Optoelectronic-VLSI packaging with polarization-selective computer-generated holograms

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We present what is believed to be the first packaged module incorporating polarization-based beam-forming optics integrated with an optoelectronic–VLSI device. The chip has multiple quantum-well modulators and detectors that are flip-chip bonded onto a silicon CMOS integrated circuit. In the assembled module a polarization-selective computer-generated hologram converts linearly polarized light into a two-dimensional spot array to illuminate the output modulators. The lenslets do not interfere with the input data or the reflected output, which is orthogonally polarized. We demonstrate a 9×10 modulator array, showing good spot-intensity uniformity and registration with modulators. © 1997 Optical Society of America

Increasing demand for data transmission and processing has spurred development of silicon very large-scale integrated-circuit (VLSI) devices with parallel optoelectric (OE) input–output.[1] OE chips with photodetector receivers and laser or optical modulator transmitters can support large-scale, high-speed parallel communication over short distances by free-space optical interconnects. The optical signals are routed to photodetectors and transmitted from the modulators or laser devices by arrays of diffractive optical elements or micro-optics components. Integration of optics directly with OE devices such as lasers and detectors permits compact, reliable packaging for optical interconnects. This was demonstrated with microlenses etched directly upon a laser substrate[2] or formed upon a separate substrate aligned with the OE chip.[3,4] In general these optical input–output signal paths are different, which implies that the optics must provide dual functionality when one is implementing the communication links. Since conventional diffractive optical elements or micro-optics components do not have this dual functionality, additional components such as polarization beam splitters are required for separating the input and the output signals. We have demonstrated polarization-selective birefringent computer-generated holograms (BCGH's) that possess independent impulse responses for the two orthogonal linear polarizations.[5–7] The unique capability of BCGH elements permits more compact, reliable packaging. Here we describe what is believed to be the first integration of diffractive beam-forming optics with OE input–output devices that are flip-chip bonded to complementary metal-oxide semiconductor VLSI electronics and what we believe to be the first integration of a BCGH with any OE device.

Figure 1(a) shows a conventional approach to package optical interconnects with OE VLSI. A polarization beam splitter (PBS) combined with a quarter-wave plate and two different conventional diffractive optical elements routes the optical signals. In addition, other bulk optics (not shown in the Fig. 1) may be required for input collimation and output imaging. The BCGH package [Fig. 1(b)] combines the functionality, replaces these three elements, and removes the need for imaging optics because the free-space propagation distances are significantly reduced. The principal advantage of this approach is that it replaces a distributed bulk optics system with a compact, rugged OE-VLSI module that has beam-forming optics permanently aligned to a chip mounted in a standard electronic ceramic pin grid array (PGA) package. The resultant package is more compact, lighter, and can have better mechanical and thermal stability.

The OE-VLSI device that we are packaging uses multiple quantum-well (MQW) diodes that are flip-chip bonded onto silicon VLSI electronics.[1] The diodes function both as photodetectors for receiving input data and as optical modulators for transmitting output data. The modulators must be powered with an optical spot array. Figure 2 shows how the OE-VLSI module might be integrated into a larger system by use of external diode lasers for collimated optical power inputs and bulk optics for a simple imaging interconnection between two modules. This design greatly simplifies the use of MQW modulator outputs and can also be applied to laser-based OE VLSI. Figure 2 shows an extraordinary polarized plane wave obliquely incident upon a BCGH, which implements a lenslets array. The lenslets create a uniform spot array, providing external optical power for each MQW modulator. The reflectivity of the MQW diode array is electrically modulated by the information to be transmitted from one OE-VLSI chip array to another. The

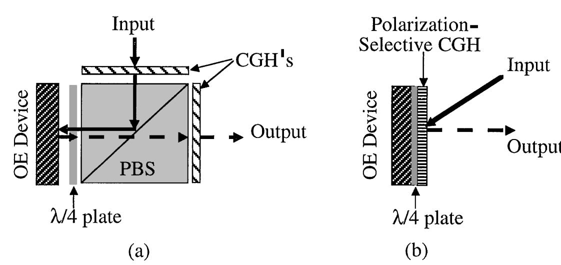

Fig. 1. Packaging optical interconnects for OE VLSI.

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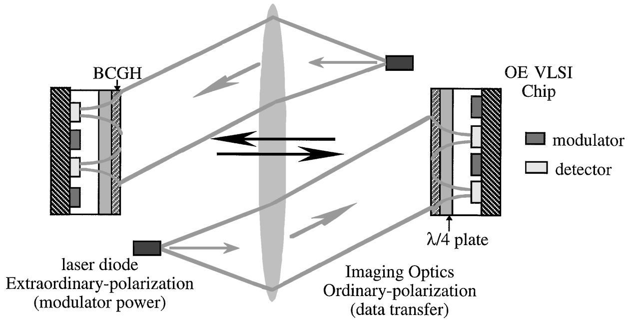

Fig. 2. System schematic with two packaged BCGH OE-VLSI modules.

