Reflective block optics for packaging of optical computing systems

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A new optical packaging technique, which we call reflective block optics, for optical computing systems is proposed and demonstrated experimentally. This technique is based on solid optics, which is advantageous with respect to stability, reliability, and alignability. Reflective lenses are used to attain high lens power, compactness, and a large space–bandwidth product. Glass blocks, cube beam splitters, and reflective optical elements are combined to form optical blocks. We can construct several optical systems by assembling the optical blocks.

The investigation of a feasible technique for packaging an optical system is important in the field of optical information processing utilizing free-space light propagation. Compactness, reliability, easy fabrication, and easy alignment are required for construction of a practical optical computing system. These requirements are, however, difficult to achieve if conventional bulk optics alone is engaged. Recently various techniques of three-dimensional optical integration have been proposed to address this problem.[1–4] These techniques are not, however, suitable for a macro-optical system, whose size is from a few millimeters to several centimeters, owing to technical difficulties in fabrication. Such a macrosystem takes on an important role in optical interconnection and optical computing because the macrosystem has a larger space–bandwidth product than the microsystem.[5] In addition, the macrosystem offers high connectivity in the large-image field and offers long-distance communication between object and image planes. These are important features because optical interconnection has advantages over electronic interconnection with respect to power and speed as communication distance increases.[6] Using the concept of solid optics,[7,8] one can build a rigid macrosystem. Solid optics is achieved by use of transparent solid media, and because lenses are implemented by use of the difference in refractive indices between adjoining solid media in the solid optics it is difficult to fabricate a lens with high refractive power.

In this Letter we propose a new optical packaging technique called reflective block optics (REBOP) and demonstrate some simple examples experimentally. REBOP is extended from solid optics by the introduction of reflective lenses. Figure 1(a) shows a 4-f system that uses REBOP. To assemble an actual optical system, we place individual components in contact with each other on plane surfaces. The reflective lens is a concave mirror coated with reflective material on the convex surface of a plano–convex lens. Reflective lenses and other optical elements are attached to the base elements, which are transparent solids and cubic polarizing beam splitters (PBS's). Light propagates in the homogeneous medium and is reflected by the concave mirror at the edge of this medium. For lossless propagation, linearly polarized light is used, and PBS and quarter-wave plates are placed in an isolator arrangement. We can construct complicated systems by connecting several elemental blocks in cascade, as shown in Fig. 1(b). The combination of several types of optical blocks provides variation in the optical systems.

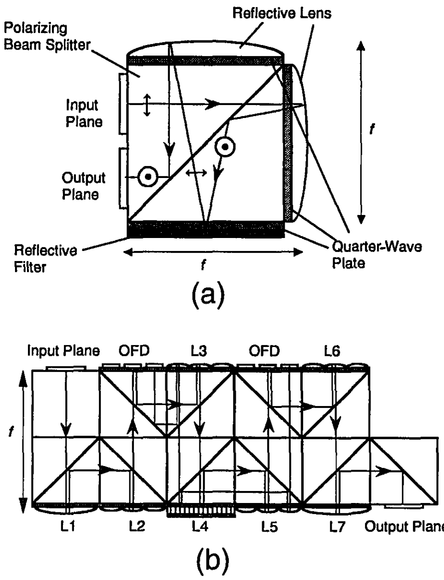

Fig. 1. Examples of REBOP: (a) a single block for implementing a 4-f system, (b) a combination of several blocks for implementing an optical computing system consisting of multiple discrete correlators. L1–L7, lenses; OFD's, optical functional devices.

