Wafer Level Packaging of MOEMS Solves Manufacturability Challenges In Optical Cross Connect

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Abstract

In the late 90's and early 2000 an all-optical network was one of the key drivers that fueled the optical telecom market. High port count (64 to 4000) optical-cross-connects (OXC) were the key enabling technology for an all-optical network. In some accounts, more than 50 start-ups were tasked with this technical challenge. OXC had promised to dramatically lower carrier infrastructure costs in the central office, and to enable creation of an all-optical network that would be transparent to transmission speeds. This paper will examine the key packaging challenges in the fabrication of a 1000x1000 OXC, using MOEMS (micro-optical-electro-mechanical-systems) mirrors in 2N configurations. It will describe how wafer-scale-integration (WSI) allowed for much greater simplification of the overall system and creation of the first fully integrated 3D MOEMS mirrors by Transparent Networks Inc. (TNI). Another key enabling technology for making such high port count OXC was the ability to align thousands of optical fibers with their corresponding mirrors. This paper will examine the development challenges and TNI's solution to this problem.

Introduction

While several technologies were competing for acceptance in OXC application, the most promising technology was considered to be MEMS based systems. The primary challenge in fabrication of high port count (>64 port) OXC was the ability to stir tiny mirrors in two axes in order to establish a new optical connection. For smaller port count switches optical connections were established with pop-up mirrors, these are referred to as the N^2 configuration. The key advantage of the N^2 switches were the simplicity of the control electronics and MEMS mirror design, since every mirror had only two states, on or off. However, N^2 systems required precision packaging and assembly of the input and output fibers to the array of digital mirrors. Furthermore, housing materials needed to be stable over all operating conditions and temperatures. For example, fabricating a 16x16 switch in N^2 configuration required 256 digital mirrors.

To fabricate a 1000x1000 optical switch, the only viable solution was to use 3D MEMS mirror with stirring capability in both X and Y axis, Figure 1 shows a representative 2N configuration design. Primary advantage of the 2N systems was that they required much smaller numbers of mirrors, only two times the number of ports. For example to fabricate a 1000x1000 OXC only 2000 mirrors are needed, conversely 1 million mirrors are needed for N^2 configuration. The main challenge with the 2N configuration was the design and fabrication of the 3D MEMS mirrors. Each mirror typically is required to move ±10° on two axes at a very high degree of precision and stability. To accomplish such task it required lots of control electronic interface and digital signal processing software.

Another design challenge with OXC products was meeting the Telcordia qualification specifications and its stringent reliability and serviceability requirements. Generally it was required that the OXC be able to establish optical connections in less than 10 ms and to maintain connection under various office vibrations and earthquake conditions. To address these requirements it was necessary to develop a sophisticated closed loop control for each mirror, which added to its complexity and fabrication cost.

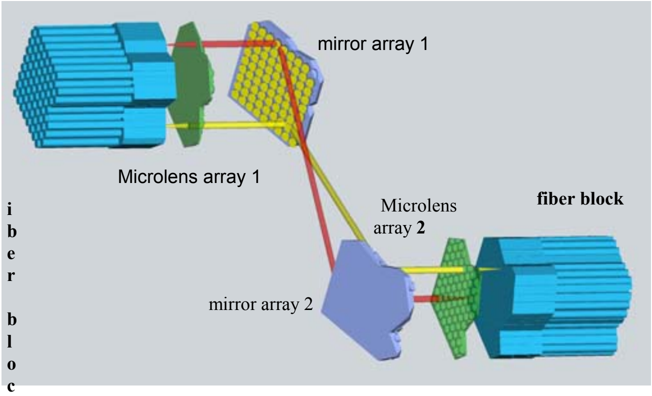

Figure 1: Generic 2N optical cross connect configuration using 3D MEMS Mirror arrays

Telecom companies require greater than 20 years of product life with very good MTBF (Mean Time Between Failures) numbers and high level of availability - five-nines or better. This has placed a very demanding requirement on the packaging and manufacturing of the MEMS' based optical switches. Presence of moisture, particles, vibration, and external factors such as temperature and sound can be very detrimental to a reliable operating performance of these switches. Packaging is arguably the most challenging aspect of delivering a high port count optical switch. It plays the most critical role in the final product cost and determines its long-term reliability of the switch. One way to reduce the manufacturing and reliability risks is to incorporate, as much as possible, much higher level of integration between the mirrors and their control electronics.

In this paper we discuss how wafer-scale-packaging (WSP) was used to integrate all the electronics for 1200 3D MEMS mirrors, reducing number of wire bonds and electronic interconnects a hundred times, while reducing the overall size and cost by greater than ten fold.

