

Progress in manufactured silicon photonics

B. Thomas Smith, Dazeng Feng, Hongbing Lei,
Dawei Zheng, Joan Fong, Peter Zhou, and Mehdi Asghari
Kotura, Inc., 2630 Corporate Place, Monterey Park, CA. 91754

ABSTRACT

While investment in sub-wavelength silicon photonics research has gained popularity, Kotura has forged significant customer traction with first generation silicon-photonics products by focusing on manufacturable designs and processes. This paper reviews recent gains in engineering developments where mature monolithic and hybrid methods are integrated to form high-performance manufacturable products with proven long-term reliability. Components and methods are described that lead to photonic modules and subsystems suitable for automated manufacturing techniques.

Keywords: Silicon, optical, waveguide, lightwave circuit, module

1. INTRODUCTION

In 1987, I joined a small team of engineers to found a firm to manufacture silica-on-silicon planar lightwave circuits (PLC) for the telecommunication market. Over the next 10 years, we demonstrated many products, but for a non-existent market. Eventually, however, the market caught up with us and we shipped, in total, over 80,000 PLC modules before the shutdown of the firm in 2002. Along the way, we developed manufacturing methods, which, as competing firms joined in, slowly turned into unofficial industrial standards, supported by a hopeful infrastructure of small-parts and specialty materials suppliers. The forces of evolution, as history has frequently demonstrated, drove prices down, improved reliability, and extended functionality – “faster better cheaper” really does happen.

In spite of the market slowdown in 2001, the need for speed continued unabated and the shortcomings of silica-on-silicon PLC became apparent. Pure silicon waveguides offered several advantages and the manufacturing methods of passive silica-on-silicon modules could be easily transferred to silicon-based modules. Silicon photonics production was born.

The vast expert base in silicon materials, device physics, and processing equipment that had been developed for electronic microcircuits, lay in waiting to support the fiber optic infrastructure for the high-speed transport of information, video, and voice. There is no doubt about the economic and technical advantages of silicon electronics and it was inevitable that silicon would be employed wherever optical fiber was deployed. Predictably, with the rise in Internet and data transmission, the need for higher speed, broader bands, and lower cost is satisfied by all four of the material benefits provided by silicon:

- o Photonic: wide band infrared transparency,
- o Electronic: low noise, high speed integrated circuits,
- o Thermal: high heat conductance, and
- o Structural: rugged 3-dimensional platforms and packages.

These material properties make possible a wide range of integrated electronic and photonic circuits. Reviews of the silicon potential are found in recent articles by Lipson¹ and Jalali². This paper will focus on current and near-term products including the first silicon electro-photonics commercial device - the electrically controlled variable optical attenuator or VOA. We begin on the outside, the module, and drill down to the silicon optical waveguide.

2. SILICON PHOTONIC MANUFACTURING

Optics is expensive. One needs a significant volume and the product must be manufactured at low cost. What are the elements of a photonic product and what makes it manufacturable? For silicon-photonics, most all the answers came from the silicon microelectronics industry: planar circuit design, large die-count per wafer, precision automation, low parts count, standard packaging methods, simplicity of assembly and fully automated test.

2.1 The silicon photonic module

A photonic module is just a box with electrical wire and optical fiber feeds through the walls. The purpose of the box is to protect the delicate internal parts from damage, maintain a controlled local environment, and provide mechanical support for mounting holes and labels. The wires and fibers terminate on a PLC, the heart of the photonic function of the module. There may also be supporting circuitry inside the module, as in signal processing or thermal compensation, but these are not covered in this discussion. Figure 1 illustrates a typical module. The case is constructed of aluminum or a non-flammable polymer. Hermetic seals are not required, as the silicon PLC, similar to silica-on-silicon PLC, is not attacked by moisture.

