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Application of Diffractive Optics to Photonic Integrated Circuit Packaging

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ABSTRACT

Photonic packaging concepts using anamorphic microlenses and second-order grating couplers were demonstrated by coupling a ridge waveguide to an out-of-plane single-mode fiber.

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SUMMARY:

One of the primary challenges in the development and application of complex photonic integrated circuits (PICs) is the packaging of the devices. The coupling of single mode fibers to a semiconductor guided-wave device is an expensive manufacturing step and a major part of the system losses. For complex circuits in which many channels need to be coupled off of the chip, the difficulties are enormous and far from solved. The requirements for a successful packaging technology for multiple channel PICs include low loss coupling from single-mode, rectangular, semiconductor waveguides to single-mode fibers, hermetic sealing of the package against environmental conditions, a means of bringing a large number of optical signal channels out of the chip without greatly increasing its size and an efficient means of aligning each of a large number of single-mode fibers with minimum losses. The losses of coupling semiconductor waveguides to single-mode optical fibers can be large because of the large mode mismatch between the elliptical mode from the rectangular cross section waveguide and the circular mode of the fiber. The elliptical waveguide mode has a very large numerical aperture (0.9 NA for our tightly confined guides) in one axis which is difficult to match to the symmetric mode of the fiber (0.16 NA in our case). Hermetic sealing is important for the utilization of PICs in stressful environments such as military, aerospace and automotive applications. Photonic circuits today are usually coupled to fibers by bringing the output waveguides to the chip edge and butt-coupling. As the number of channels is increased, more and more of the chip real estate is use for routing of the waveguides and to allow sufficient space along the chip edge for coupling. Guided-wave devices with one or two fiber connections are often manually aligned to single-mode fibers. This would be a prohibitively expensive process with a large number of fibers. Consequently, much effort has gone into methods of monolithically aligning a number of fibers at once with techniques like silicon v-groove and solder-bump bonding technology [1].

The approach being investigated at Sandia is based on bringing the optical signals of a complex PIC off the chip nearly perpendicular to the chip surface. This allows more efficient use of the wafer by not having to route the signals via waveguides to the chip edge. It also eliminates the need for a carefully cleaved chip edge for butt-coupling. The surface-emission out of the waveguides can be accomplished by second-order grating couplers. The vertical coupling of the signals then allows the use of auxiliary optical elements to provide mode matching to the fiber. These optical elements are currently diffractive microlenses and allow the fiber to be placed further from the chip surface. This enables the placement of the optical fibers in a monolithic carrier outside of the transparent package wall with the binary optical elements fabricated in the wall material. The proper center-to-center spacing of all the component groups (waveguide couplers, auxiliary lenses and fiber array holder) is assured by use of photolithography to fabricate each part. The alignment steps are then simplified to the alignment of the two monolithic components (PIC chip and package lid/fiber array holder). A depiction of the entire scheme is shown in Fig. 1.

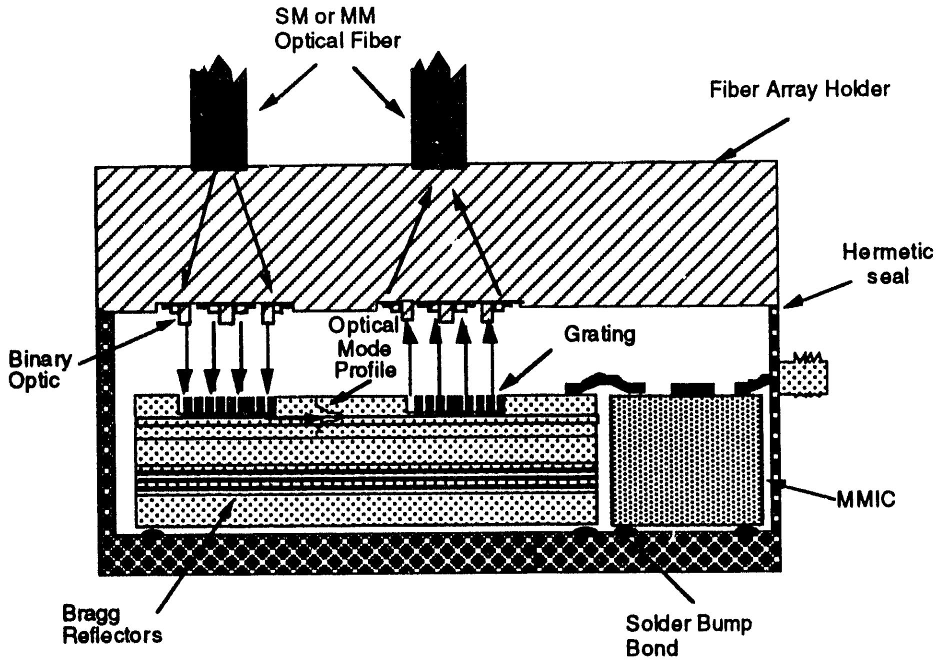

Figure 1. Advanced packaging concept for complex PICs.

