Planar Packaging of Free-Space Optical Interconnections

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Invited Paper

Planar optics is an approach to build integrated free-space optical systems on single substrates. Computer-aided design, lithographic fabrication, and micro-bonding techniques are used to package the optics in a compact way. This paper reviews recent work on planar optics. It discusses various aspects of the fabrication, the design, and the application of planar optics as an interconnection technology for optoelectronic computing and switching systems.

I. SHORT-DISTANCE COMMUNICATIONS USING FREE-SPACE OPTICS: PROMISES AND PROBLEMS

For data communications over long and medium distances, optical fiber transmission has become the dominant technology in the past ten years (Fig. 1). For short and very short distances, however, i.e., in the range of a few meters down to a couple of millimeters, physical advantages of optical communications have been offset until now by technological disadvantages. As a consequence, optics has not been able yet to make a breakthrough in areas such as chip-to-chip and board-to-board communications. Nonetheless, there exists a continued interest to remove the technological barriers and make use of the fundamental advantages of optical communications. Unlike electric signals, light beams do not suffer from electromagnetic interference and signal frequency-dependent attenuation. For free-space optics, the possibility of transmitting many channels in parallel with high densities is of interest. This property may be useful, for example, to transmit thousands of channels between the chips of a multiprocessor and thereby alleviate the communication problems that begin to plague all-electronic computers [1]–[3]. In order to tap that potential, suitable input/output devices and practical packaging schemes for free-space optics need to be developed. Both areas have been addressed during recent years in the research on optical computing, photonic switching, and optical interconnections [4], [5]. On the device side, the main requirements are high speed and low power consumption. The latter point is especially crucial for two-dimensional device arrays with high densities for which thermal dissipation is an important issue. On the packaging side, problems arise because of the usually tight tolerances that optical systems have to satisfy. For practically all photonic applications, one or several of the following requirements must be met: precise alignment in the micrometer or submicrometer range, mechanical robustness, and temperature stability. In addition, these requirements usually have to be satisfied at low cost. The difficulty of achieving this goal with conventional optomechanical technology has so far been a major stumbling block for the use of photonics in many different areas. This is true in particular for interconnection applications, where the usually bulky optomechanics makes it impossible to fit the optics into the highly integrated world of microelectronics.

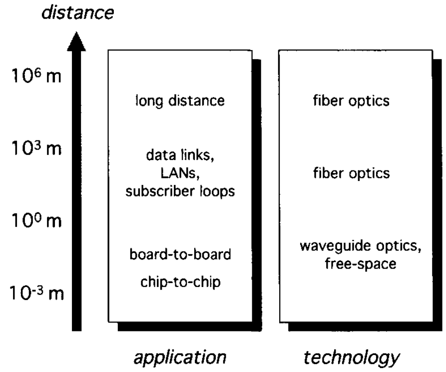

Fig. 1. Hierarchy of optical communication applications and technologies.

Consequently, there is a need for an optical manufacturing and packaging technology that is fundamentally different from conventional optomechanics. "Planar optics" was proposed as an approach that makes strict use of standard microfabrication techniques [6]. The basic idea of this approach is to fold three-dimensional optical systems into a two-dimensional geometry and integrate them on a single substrate with the light signals traveling inside the

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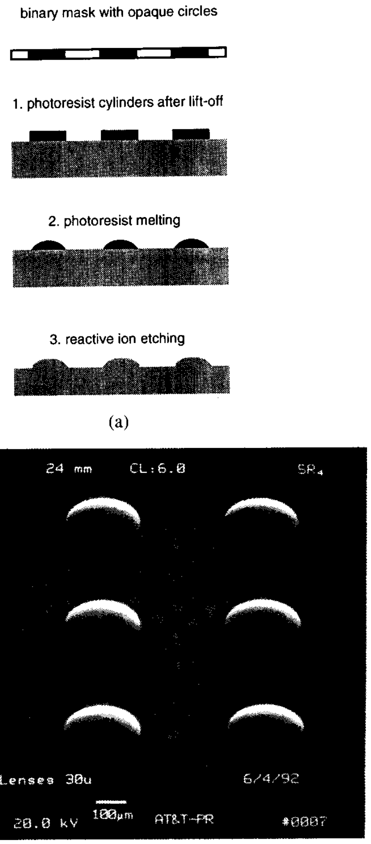
substrate. The two-dimensional layout is important since it makes the optics compatible with planar manufacturing techniques such as lithography, dry etching, thin film deposition, etc., [7]. In addition to these microstructuring techniques, bonding techniques such as flip-chip bonding can be used to combine the passive micro-optics with optoelectronic and electronic chips.