The fiber ribbons pass through rubber bend reliefs. There are no industry standard cases and, surprisingly, no standard bend relief, even though 8-fiber ribbon is standard. Every module manufacturer makes custom bend reliefs and I have seen many that oddly – don't bend. The electrical leads are clamped, that is, the clamp is a strain relief and not a bend relief. A bent wire conducts electricity quite well, whereas a bent fiber is lossy and will break in time – a reliability failure. The ribbon bend relief does not provide strain relief. All the strain is transferred to the fiber-PLC connection.

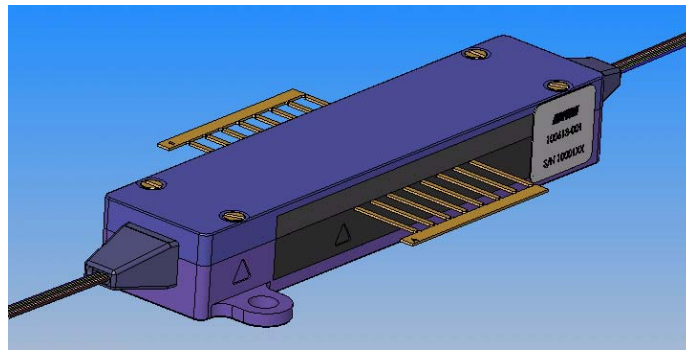


Figure 1. Typical silicon photonic module. Fiber ribbon feeds into the aluminum case through rubber bend reliefs while electrical connections are realized with the 14 gold plated butterfly leads along the sides. Note the mounting tabs and label.

A plan view of a silicon photonic module with the cover removed is shown in Fig. 2. In the center of the module is the silicon PLC. Fiber ribbons, embedded in V-blocks are bonded to the PLC at the left and right ends. Wire bonds connect the PLC bonding pads to the lead frame. The red and black coated wires on the right side lead to a thermal electric cooler placed between the PLC and the case floor. Thermal control is not required and may be eliminated or replaced by using electronic thermal compensation techniques.

In the course of manufacturing, the silicon die is bonded to the fiber block before final assembly into the case. A typical “bonded assembly”, a silicon die with attached optical fibers, is shown in Figure 3. Here you can see that the plane of the silicon is not in line with the fiber as it would be in a silica-on-silicon PLC. As in silica-on-silicon the fiber interface is cut at a small angle (5 degree) to reduce back reflection below - 40 dB. However, because the light refracts at the interface between the high index of silicon and the low index of the silica fiber, the interface has a net 7-degree tilt to maximize the coupling between the fiber and the silicon waveguide. In addition, an antireflection coating is applied to the silicon surface to index match the silica fiber.

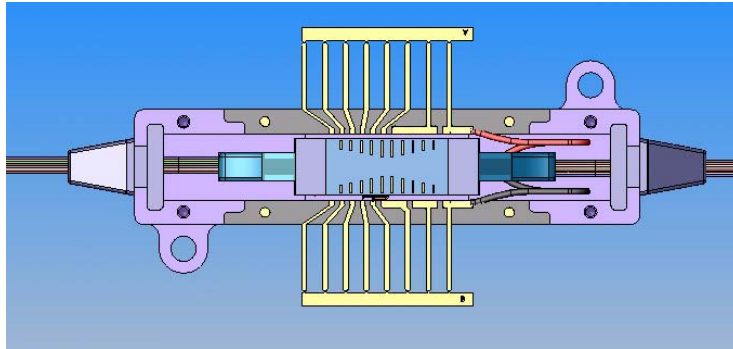


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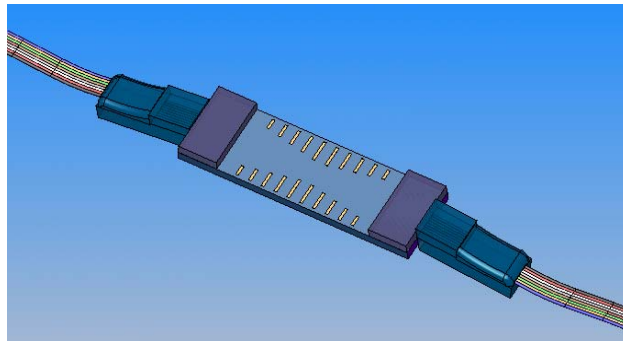


Figure 3. Silicon PLC bonded assembly.