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The merits of solid optics, such as rigidity, no dust intrusion, and easy alignment, are retained in the REBOP system. By virtue of the reflective elements, imaging and Fourier transformation can be achieved with rather compact setups. A reflective lens is preferable to a refractive lens in terms of lens power because the lens power of a spherical mirror corresponds to that of a refractive surface whose differential refractive index is 2. Moreover, a spherical mirror has less aberration than a spherical refractive surface has.[9] In particular, spherical aberration, coma aberration, and astigmatism are eliminated in a 4-f system composed of parabolic mirrors. If lens aberrations are corrected sufficiently, the width of a minimum spot focused by a lens with a square aperture is given by

$$a = 2\lambda F, \tag{1}$$

where λ is the wavelength and F is the f-number of the lens. When the f-number is restricted to 1/2 tan 5° by the available incident angle of light into the PBS and $\lambda = 700$ nm, then the width of the spot is ~8 μm. This resolution is comparable with the cell size of optoelectronic devices.

Figures 2 and 3 show the results of experiments for verifying the concept of the REBOP system. The reflective lenses are plano–convex lenses coated with aluminum on the spherical surfaces. The focal length and the diameter of the reflective lenses are 25.95 and 20 mm, respectively. Figure 2(a) shows an imaging system based on REBOP. A test chart is placed on the input plane and illuminated by a He–Ne laser through a diffuser. By observing the output image of the test chart shown in Fig. 2(b) we find that the resolving power is 16 line pairs/mm. Ghost images are observed on the output plane. This phenomenon is caused by reflection at the boundary of the contacted blocks and by the inferior characteristics of the PBS and quarter-wave plates. We can avoid the reflection at the boundary by matching the refractive indices correctly and by filling the air space with matching oil. For the problems associated with polarization we must improve the polarizing components and insert analyzers to eliminate undesired polarized light.

Figure 3(a) shows the experimental results of a 4-f system based on REBOP. The size of the input object shown in Fig. 3(b) is 5 mm × 5 mm. The input object is illuminated by a He–Ne laser through a diffuser. The holographic filter is composed of two kinds of one-dimensional grating recorded on a photographic plate by use of a multiple-exposure technique. Figure 3(c) shows the image focused in the position of the first diffraction order on the output plane. In the output plane the input pattern is duplicated, and the duplicated patterns are shifted and overlap each other. Although the light source and the collimator lens are not integrated with other optical components in the experiments, it is possible to integrate the components for illumination in the same manner of REBOP by use of a laser diode as a light source and a reflective lens as a collimator.

Figure 4 shows photographs of the output field illuminated by uniform light on two different 4-f configurations. Shading caused by the angular dependence of the reflectance (or the transmittance) is observed. For both configurations, collimated light passes through the first PBS and meets the first reflective lens. After reflection the light reenters the PBS with a position-dependent angle as a result of the converging power of the lens. The incident angle is uniquely determined at the specific position of the object plane. Thus the spatial distribution of intensity on the output plane indicates the characteristics of reflectance or transmittance versus incident angle on the PBS.[10] The restriction of the incident angle can be relaxed by the design of a multilayer configuration capable of enlarging angular range at the expense of spectral range.[11]

An important feature of REBOP is the easy alignment of the distance between planes. We consider a parallel optical interconnection system between a surface-emitting laser-diode array and a photodetector array for the purpose of a discussion of the tolerance for defocus that is due to fabrication errors of the optical blocks. We assume that the light from each element is propagated as a Gaussian beam and that the width of a detector is equal to the width of the beam waist, $2w$. An error in the distance between a lens and an image plane makes a spot on

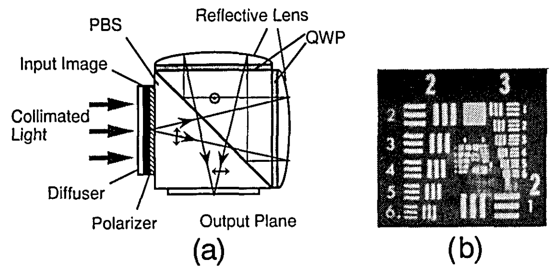

Fig. 2. Basic experiment of an imaging system: (a) optical system, (b) observed image of a test chart. QWP, quarter-wave plate.