Planar fabrication techniques have been demonstrated successfully in the fabrication of micro-optic components. We will give a brief overview of micro-optics in Section II. The planar optics concept builds on the micro-optic technology and extends it towards the systems level. We will describe the concept of planar optics in Section III and show various experimental demonstrations in Section IV with an emphasis on interconnection applications. In order to give the reader an overview of the various projects, the presentation is descriptive in style rather than analytic. Numerous references are provided that the interested reader may consult for details.

II. MICRO-OOPTICAL ELEMENTS FOR PLANAR OPTICS

Micro-optics is a broad term that comprises passive and active optical or optoelectronic elements or devices. Passive micro-optical elements include microlenses, beamsplitters, computer-generated holograms, etc. As in conventional optics, passive micro-optical elements can be classified as refractive, reflective, diffractive, and combinations thereof. Examples of active components are multiple-quantum-well modulators and miniature light sources such as vertical cavity surface-emitting lasers (VCSEL's) and photodetectors such as metal–semiconductor–metal detectors. The goal of this section is to give a brief overview of micro-optic components for free-space optical applications and convince the reader that micro-optics has reached a mature status that allows one to think of systems applications. The overview is not very deep in the description of the physics or fabrication of the components nor complete in presenting the whole spectrum of micro-optic elements. The interested reader will find useful literature in [8] as well as the references given below.

Refractive Microlenses: Several techniques exist to make refractive microlenses. The miniaturized version of the classical convex refractive lens can, for example, be fabricated by patterning a substrate (usually, fused silica or silicon) with little cylinders of photoresist. Upon melting of the photoresist, mass transport and surface tension mechanisms minimize the surface area of the photoresist resulting in an approximately spherical shape [9]–[11]. The resist droplets can be transferred into the substrate by using reactive ion etching. An example of an array of refractive microlenses is shown in Fig. 2.



(a)

(b)

Fig. 2. Array of refractive microlenses (courtesy K. Mersereau and C. Nijander, AT&T Bell Laboratories).

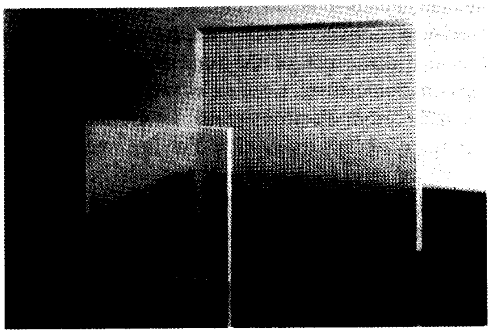


Fig. 3. Microscope picture of planar gradient-index microlens array (courtesy M. Oikawa, Nippon Sheet Glass, Inc.).

Refractive microlenses can also be made by using a gradient index profile inside a glass substrate [12], [13]. The fabrication of gradient-index lenses is based on ion diffusion and ion implantation technology. This technique allows one to make lenses with a flat surface, a feature that can be useful to package components, and imaging systems with a magnification of +1 with a single component [14]. This latter property is exploited in the optics of one-dimensional line scanners. A microscope photograph of a planar GRIN lens array is shown in Fig. 3.