The die was cut from a 6- or 8-inch silicon-on insulator (SOI) wafer, which will be described in the next section. The end faces of the die are polished and A/R coated for broadband transmission centered at 1550 nm. Transmission is better than 99.5 %. The dicing step is accomplished with a standard automated semiconductor dicing saw. Polishing of the end faces is not a standard semiconductor process, but automated commercial polishers with standard grits are employed. Polishing jigs are custom made and kept proprietary. The polishing quality of silicon is more stringent than that required for silica, but easily achieved at production rates.

Bonding fiber to A/R coated silicon requires rigorous cleaning and precision alignment. Alignment is automated using 0.5-micron precision X-Y-Z translation stages. As there is a net angle between the fiber and the die, it is also necessary to maintain 0.5-degree rotation accuracy in pitch, roll, and yaw. Precision jigs are sufficient to meet the angle requirements. The bonded assembly may be tested at this stage if necessary, depending on down-stream yield. (Down stream yield should exceed 95 % .)

The next process step is die attachment – bonding the silicon-fiber bonded assembly to the case structure. A soft thermal conducting epoxy is used to avoid stress birefringence. The silicon index is, as is silica, sensitive to stress. After wire bonding, the module may be tested for optical, electrical, and electro-optical performance. Analyses of failures usually indicate root causes to be scratches or residue on the polished silicon surface or damaged waveguides due to handling.

A module contains only five parts: 2 bend relief, and 2 case parts (base and lid), and the silicon bonded assembly. Assembly yield should exceed 95 % . Details of the silicon die are discussed next.

2.2 The silicon photonic die

The silicon photonic devices are probe tested during and after wafer fabrication. There are, of course, many standard silicon process metrologies: film thickness, etch depth, critical dimensions, resistivity, step coverage, etc. In addition, we incorporate electrical tests that are excellent predictors of electrooptical performance, for example, the reverse recovery diode method of measuring carrier lifetime, an important parameter for the silicon optical attenuator.³

A completed and tested wafer is diced into chips and the end-faces polished. A chip with three VOA die is shown in Figure 4. Each die has 8 independent channels, each with an independent VOA device. Each VOA device comprises 4 transverse diodes in series. Attenuation occurs when a current passes through the diodes. The basic design and performance is described by Whitman et. al.⁴ Multi-die chips are polished to increase throughput and reduce the likelihood of handling damage.

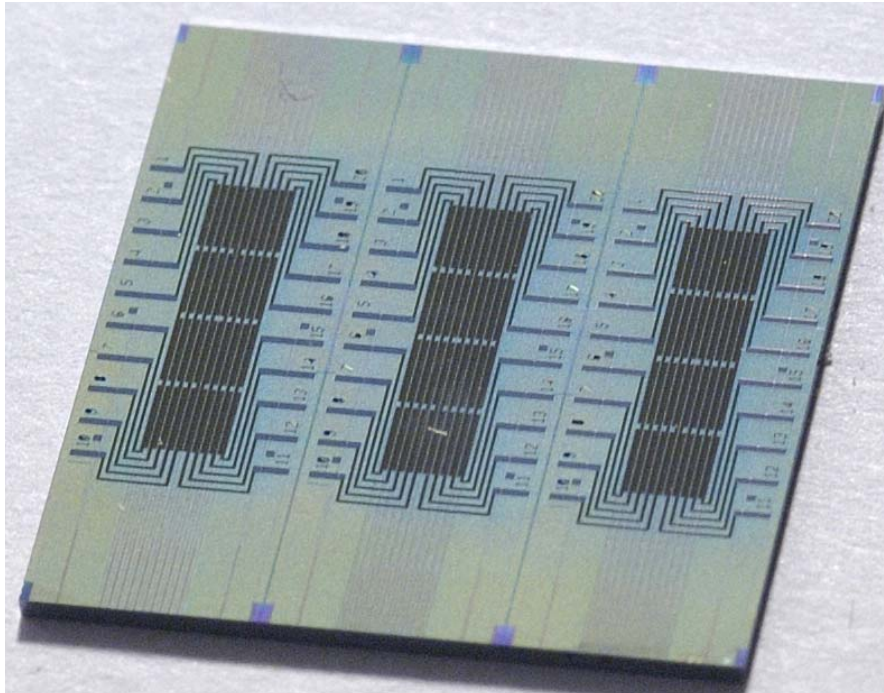
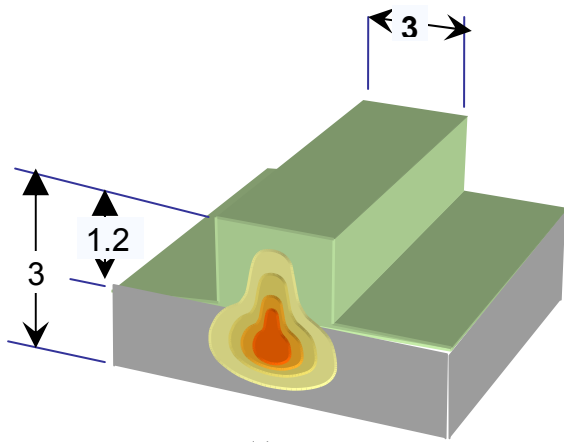