3D MEOMS Mirror

Figure 1 shows a generic 2N configuration for a 1000x1000 OXC using 3D MEMS mirrors. Every mirror has four degrees of freedom, ± X and ±Y, allowing it to point freely in the required direction. Every mirror requires minimum of 4 interconnects for a complete control. For a large array of 1000 mirrors this is greater than 4000 interconnects. One popular mirror driving technology has been electrostatic actuation, either as a comb or parallel plat. Many companies had utilized dual-gimbals of their 3D mirror design, figure 2 is an example of such design made by Lucent. There are two primary drawbacks with the dual-gimbals design; first is the low fill factor number due to having the gimbals structures on the same plane as the mirrors, the second is the need for applying high drive voltages, as high as 300-400 volts depending on the switch size and angle of rotation. This has eliminated any possibility of integration of the control electronics with the mirrors. This forces designers to make thousands of high voltage interconnects between the mirrors and their external drive electronics. Routing thousands of high voltage traces to each mirror is a very challenging task with many potential issues. As an example, cross talk between traces and other mirrors causing errors, yield losses due to shorting between traces, and reliability issues associated with high voltage and manu high densith traces.

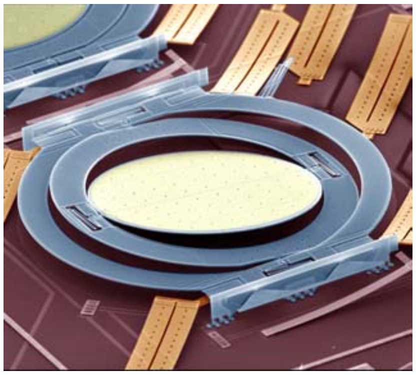

Figure 2: Lucent Dual-Gimbals Mirrors, surface Micromachined

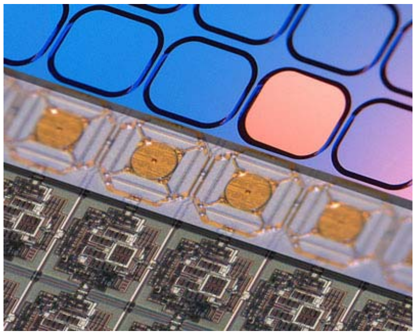

Figure3: TNI MEMS Mirror with vertical Integration of Electronics

Figure 3 shows the first generation of TNI mirror with WSI of the electronics. TNI design uses a unique actuation mechanism shown in Figure 4, called Nasiri-Platform. It utilizes the virtual pivot concept and uses four bi-directional torsional plates that can be actuated to rotate the mirror in all four desired directions. The primary advantages of this approach are:

1- Ability to fold the actuating mechanisms under the mirror to provide the maximum fill factor possible. This is very important for keeping overall size of arrays small and hence reducing the required angle of rotation and drive voltage.
2- Incorporation of a mechanical angular amplification is a very critical requirement for reducing the required drive voltages. In this design an angular amplification of 4.5 was used, which allowed the applied drive voltages to the electrodes to be reduced to an acceptable range of 100-120 volts.
3- Integration of the drive electronics underneath the mirror, eliminating routing of thousands of wires to every actuator. This allowed for fabrication of the largest single array of 3D MEMS mirrors, with 1200 mirrors integrated on a single substrate.

Figure 5 shows TNI's 1200 integrated mirror array attached to a substrate. This array requires less than a few hundred wire bonds and only one hundred interconnects to the rest of the control electronics.

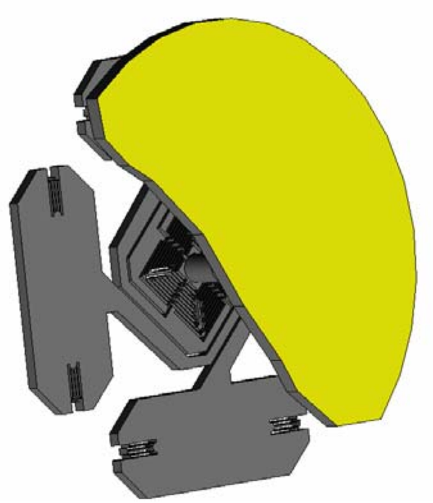

Figure 4: TNI Mirror based on Nasiri-Platform

Another system level challenge, and a major cost driver for the OXC, has been the closed loop control of the mirrors. Many have tried to avoid this by just performing the outer loop control. This is done by coupling a telecom light into each incoming fiber and monitoring the coupled light at the outgoing fiber. Since light has to bounce from two mirrors before coupling into the outgoing fiber, with four degrees of freedom (DOF) on each mirror it results in a 16 DOF system. To solve for the optimum solution it requires a very complex algorithm and lots of DSP power. This is called the outer loop control, which is also very slow, and is used primarily for optimizing the optical connection losses. A more robust system, with much faster closed loop that is capable of providing critical damping of the mirrors and rejection of external vibrations, is required. Figure 6 shows the next generation of the TNI mirror design, based on the same driving principles as the first generation, but it has four integrated capacitive position sensors underneath each mirror. Integration of the position sensors provides a drastic simplification of the closed loop electronics and can be driven at very fast speeds for rejection of office vibrations, resulting in a more robust solution at much lower cost.