Diffractive Micro-optics: Diffractive micro-optics is based on the use of computer-generated patterns that are transferred onto a substrate by etching or thin film deposition. In order to achieve high light efficiencies, diffractive elements are implemented with multiple discrete phase levels [15] or with continuous sawtooth-like phase profiles [16]. The wide range of patterns that can be

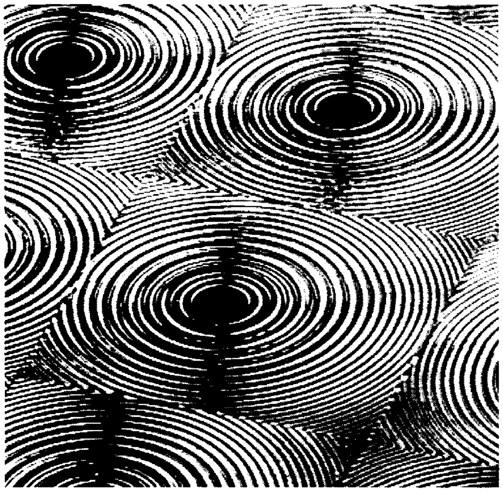


Fig. 4. Scanning electron microscope picture of diffractive lenslets.

generated results in a large variety of functions that one can realize with diffractive optics: it is possible to implement diffractive lenses [17], beam splitters and deflectors [18], polarization components [19], antireflection coatings [20], etc. A photograph of a diffractive lens array made with multiple discrete phase levels is shown in Fig. 4. The design flexibility is enhanced by the large variety of substrate materials that can be used as well as by advanced fabrication techniques including direct write techniques with electron or laser writers and by replication techniques.

In comparison to refractive elements, diffractive optics exhibit a stronger wavelength dispersion and always have an efficiency smaller than one because of light lost to unwanted diffraction orders and scattering. Various fabrication errors may contribute to the losses [21].

Reflective micro-optics are of particular interest for planar optics. Refractive and diffractive micro-optic elements can be used in reflection by backcoating them with a metallic or dielectric mirror. Although the fabrication is the same as for transmissive elements, the physics of transmissive and reflective elements is different due to different boundary conditions [22]. This results in the fact that reflective-diffractive elements perform better in terms of their efficiency and aberration properties than transmissive-diffractive elements, as it was demonstrated by Shiono and co-workers [23]. The same group recently also reported purely reflective microlenses for planar optics that were fabricated by direct electron beam writing [24].

Vertical Cavity Surface-Emitting Lasers: The surface-emitting geometry of VCSEL's makes them attractive components for use in free-space optical interconnection systems [25], [26]. One- and two-dimensional arrays with arbitrary geometries can be realized. A two-dimensional 10 × 10 array of VCSEL's is shown in Fig. 5. VCSEL's have been demonstrated with high optical output power of several milliwatts at CW operation, high speed of up to 10 GHz, high temperature (> 130°C), and low voltages (<2 V) [27]. They operate in the wavelength range from 780 to 980 nm. A particular problem that needs to be considered for optical interconnections is the addressability of large arrays. Matrix-addressing schemes have been demonstrated [27], but are too slow for parallel interconnects. Optical addressing may be a solution for this problem but requires the integration of a detector device with each individual laser and has been demonstrated only for small arrays [28]. Nonetheless, the ease of operation in an optical system makes VCSEL's highly attractive components.

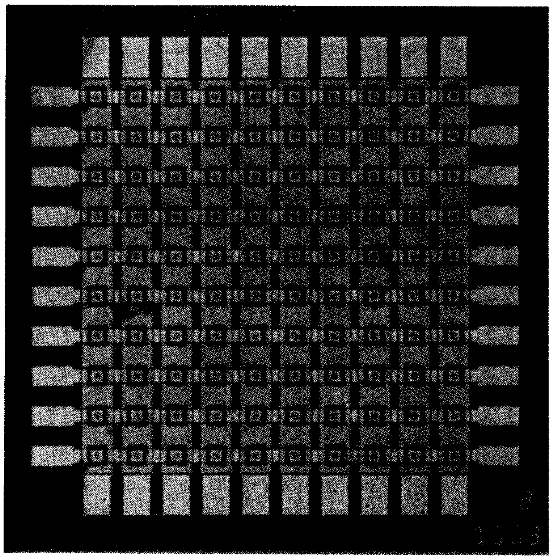


Fig. 5. 10 × 10 array of vertical-cavity surface-emitting lasers (courtesy R. A. Morgan, AT&T Bell Laboratories).