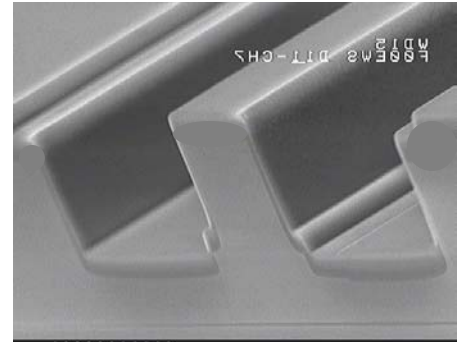
Figure 4 Silicon photonics chip with three VOA die. Each die has 8 independent channels with VOA device. The multi-die chip is polished to increase throughput and reduce the likelihood of handling damage.

The silicon rib waveguide in the VOA region has a height of 3 micron above the buried oxide and is 3 micron wide. The waveguide geometry is shown in Figure 5a. The ridge depth is optimized for zero PDL. A 3-D waveguide taper lay between the VOA region and the polished end face. This taper serves to match impedance between the small ridge waveguide and the mode field of the SMF fiber. Example mode fields are shown in Figure 6. An SEM of the 3-D mode transformers on an 8-channel die is shown in Figure 7 and another SEM of the polished end face is shown in Figure 5b. Registrations of the transformer tip to the center of the rib as well as the height of the tip above the waveguide are critical dimensions.

Processes have been optimized over several years of development and now the technique is in volume production. Several thousand VOAs have been shipped and many field units now carry live traffic. Manufacturing methods have been proven and the device has passed a rigorous reliability program.

