Optical interconnections made using two-dimensional arrays of top-surface-emitting microlasers and integrated free-space optics are discussed for use in chip-to-chip communications. A demonstration setup with a $2 \times 2$ array of lasers is presented. System parameters, such as light efficiency, the number of data channels, thermal effects, power requirements, and the issue of hybrid integration of laser chips with passive optics, are considered.

Key words: Optical interconnects, optical packaging, diffractive optics, micro-optics.

I. Introduction

Optical interconnects offer an advantage over electric wires in terms of the amount of energy required to communicate logic-level signals in a computer or switching system. Miller made the assumption that optical sources, modulators, and detectors can operate efficiently as impedance transformers and estimated that, for communication distances over a few hundred micrometers, optics should have an advantage over electronics. In addition to their answering the need to keep the energy requirements of a system low, optical interconnects are interesting because of their lower sensitivity to signal interference and cross talk and, as far as free-space optics are concerned, have a higher interconnection density than can be achieved with two-dimensional wiring. Free-space optical interconnections in very large-scale integrated (VLSI) systems and in optical computers have been discussed over the past few years in the literature (see, for example, Refs. 2–7). The use of free-space optics is linked to the availability of two-dimensional device arrays, such as multiple quantum-well light modulators and surface-emitting laser diodes. Recent advances in the development of these devices have stimulated further work on the use of optical interconnects on various levels within an electronic or optical computer.

The use of free-space optics for interconnects has been hampered, however, by problems connected with the packaging of optical systems. It was pointed out earlier that conventional optomechanical packaging is not adequate in terms of size, robustness, and manufacturability for building complex systems. Integration and miniaturization of optoelectronic systems is therefore a major issue for the future development of optical interconnects. One approach to solving the packaging problem is to use folded optical systems consisting of micro-optical components fabricated on glass substrates by holographic or lithographic means, with light propagation inside the substrate. We chose the term planar optics to describe this technique of integrating free-space optical components, indicating that the optical components are arranged in a plane rather than in three dimensions. Planar optical imaging systems can be built smaller than conventional optical systems and with fewer problems with thermal and mechanical stability.

One issue connected with the use of integrated optical imaging systems is the problem of integrating the passive optics (which might consist of a glass plate, for example) with devices made of GaAs, or some other optoelectronic material, in order to build a compact system. Hybrid integration techniques such as flip-chip bonding might be useful for this purpose. Other ways of building integrated systems may be possible if other substrate materials, such as silicon, are used and if the current efforts at building either silicon-based devices or intergrating devices made of compound III–V materials on Si (Ref. 17) are successful.

Here we consider the use of integrated optical interconnects using planar optics and surface-emitting microlasers. Two-dimensional arrays of microla-
sers have been demonstrated recently to operate at room temperature with low thresholds in a cw mode. In our experiment, top-surface-emitting lasers were used. In this structure, current funneling into the laser cavity is achieved by deep ion implantation. This permits the fabrication of planar device arrays, which might be beneficial for integrating the laser chips with a planar glass substrate. Top-surface-emitting microlasers have shown stable room-temperature cw characteristics with high output power and efficiency.

Below, we describe a three-dimensional interconnect system consisting of a planar imaging system and microlaser devices and show an experimental demonstration (Section II). In Section III, several integration issues are discussed.

II. Interconnects with Microlasers and an Integrated Imaging System

The basic optical system that we investigated is shown in Fig. 1. It consists of two diffractive off-axis lenses that can be fabricated by lithographic or holographic techniques. In our case, reactive ion etching was used for making the lenses. On the bottom side of the substrate, opposite the lenses, are the laser input array and a detector array. In order to make the light propagate inside the substrate, the top and bottom surfaces are coated with a metallic layer that has a high reflectivity at the wavelength used. The lenses act simultaneously as focusing elements and as beam deflectors. The focal length $f$ of the lenses is assumed to be equal to the thickness of the substrate, so that light from a laser source is turned into a tilted collimated wave by the first lens and focused to a small spot again by the second.

The thickness $h$ of the glass plate and the angle $\alpha$ at which the light travels between the lenses determine the lateral offset $s$ between the microlaser array and the detector array, i.e., $s = 2h \tan(\alpha)$. This is true if the light makes one reflection between the two lenses. In our experiment, the substrate thickness was 6 mm and $s$ was 2 mm, which corresponds to $\alpha \approx 9.5$ deg. The value for $s$ can be increased by allowing several bounces between the two sides of the glass plate while using thinner substrates at the same time.