Multiple Quantum-Well Modulator Devices: The use of multiple quantum-well modulator devices made of GaAs for use at 850 nm has been studied by various groups, see, for example, [29]–[33]. A particular device that was also used in system experiments for optical computing and photonic switching [34], [35] is the SEED (self-electrooptic effect device) modulator. Functionality and electronic gain can be added by monolithic integration of the modulators with GaAs field-effect transistors [36]. These "smart-pixel" FET-SEED's were demonstrated to operate at 500 Mb/s with optical input switching energies of 400 fJ [37].

A specific aspect of modulator devices is the fact that they require special optics to write information to and read it from the devices. This requires the use specially designed components for spot array generation (for example, "Dammann gratings") and efficient techniques for beam splitting and beam combining [39].

III. FROM "FAT WAVEGUIDES" TO "FLAT OPTICS"

Planar optics (or sometimes called "flat optics") addresses the specific issue of packaging free-space optical interconnections. There exist several forerunners to the planar optics concept that we want to review briefly in this section.

In the mid-1980's, Hase [40] suggested and demonstrated the use of optical broadcasting for chip-to-chip commu-

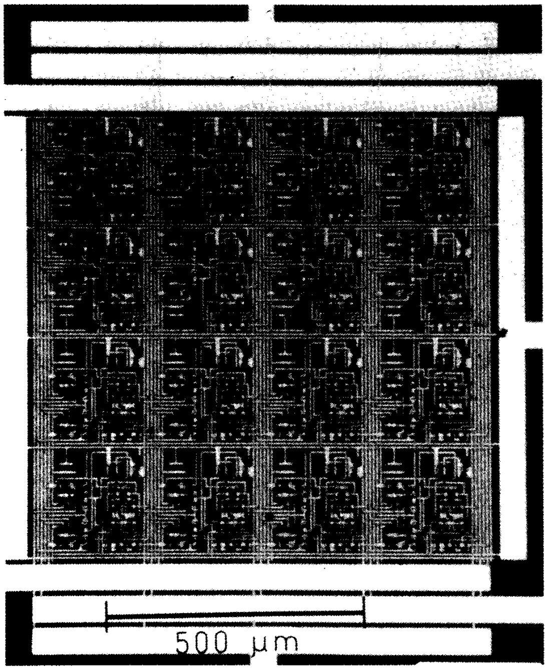


Fig. 6. 4 × 4 smart-pixel array in FET-SEED technology (courtesy T. Woodward, AT&T Bell Laboratories).

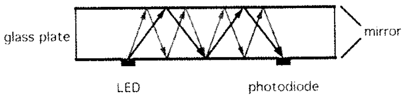


Fig. 7. Optical backplane implemented by broadcasting light inside a glass substrate according to Hase [40]. Different light paths from the emitter to the detector are indicated by different shades of the light rays.

nications inside a thin substrate of glass (Fig. 7). Light from a light-emitting diode (LED) is sent into the substrate and broadcast to one or several detectors that can be positioned at arbitrary locations on the surface of the glass slab. Physically, the substrate acts as a "fat waveguide" in which the light can propagate in a large number of modes. Emitters and receivers can be placed on the substrate surface in a two-dimensional (2D) configuration. The virtue of this scheme is its simplicity. There are practically no requirements to the quality of the glass plate nor to the alignment of the emitters and receivers. However, the setup also has inherent weaknesses. First, the mechanism for coupling the light in and out of the waveguide is inefficient resulting in weak light signals detected at the receivers. Second, due to the thickness of the glass plate and the nondirected transmission of the light signals, there is considerable mode dispersion that broadens the pulses and therefore limits achievable data rates. Third, due to the broadcasting in a shared communications medium, without using multiplexing techniques only one emitter can talk at a given time. All of these disadvantages limit the data throughput of the broadcast approach.

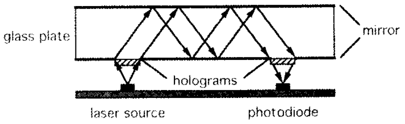


Fig. 8. Holographic optical interconnect using directed light propagation inside a substrate according to Sauer [41].