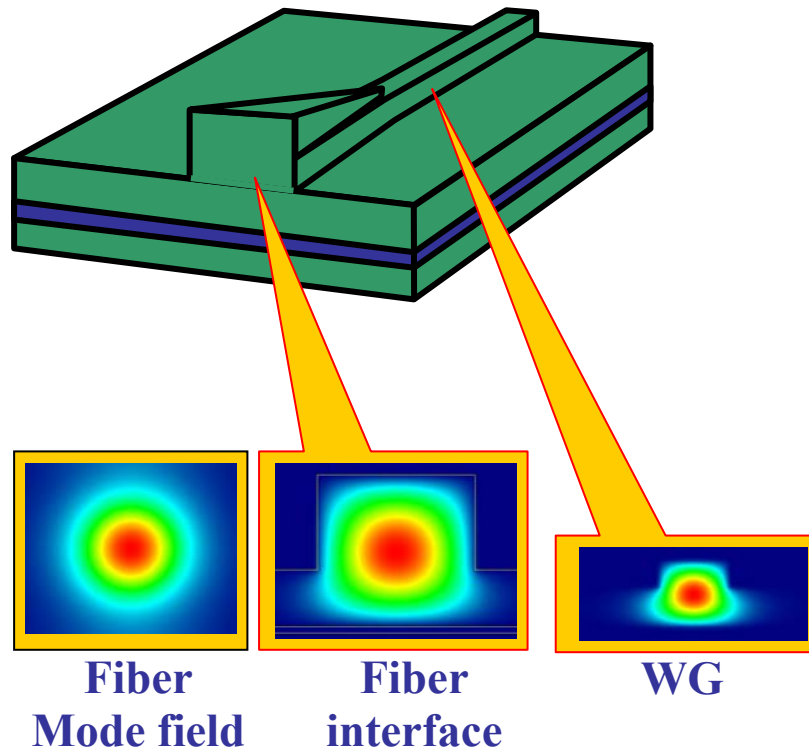


(a)



(b)

Figure 5. Silicon ridge waveguide; (a) sketch showing dimensions in micron, (b) SEM view of polished endface.



**Fiber
Mode field**

**Fiber
interface**

WG

(a)

(b)

(c)

Figure 6. Mode field patterns at 3 locations: (a) at fiber exit face, (b) at transformer end-face, and (c) at waveguide.

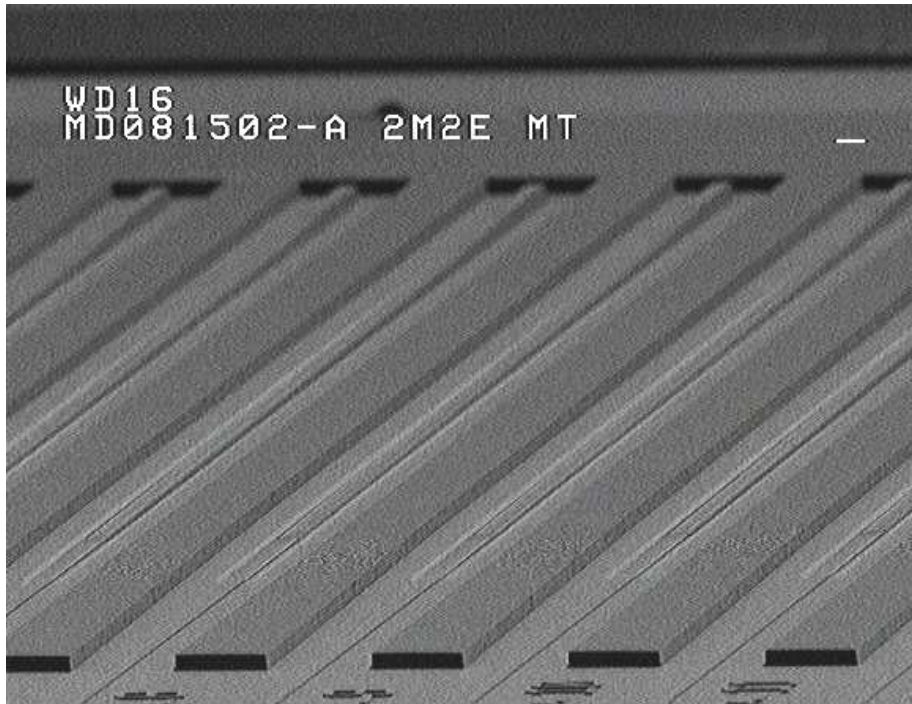


Figure 7. SEM of 3-D mode transformers on 8-channel VOA die.

3. RELIABILITY TESTS –PROOF OF MANUFACTURABILITY

The 8-channel VOA module has passed a stringent reliability qualification program. Reliability and characterization test conditions were based on the central office (CO) environment described by Telcordia Technologies, EIA standards, and Kotura's reliability test methods:

- Telcordia GR-1221-CORE Generic Reliability Assurance Requirements for Passive Optical Components,
- Telcordia GR-1209-CORE Generic Requirements for Passive Optical Components,
- Telcordia GR-468-CORE Generic Reliability Assurance Requirements for Optoelectronic Devices used in Telecommunication Equipment,
- EIA/JEDEC standard, JESD22-A114-B Electrostatic discharge (ESD) sensitivity testing human body model (HBM),
- EIA/JEDEC standard, JESD22-B106-B, Resistance to soldering temperature for through-hole mounted devices,
- Kotura defined high power laser test.