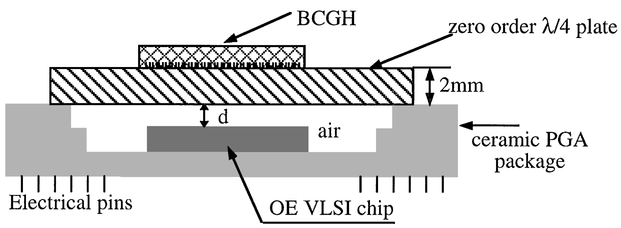

Fig. 3. Component geometry for the BCGH and the OE-VLSI chip.

reflected, information-carrying optical wave is now ordinary polarized owing to the two passes through the quarter-wave retardation plate. This ordinary polarized information-carrying wave passes through the BCGH without being affected and is then imaged onto the detector array of the secondly similarly package, OE-VLSI chip, once again without being affected by the BCGH element.

For our experiment we use a BCGH to package an OE-VLSI fabricated through the Bell Labs/GMU Co-Op Foundary. The MQW modulators require 850-nm optical input power. Our particular chip had a 10×10 modulator array interleaved with a 10×10 detector array. The period of the two arrays in both the x and the y directions is 125 μm. The size of the optical window on each diode is roughly 18 μm $\times$ 18 μm. Thus, for nonoverlapping lenslets, the maximum f-number of the focusing optics must be less than $f\text{-number}_{\max} = \text{FWHM}/(1.22\lambda) = 17.4$, where λ is the wavelength of the light and FWHM denotes the full width at half-maximum at the focal plane. An illustration of the OE-VLSI chip packaged by use of a BCGH in a standard PGA housing is shown schematically in Fig. 3. The BCGH's surface relief is in contact with the retardation plate and faces the chip. The zero-order quarter-wave plate is 2 mm thick with a refractive index of 1.45 and is antireflection coated for 850-nm light. The distance from the chip surface to the bottom of the wave plate d is 0.34 mm, so the focal length of each lens in air is $2\text{ mm}/1.45 + 0.34\text{ mm} = 1.72\text{ mm}$.

The BCGH element was designed and fabricated as a binary phase level 10×10 off-axis diffractive lenslet array for extraordindary polarized illumination but remained an optical flat under ordinary polarized illumination. We employ a design and fabrication based on the multiple-order delay approach[6] on a 10 mm $\times$ 10 mm x-cut YVO_4 substrate. The first-order diffraction efficiency (excluding reflection loss) of the fabricated element was measured to be 35% with an average polarization contrast ratio (defined as the ratio between intensities measured under two orthogonal polarizations for a certain diffraction order) of 40:1. The image transmission through the fabricated BCGH for ordinary and extraordinary polarizations is shown in Fig. 4. With ordinary polarized light, the BCGH is transparent, permitting input–output data to be imaged without scatter. The extraordinary polarized light is transmitted through the lenslet array for spot-array generation.

During the module assembly we constructed a 20$\times$ magnification imaging system. An 850-nm Ti:sapphire laser illuminated the chip through a rotating ground-glass diffuser to break the spatial coherence of the laser beam, permitting speckle-free incoherent imaging. A Glan–Thompson polarizer controlled the polarization of the incident beam after the diffuser. According to the lenslet design, the laser beam was incident upon the BCGH surface at $\sim 3°$ incidence angle. An analyzer in front of a CCD camera eliminated reflected light from the BCGH surfaces while transmitting light reflected from the modulator array. We used this reflected beam to create the CCD image of the spot array as well as the modulator array.

The module was assembled as follows: (i) The BCGH was glued (with Aremco Crystalbond 509) onto a zero-order quarter-wave plate with the c axis of the BCGH oriented at 45° with respect to the wave plate's fast axis. The integrated BCGH and the retardation plate were held by the edges by a stable optical mount. The wire-bonded chip (a standard Kyocera 84-pin PGA package) is mounted upon a four-degree-of-freedom (x–y–z and rotation) stage. (ii) The wave plate integrated with the BCGH was set directly on top of the package, the wave plate– BCGH was fixed, and the PGA package was lowered to permit x–y translation and rotation. (iii) The final alignment was made

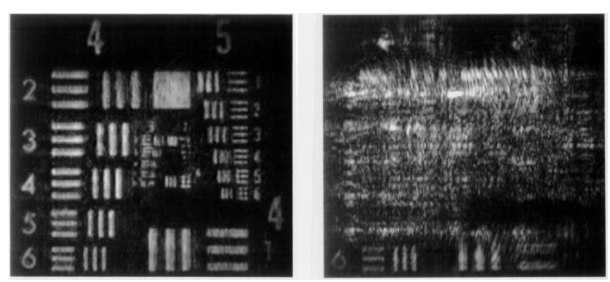

Fig. 4. Image transmission through the BCGH for ordinary (left) and extraordinary (right) polarization.