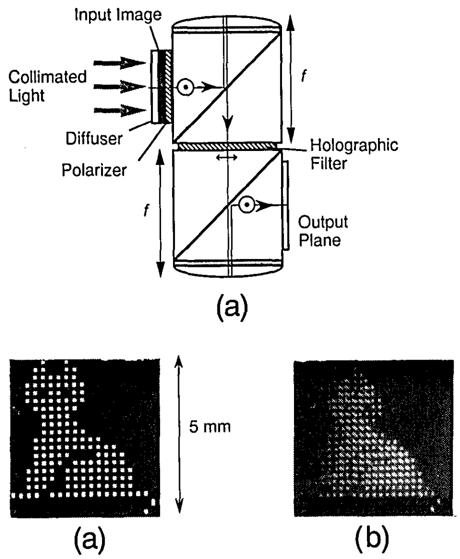

Fig. 3. Experiment of a 4-f system with a holographic filter: (a) optical system, (b) input pattern, (c) observed image.

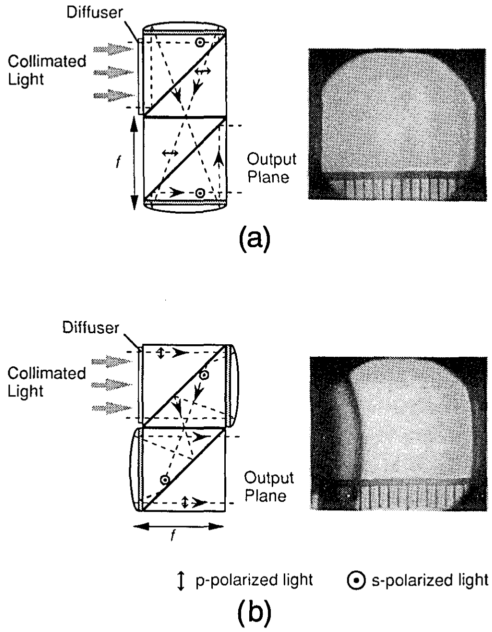

Fig. 4. Restriction of the image field as a result of the angular characteristics of a PBS by use of two different 4-f configurations: (a) converging p-polarized light, (b) converging s-polarized light.

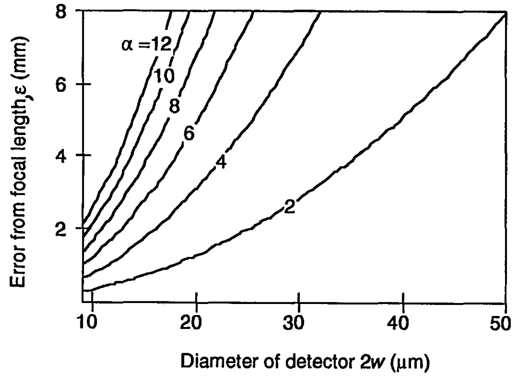

Fig. 5. Tolerance for defocus, without cross talk with adjacent detectors, for each spacing.

the detectors spread. To avoid cross talk with adjacent detectors, the diameter of the spot, $2w'$, should satisfy the following condition:

$$w + w' < s\,, \tag{2}$$

where s is the spacing of detectors. The permissible error from the focal length, ε, is derived from relation (2) and Gaussian propagation:

$$\varepsilon < \frac{\pi w^2}{\lambda}\left[\left(\frac{s}{w} - 1\right)^2 - 1\right]^{1/2}. \tag{3}$$

Figure 5 shows the maximum permissible error in focus for each spacing ($\alpha = s/2w$) when $\lambda = 700$ nm. Fabrication accuracy of optical blocks within this tolerance can be achieved with current technology.

An easy and precise mechanism for aligning individual optical blocks is important in REBOP. By introducing guide grooves on the contacting surface of each block and the PBS, using a photolithography technique, one can align optical components accurately. In particular, the self-aligning techniques using flip-chip solder bonding[12] or an optical plug and jack[13] provide a means of useful easy alignment.

In conclusion, we have demonstrated a new concept of optical packaging, called reflective block optics, for constructing optical interconnection and optical computing systems. The principle is verified by basic experiments of simple imaging with 4-f optical systems. In the future it will be necessary to study the feasibility and the design of components for high optical performance.

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