A standard and most stringent test for fiber optic products is the damp-heat test. In this test the module is exposed to high temperature (85 C) and high humidity (85 %). Pass criterion is less than 0.5 dB insertion loss change during a 500 hour exposure. The data in Figure 8 clearly indicate less than 0.2 dB change after 2,500 hours. This level of damp-heat stability is state-of-the-art for passive optical components.

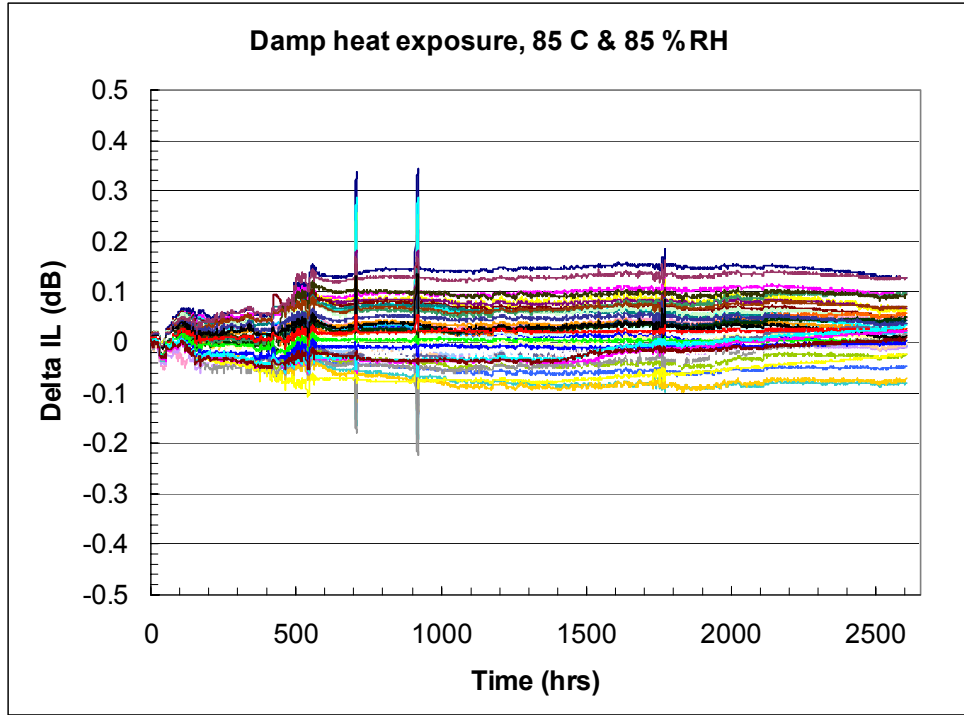


Figure 8. Very low insertion loss change of 11 modules exposed to an 85/85 environment for over 2,500 hours.

Having proven that silicon photonics modules are reliable and manufacturable, it is interesting now to look at a couple of near term developments: monolithic functions and hybridization.

4. NEW PRODUCT DEVELOPMENTS

Just as in the electronics industry, the benefits of silicon grow with functional integration. In this section we will introduce a monolithic circuit and a hybrid circuit that utilize the unique material and processing capabilities of silicon. Both of these circuits are in development.

4.1 Monolithic integration

The silicon-photonics VOA array, discussed above, is often mated with a splitter. A monolithic version of the splitter-VOA combination eliminates two fiber connections and dramatically reduces the size of a 2-module version. The die layout is shown in Figure 9. With bonding pads, the die is 2 mm wide and 22 mm long. Over 400 die can be produced on a 150 mm wafer. Insertion loss of the monolithic silicon splitter-VOA is less than the hybrid version of silica splitter fiber coupled to a fast silicon VOA. Another big advantage for the Si monolithic version is a much reduced package size.

