power of the lenses.

Focal length	Optically limited	Mechanically limited
$1350\mu\text{m}$	$32\times 32$	$13\times 13$
$1500\mu\text{m}$	$35\times 35$	$15\times 15$
$1650\mu\text{m}$	$37\times 37$	$17\times 17$
$1800\mu\text{m}$	$44\times 44$	$20\times 20$

Table 2: Maximum array size as a function of focal length.

It is worth noting that the maximum realizable array size is approximately the same for MEMS mirror sizes from  $400\mu\text{m}$  to  $600\mu\text{m}$ , given a constant focal length. There are

competing attributes with the larger mirrors; they enable larger arrays to optically satisfy the design criteria, but they ultimately limit the array size by their reduced tuning range.

### 3 FUTURE WORK

In the next steps, the MEMS mirrors are connected to our optical mirrors and the sensitivity of optical loss to voltage variations can easily be simulated as in the previous paper[2]. Using our device level solvers, detailed physical simulations on the MEMS device are also possible such as electromechanical co-solves, mechanical solves for stress gradients, and most recently diffractive optical simulations using Rayleigh-Sommerfeld approximations. Additionally, we are working to implement a 2-D control system for this cross-connect, another feature that can be integrated in this design using Coventorware™ software.

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