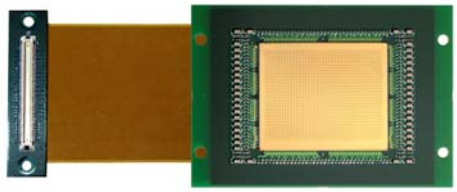

Figure 5: 1200 integrated Mirror arrays are controlled with less than hundred pins

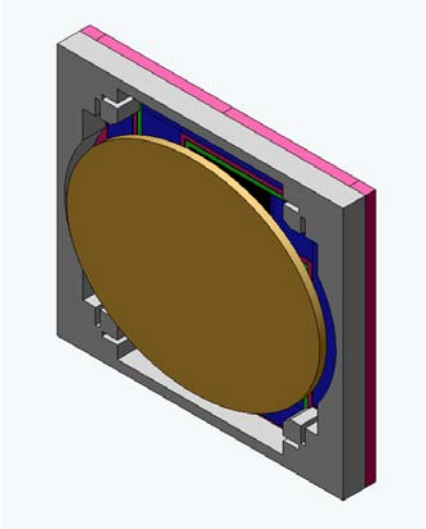

Figure 6: 2nd generation TNI Mirror Design with integrated capacitive position sensors

Hermetic Input/Output Fiber Bundles

Fabrication of 1000x1000 OXC requires efficient and reliable methods of handling lots of input and output optical fibers. Every OXC requires a minimum of two fiber-blocks, one for the incoming fibers and another for the outgoing fibers. This was considered yet another major obstacle that must be overcome by the OXC manufacturers.

As it was shown in the figure 1, in OXC systems all the incoming lights must be collimated in order to perform the switching functions. This requires the use of microlenses for lights out of the fibers and light going back into the fibers. To keep the optical coupling losses to the minimum, all fibers must be kept at a precise position behind these microlenses. Typically, each fiber is required to be held within ±2 μm in the planar and ±0.5° in pointing direction accuracy over all operating conditions and the life of the products.

Many companies have developed different technologies to meet the above required specifications. Some had used individual precision fiber collimators and highly precision-machined housings to meet the optical specifications, at a major cost penalty. One vendor had developed a method of aligning each fiber individually to each lens, in an array form, using five-degree-of-freedom stages and gluing the fibers in position, still fairly costly and limited on the array size and number of fibers.

Figure 7: 1200 fiber bundles in hermetic housing with aligned microlens collimators

Most commercially available solutions were not capable of delivering a 1200 fibers bundle in a hermetic enclosure. Furthermore, most off-the-shelf solutions for the lower port counts were already very costly. Figure 7 shows TNI’s fiber-block with 1200 fibers and an integrated microlens array in a hermetic housing.

Figure 8: Tree layer of MEMS’ integrated at wafer level to make 1200 fiber positioner

This fiber-block was designed based on a single precision bulk micromachined plate, shown in figure 8, and it was designed based on a stack of three MEMS silicon wafers using WSI. The fiber positioner plate, figure 9, had the required geometry that guaranteed the fiber positions' accuracy by design.

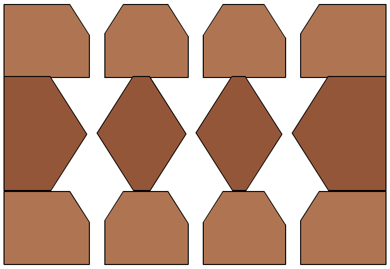

Figure 9: Tree layer of MEMS' integrated at wafer level to make 1200 fiber positioner

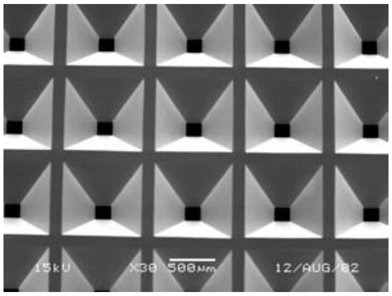

Figure 10: Bulk Micromachined Silicon with Chamfer Opening for Self-guided

Conclusions

This paper has discussed challenges with OXC equipment design and fabrication. It demonstrated how it was possible to achieve lots of system level simplification and cost reduction by utilizing WSI and WSP. It was shown that more reliable, and lower cost MEMS mirrors were fabricated using WSI. One key advantage of employing this technology is that the electronics are fabricated on standard IC fabrication lines independent of the MEMS process and IC industry. Also, MEMS fabrication is done independent of the electronics and can benefits similarly from any new process development and/or new foundries. Further, it was shown that by using WSP one can drastically reduce the mechanical complexity and cost while improving the reliability as was shown in the design and fabrication of the fiber-block.

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