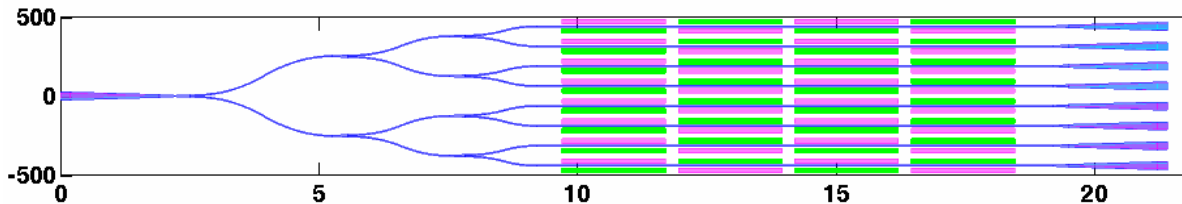
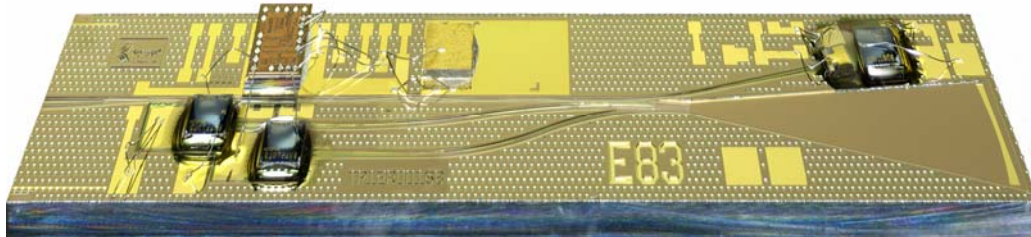


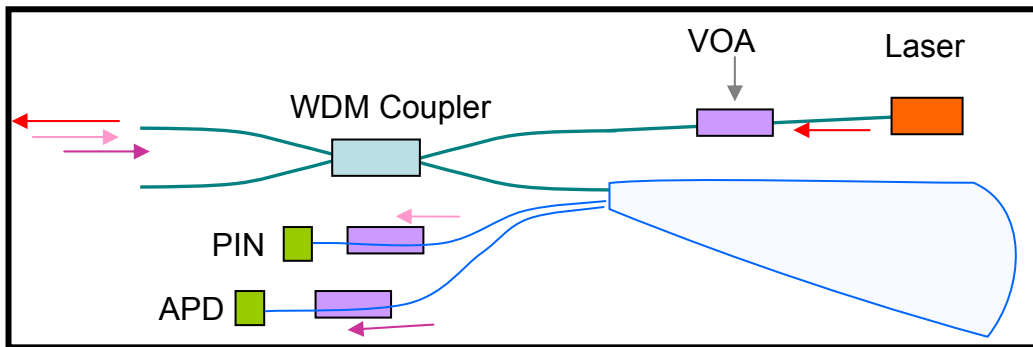
Figure 9. Monolithic design of a 8-channel splitter-VOA in silicon technology.

4.2 Hybrid integration

A hybrid version of a FTTH triplexer has considerable size and cost benefits. Figure 10a is a photograph of a triplexer with two detectors, a preamp, a laser and two VOAs. The die is only 3 mm by 12 mm. A detailed description of a similar device is presented in another paper in this volume.⁵ A circuit diagram of the Si die is shown in Figure 10b. The key advantage of this circuit is the potential to fabricate over 400 die per wafer.



(a)



(b)

Figure 10. FTTH triplexer, a hybrid implementation using a silicon grating to demultiplex the signals.

5. CONCLUSION

Silicon photonics is a reliable and manufacturable technology. Most all the packaging processes had been developed and proven over a 20-year history of silica-on-silicon modules. The silicon die manufacturing processes utilize standard CMOS processing equipment that is highly automated and standard equipment from the mature microelectronics industry.

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