The optics for our experiment was fabricated by lithographic techniques. This provides precise positioning of the two lenses relative to each other within a submicrometer tolerance. Diffractive lenses can be made lithographically with multiple discrete phase steps in order to achieve high diffraction efficiencies. A problem that occurs with the lithographic fabrication of off-axis components is that the rings become extremely fine, which makes it hard to make multilevel elements. For this reason, binary lenses were used in our experiment, with the result that a large amount of the light energy was sacrificed. A diffractive lens with two phase levels has a theoretical efficiency of approximately 40%. The tandem configuration of two lenses as used in our setup, therefore, had an efficiency of 16%. This value was further reduced by errors induced during the fabrication and by losses resulting from reflectivities of the mirrors smaller than 100% (approximately 98–99% for silver at 850 nm). Therefore it can be estimated that the overall efficiency for our experimental setup was somewhat smaller than 15%. In order to improve this value, it would be necessary to fabricate diffractive lenses with multiple phase steps by using submicrometer optical or electron-beam lithography or by using holographic techniques.

A $2 \times 2$ array of top-surface-emitting microlasers was used in the experiment. The wavelength of operation was near 850 nm. A picture of the packaged laser array is shown in Fig. 2(a). A schematic diagram of each laser is given in Fig. 2(b). The diameter of each individual laser is 15 $\mu$m and the lasers were separated by 240 $\mu$m in one direction and 320 $\mu$m in the other. The optical input to the integrated imaging system and the output signal are shown in Fig. 3. In the experiment, the continuously operated lasers were not brought into physical contact with the integrated imaging system, but rather were imaged onto the input window on the substrate.

It is interesting to consider how many data channels a system as shown in Fig. 1 can support. To determine this, we investigated the imaging properties of the optical system, using a ray-tracing analysis. Figure 4 shows one result of that analysis in the form of a spot diagram. This plot was obtained by tracing the light rays emitted from various points in the input plane through the two lenses and computing the positions where those rays hit the output plane.

The spot diagram, a function of the coordinates in the input plane, can be considered to be a qualitative map of the aberrations of the system. For an optical system with few or no aberrations, all the light rays from a point source in the input plane will end up in the same output position.

The diagram shown in Fig. 4 was computed for a system that has an $f$/number of 5. It shows the spot diagram for an input array of $8 \times 8$ spots. We chose to separate the positions of the point sources by 20 $\mu$m in each direction. It can be seen that, at most of the output positions, the spots are contained within an area considerably smaller than the spacing of 20 $\mu$m. This indicates that, for these positions, there are practically no ray aberrations, and the size of the output spot is determined by the diffraction at the
lens apertures. Given an $f$-number ($f/#$) of 5, the size of the output spots would be $2 \times \frac{\lambda}{f/#} = 8.5 \mu m$ (assuming that the wavelength $\lambda = 0.85 \mu m$ and that the lenses are rectangular in shape). The corner positions show some increased aberrations. At those positions, the actual spot size would be determined by the convolution of the ray diagram with the point-spread function of the system. From the simulation, we can conclude that our integrated two-lens system can handle an array of $8 \times 8 = 64$ optical data channels and generate spots of a size $< 10 \mu m$ in the detector plane. For larger spot sizes, i.e., less required resolution of the optical system, the space-bandwidth product would increase.

Another point of interest is the wavelength dependence of the integrated system. This is important since, owing to fabrication tolerances, the wavelengths of the light emitted by different lasers in an array might vary slightly. Two effects are of importance: first, a change of the wavelength means a different diffraction angle according to $\sin(\alpha) = \frac{\lambda}{d}$, where $d$ is the grating period. The second grating, however, would compensate for this effect exactly as indicated in Fig. 5(a). Therefore, given finite apertures of the lenses, this effect causes only a mild drop in the intensity of the output beam. The second effect is defocusing, since the focal length of a diffractive lens is also wavelength dependent. The influence of this effect depends on several geometrical parameters such as the focal length of the lenses, the $f$-number, and the detector size $d_s$. Figure 5(b) shows a computer simulation that is based on a ray-tracing analysis in which the relative intensity $\Delta I/I_0$ is calculated as a function of $\Delta \lambda = \lambda_1 - \lambda_0$. Here we denote by $\lambda_0$ the ideal wavelength for which the system was designed. $\lambda_0$ is held constant during the computation. $I_0$ and $I_1$ are the intensities arriving at the detector for the wavelengths $\lambda_0$ and $\lambda_1$ respectively. It is assumed that the beam emitted from one laser has a Gaussian
profile described by \(\exp(-r^2/\omega^2)\), where \(r\) is the radial coordinate in the plane of the first lens. According to the plot, the intensity first decreases slowly because of the angular effect we described and then at some point starts to drop rapidly because of the defocusing. Depending on the specific geometric situation, the tolerance range \(\Delta \lambda_{\text{max}}\) for the wavelength can be of the order of a few nanometers. In the particular example chosen, we find that \(\Delta \lambda_{\text{max}} = \pm 4\) nm, provided that we tolerate a 10% drop in the intensity. It should be noted that the value for \(\Delta \lambda_{\text{max}}\) can vary significantly for other values of the system parameters.