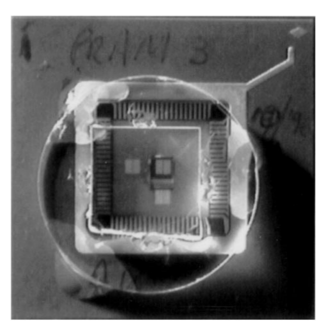

Fig. 5. Photograph of the packaged OE-VLSI module.

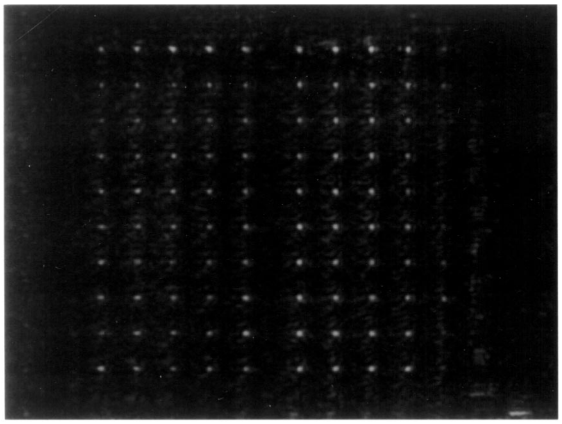

Fig. 6. OE-VLSI module output in a 10 × 9 spot array.

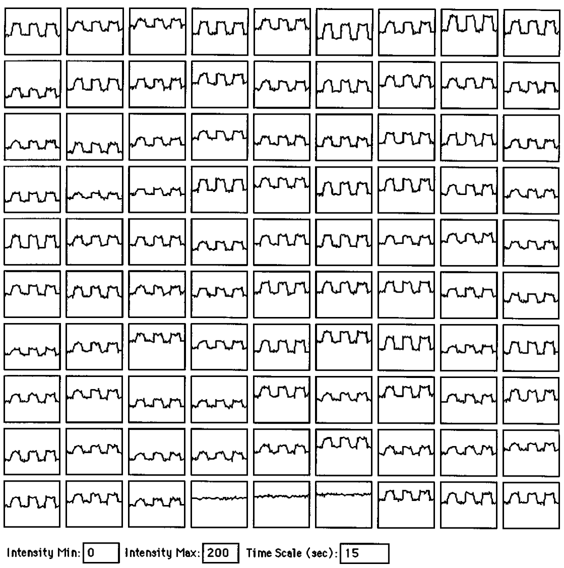

Fig. 7. Intensity versus time traces for all 90 modulator outputs.

when the spot array generated by the BCGH lenslets was overlapped with the MQW modulator array. The alignment accuracy was ~5 μm (0.25% of the optical spot FWHM). (iv) When the final alignment was achieved, the PGA housing was brought into contact with the wave-plate–BCGH duo, which was fixed in place with several drops of UV-curing epoxy (Norland 68 optical adhesive) applied to the edge of the wave plate. Figure 5 shows the BCGH packaged with the OE-VLSI chip.

We tested the packaged module by illuminating the system with a collimated beam and imaging the reflected output onto a CCD by using a $4F$ telescope imaging setup. Figure 6 is an image of the generated spot array reflected off the modulator array; the results demonstrate good BCGH performance, except that the spot array reflected from the modulator array consists only of 10 rows and 9 columns. Owing to an inversion in the chip layout, the 10th column of the spots landed on a row of detectors rather than on an active row of modulators. The CCD camera output was collected by a Macintosh computer running VIDSCOPE, a real-time image-analysis program.[8] With a pulsed input, this program can be operated as a sampling oscilloscope for high-speed measurement of repeated data patterns.

We modulated the modulator array at low speed to test the array uniformity rather than device frequency response. The reflected intensity at each of the output modulators was measured and plotted as a function of time, permitting simultaneous measurement of the entire array. Each measurement of the entire array is obtained by integration of the light intensity upon a 3 × 3 pixel square on the CCD. Figure 7 shows the VIDSCOPE output, which includes traces of each of the 90 optical output channels of the packaged BCGH and the OE-VLSI chip. These results show that the BCGH element-functioned as designed. The spots are uniformily generated (within ±20% deviation from the average). These spots registered with the modulators with good accuracy across the entire array. The two functions of the BCGH did not interfere with each other. The modulation contrast of 1.5:1 was less than the 2:1 contrast measured with a tightly focused (5-μm FWHM) beam, which indicates that a lower-f-number lenslet array could improve performance.

We have demonstrated what we believe to be the first use of polarization-selective CGH for optoelectronic device packaging. The unique dual-functionality property of BCGH elements permits more-compact, lighter packages than those achieved with the conventional approach. We achieved uniform modulator illumination and correct spot registration. Possible future directions for improved performance include incorporation of alignment marks on both the die and the BCGH for a simpler alignment process and use of overlapped lenslets for a reduced modulator illumination spot size.

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