The semiconductor waveguide technology in development at Sandia is based on GaAs/AlGaAs etched-rib waveguides for 1.3 microns in which components such as phase-modulators [2] and directional couplers [3] can be fabricated. Typical losses for these waveguides are 1.2 dB/mm. This technology is being developed for complex PICs for applications such as phased-array radar steering.[4] A basic test structure has been designed for prototype testing of photonic packaging technology that incorporates waveguide segments with phase modulators and second-order grating couplers as shown in Fig. 2.

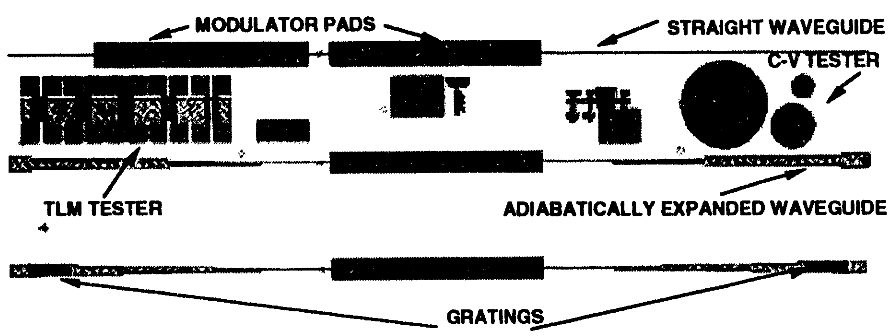

Figure 2. Test structure for development of advanced packaging technology.

A unique combination of second-order grating coupler and adiabatically tapered waveguide segment has been developed for coupling the optical signals out of the waveguides. The waveguide taper goes linearly from 2 to 50 microns in width in 1 mm. This expansion was designed using beam propagation methods to maintain a single-mode output with a reduced lateral divergence. A 200-micron-long grating is etched into the waveguide after the complete expansion. A 2D Helmholtz equation solver was used to model the fields in deeply etched waveguide grating segments to design a short grating with high coupling efficiency.[5] The short grating length and increased waveguide width improve the beam's aspect ratio. The grating is slightly detuned to minimize back reflections in the waveguide and emits approximately 10 degrees off normal. A distributed Bragg reflector stack is grown below the waveguide cladding to enhance the efficiency of the top-emitted beam from the grating.

The grating coupler was fabricated by e-beam lithography for both the grating and the tapered segment. Special care was taken to ensure a smooth transition between the taper and grating region, smooth sidewalls along the taper, and uniform grating lines. The grating pitch is 0.3825 micron with a 50% duty cycle. The grating is etched to a critical depth using an interferometrically monitored etch process. The grating has a 59% out-coupling efficiency with a beam divergence of 1 degree along the waveguide length and 2 degrees transverse to the waveguide. This reduced divergence decreases the NA requirements for the coupling lenses.

The diffractive lenses were fabricated in silicon. The lenses were 4 and 8 phase-level binary optic designs fabricated by conventional photolithography and dry etching of silicon. The designs included both symmetric Fresnel zone designs and anamorphic designs [6] to compensate for the remaining astigmatism of the grating output. The surface of a 4-phase-level lens is shown in Fig. 3. A variety of 500-micron-diameter lenses with NAs ranging from 0.10 to 0.32 were fabricated. The 8-phase-level designs were not significantly better in diffraction efficiency (76%) than the 4 level designs, indicating that alignment errors were reducing the diffraction efficiency. Widths of the phase-zones on the photomasks were held to 1 micron or larger, so the third level of the larger numerical aperture patterns were truncated, further limiting the utility of additional phase-levels in the designs. E-beam lithography is being used for a second generation of microlenses to improve the alignment and allow complete fabrication of high NA designs.