Finally, we are going to analyze the temperature sensitivity of an integrated system. Two effects have to be considered: the influence of a temperature change on the focal length of a diffractive lens and on the diffraction angle of a linear grating (Fig. 6).

The diffraction angle \(\alpha\) of a grating is determined by
\[
\sin(\alpha) = \frac{\lambda}{(nd)},
\]
where \(\lambda/n\) is the wavelength of the light in a medium with index \(n\) and \(d\) is the grating period. The lateral position of the light beam at the right side of the substrate is given as \(s/2 = h \tan(\alpha)\). We use the relationships \(\partial s/\partial T = \beta d\), where \(\beta\) is the thermal expansion coefficient of the material, and \(\partial n/\partial T = \gamma n\), where \(\gamma\) is the temperature coefficient of the refractive index, and we find that
\[
\partial s/\partial T = (\beta - (\beta + \gamma)/\cos^2(\alpha))s.
\]

As an example, we use the values for quartz glass for which \(\beta = 0.55 \times 10^{-6} \text{K}^{-1}\) and \(\gamma = 9.5 \times 10^{-6} \text{K}^{-1}\). For a temperature swing of \(\Delta T = 100 \text{K}\) one gets a relative change in the lateral position of the output beam of \(\Delta s/s = -1.67 \times 10^{-4}\). Here we assumed a diffraction angle \(\alpha\) of 20 deg. It follows from this that for a substrate thickness \(h = 3000 \mu\text{m}\) with \(s/2 = 1092 \mu\text{m}\), the lateral shift would be only \(\Delta(s/2) = -0.18 \mu\text{m}\).

Similarly, one can calculate the change in the focal length of a diffractive lens with the temperature. It is given as
\[
f = nR^2/2\lambda.
\]

Here, \(R^2\) denotes the spatial period of a Fresnel zone pattern in \(r^2\), where \(r\) is the radial coordinate. We use the equations \(\partial R/\partial T = \beta r\) and \(\partial n/\partial T = \gamma n\) and find that
\[
\partial f/\partial T = (2\beta + \gamma)f.
\]

As the focal length of a lens gets longer with increasing temperature, according to Eq. (4) the thickness \(h\) of the glass substrate also gets longer:
\[
\partial h/\partial T = \beta h.
\]

At a given temperature \(T_0\), the focal length \(f\) is equal to the substrate thickness \(h\). With changing temperature, the amount of defocusing is given as the difference \(\partial f/\partial T - \partial h/\partial T:\)
\[
\partial(f - h)/\partial T = (\beta + \gamma)h.
\]

Using the same values as above, we find that, for a temperature change of \(\Delta T = 100 \text{K}\) and a substrate thickness \(h = 3000 \mu\text{m}\), the amount of defocusing is \(0.03 \mu\text{m}\).

From these calculations and examples, we can conclude that temperature effects in integrated micro-optic systems are very small. This is an important property for systems applications.

III. Hybrid Integration of Devices and the Optical System

We would like to address briefly the issue of integrating passive optics with active devices such as microlasers. We assume that the passive optical system will be fabricated in glass (fused silica, for example). Then

![Fig. 5. (a) Bulk-optical system equivalent to the integrated system of Fig. 1. The off-axis lenses are shown as a superposition of a lens and a grating. The effect of a varying wavelength is indicated by showing two different light paths. The solid lines indicate the light rays for wavelength \(\lambda_0\), the dashed lines for \(\lambda_1\). (b) Wavelength dependence of the intensity at the detector; the results of a computer simulation are shown. For this particular case, the following values were chosen: detector size \(ds = 20 \mu\text{m}\), \(f/\# = 5\), focal length \(f = 3000 \mu\text{m}\), center wavelength \(\lambda_0 = 1 \mu\text{m}\), and beam radius \(\omega = 150 \mu\text{m}\).]
the integration requires hybrid mounting of the GaAs chip on the substrate with a high alignment precision.

One technique that is of interest for achieving this goal is flip-chip bonding using self-aligning solder bumps. The principal idea is to have solder bumps in defined positions on both substrates, as indicated in Fig. 7. With the bumps facing each other they are brought in contact with relatively low positioning accuracy. When they are heated, the surface tension in the liquid solder tends to align the bumps to a high degree of accuracy. Tolerances of less than 2 μm have been reported in the literature, with estimates that they could be as small as a few tenths of a micrometer.

In integrating substrates of two different materials, one concern has to be the difference in the thermal expansion coefficients. A change of the temperature \( T \) by \( \Delta T \) causes the two substrates to expand or shrink by different amounts, thus causing mechanical strain between the substrates that could result in deformations or cracks. We denote the coefficients of thermal expansion by \( \beta_1 \) and \( \beta_2 \), respectively, their difference by \( \Delta \beta \), and the size of the area of contact between the two substrates by \( L \). A temperature swing of \( \Delta T \) results in a relative lateral shear of \( \Delta L/L = \Delta \beta \Delta T \). \( \Delta L \) has to stay smaller than a certain limiting value \( \Delta L_{\text{max}} \). If we set \( \Delta L_{\text{max}} = 1 \) μm and assume a fixed temperature range in which the system has to be able to operate, then we obtain a maximum size for the laser chip that is given as \( L_{\text{max}} = \Delta L_{\text{max}}/(\Delta \beta \Delta T) \). To get an estimate, we take the following situation: \( \beta_1 = 0.55 \times 10^{-6} \text{K}^{-1} \) (for fused silica at room temperature), \( \beta_2 = 3.6 \times 10^{-6} \text{K}^{-1} \) (for GaAs), \( \Delta T = \pm 50 \text{K} \), and \( \Delta L_{\text{max}} = 1 \) μm. From this it follows that \( L_{\text{max}} = 6560 \) μm. This would correspond to the maximum allowable substrate size of the GaAs chip mounted on a quartz glass substrate. Our example represents a worst-case consideration, since the thermal expansion coefficients of quartz glass (fused silica) and GaAs differ by almost 1 order of magnitude. For substrate materials other than quartz glass, the value for \( \beta_1 \) might be closer to \( \beta_2 \), therefore allowing larger substrates to be bonded together.

For the use of our imaging setup as a parallel data link for chip-to-chip communications in a VLSI system, we have to consider integration with a silicon substrate. The basic configuration might appear as shown in Fig. 8 with the Si wafer as the motherboard. Again, bonding of the various layers could be achieved by a flip-chip technique. It would be appealing if the laser chip and the detector array could be recessed into the Si substrate or be an integral part of it, respectively. This might require the etching of an area equivalent to the laser chip size into the Si substrate and bonding of the chip in that recessed area. In that case, another technique, called thermal anodic bonding, might be used to integrate the glass with the Si substrate.

Other parameters of interest for a high-speed communication link are the required power to drive the lasers and the dissipated heat. At the moment, threshold currents of the top-surface-emitting lasers are in the ranges 2–5 mA and 4–5 V. This means that a single laser requires 10–20 mW of electrical power. Accordingly, the spacing and the number of the lasers in an array are limited by the thermal load. However, there is still room to reduce the threshold current by 1 order of magnitude, and currently research efforts are focusing on this goal.

IV. Summary and Further Outlook

We have described the use of surface-emitting microlasers and integrated imaging systems for implementing optical interconnections with a high interconnection density. Applications for this scheme might exist in chip-to-chip communications in a VLSI system or in an optical computer. Another possibility of using two-dimensional arrays of microlasers might be to send optical power beams to arrays of (self-electrooptic effect) devices in an optical processor or switching system. The optical interconnections might also be implemented by using lenslet arrays in which each pixel is assigned its own optical imaging system. Lenslet-array-based systems have been investigated recently and could potentially be useful in context with the "smart pixel" concept.

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Fig. 6. Thermal effects on diffractive lenses and gratings.

Fig. 7. Flip-chip solder bumping for hybrid integration.

Fig. 8. Hybrid integration of an integrated optical system on a silicon substrate.
More work is necessary to improve the performance of the system. This holds particularly for light efficiency, which needs to be improved. High-resolution lithography, such as electron-beam lithography, as well as holographically formed optical elements might be useful for that purpose. Finally, and most importantly, the issue of hybrid integration requires attention. This problem is important not only to the system and application described in this paper but to a wide variety of optoelectronic systems.

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References and Notes