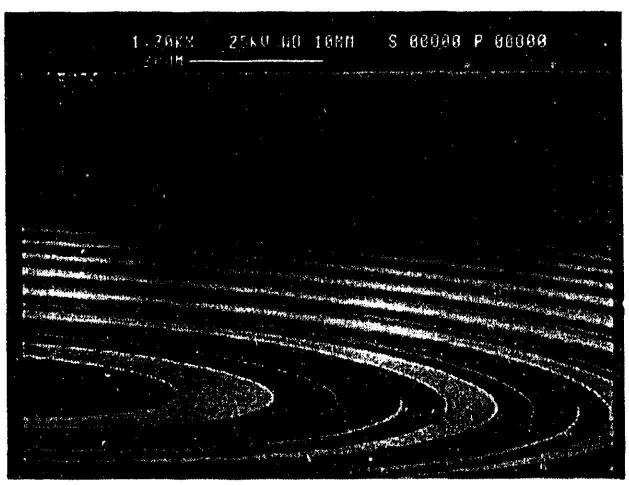

Figure 3. A scanning electron micrograph of a silicon 4 phase-level binary optic.

The package concept was demonstrated as illustrated in Fig. 4. A 1.3 micron diode-pumped YAG laser was coupled via a polarization-preserving single-mode fiber into a GaAs/AlGaAs waveguide on a fabricated test chip. The light was then coupled out of the chip surface by the adiabatic taper and grating and collected by a silicon microlens 2 mm away. The silicon microlens focused the light into the same type of single-mode fiber. The waveguide losses, grating output efficiency, and microlens diffraction efficiency were all measured independently. The total loss through the system was -18.5 dB. Neglecting the -8.8 dB loss for butt-coupling into the waveguide, as measured by OTDR, the coupling loss through the waveguide-grating-lens-fiber route was -9.7 dB, including a guiding loss of -2.3 dB in the semiconductor waveguide. The efficiency of coupling through the silicon lens into the fiber was 30% (-5.2 dB) after emission from the grating. We believe this is a promising indication of the potential for this application of diffractive optics to packaging of complex PICs. Some obvious areas of improvement are improving the diffraction efficiency of the silicon microlenses and optimizing the lens design for coupling of the grating output into the fiber mode. The coupling data indicates the anamorphic lenses bracketed the optimum configuration for this application and improvement is expected for the next generation. The off-axis emission of the grating is necessary because of the need to detune the grating to eliminate feedback problems for the PICs. Consequently, the next lens designs will include optimization for off-axis performance so they can be positioned with their surface parallel to the chip surface as required for the packaging concept.

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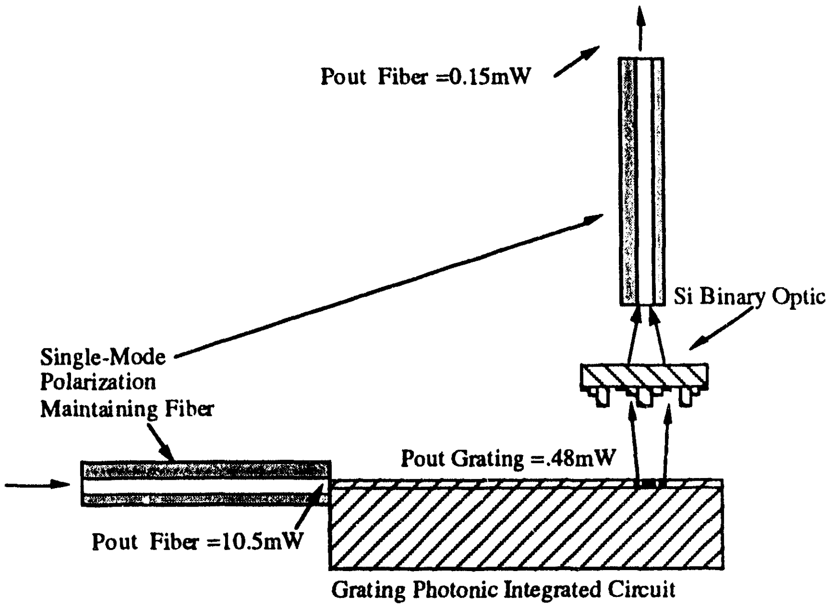

Figure 4. Configuration for coupling from ridge waveguide to single-mode fiber via waveguide grating-coupler and silicon microlens.

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