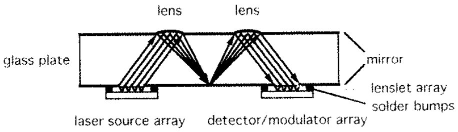


Fig. 9. Parallel planar optical interconnections using micro-optical elements and optoelectronic chips integrated onto the substrate.

Some of the limitations of Hase's scheme are eliminated by going from an undirected to a directed way of transmitting the light signals [41]–[43]. This is achieved by using volume holograms for collimating and focusing of the light beams (Fig. 8). The holograms improve the coupling efficiency significantly and eliminate modal dispersion. In addition, due to the directed propagation of the light signal, many signals can be sent through the substrate simultaneously by using a suitable 2D layout. However, limitations still remain: first, only relatively low interconnection densities can be achieved since each light beam requires its own pair of holograms. Therefore, the density of the optical channels is limited by the density of holograms. The second problem is related to the packaging of the optics: the directed way of transmitting signals requires precise alignment of the emitter/receiver board relative to the glass plate so that the light signals can hit the detectors at the output. In the experiments, this was achieved with conventional mechanical mounting and alignment which is expensive and results in bulky setups. Thirdly, the use of volume holographic elements is not very practical because of a wavelength mismatch between the recording and the replay wave. The recording of volume elements has to be done at relatively short wavelengths of less than 500 nm whereas the interesting wavelengths for interconnections lie in the near-infrared.

The general importance of the alignment, integration, and packaging of free-space optical sytems was pointed out in [6]. Planar optics was suggested in order to make free-space optics compatible with the manufacture of integrated circuits. The use of lithographic fabrication and microbonding techniques eliminates alignment problems. One might consider the planar optical system shown in Fig. 9 as a combination of the broadcast system of Fig. 7 and the directed system of Fig. 8. Light transmission is directed, but as in the broadcast system, the substrate is also used as a mounting plate or backplane for optoelectronic devices. Instead of routing single light beams with single holograms, optical imaging systems are integrated on the substrate that allow one to transmit many signals in parallel at high densities. The need for mechanical alignment is eliminated since all components are monolithically integrated onto a single substrate. In the next section, the planar optics concept will be discussed in more detail.

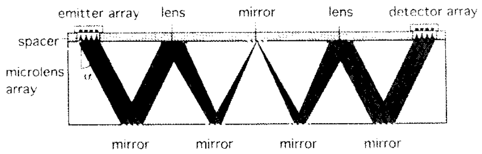


Fig. 10. Planar–optical interconnect using a hybrid imaging system. A spacer with windows for the light signals is used to provide the physical separation between the input and output devices and the optical substrate. The spacer might be a Si wafer with a thickness of a few hundred micrometers thickness matched to the focal length of the microlenses.

IV. Planar Optics: Three-Dimensional Optics with a Two-Dimensional Geometry

In this section, we will discuss briefly the merits of the planar optics concept and review some of the experiments that were performed so far.

A. General Considerations

Folding the optics into a two-dimensional geometry makes it compatible with the planar fabrication techniques that are used for the processing of integrated circuits. It also allows one to use surface-mount technologies to place optoelectronic chips on the substrate surface. The chips are therefore accessible for handling, cooling, testing, and repair purposes. The substrate may be either glass or a semiconductor material such as silicon or gallium arsenide provided it is transparent at the used wavelength. Substrates with a thickness of several millimeters are used in order to allow for laterally unguided free-space optical light propagation along a zigzag path as indicated in the figure. It is important to note that planar optics is free-space optics. Although the light is confined to propagation inside the substrate, it is not confined in the direction lateral to its propagation direction.

The surfaces of the substrate including the optical components are coated with a reflective (metallic or dielectric) layer to keep the light inside the substrate. Only the optical windows that are used to to couple light in and out of the substrate are transmissive. The fact that the light signal experiences only very few interfaces between different media, makes the optics insensitive to environmental influences such as dust and humidity. The light propagation inside the substrate is controlled by lenses, beamsplitters, and beam deflectors that are etched into the substrate surface at well-defined positions with submicrometer precision. All components on one side of the substrate can be fabricated simultaneously using optical lithography. Replication techniques might be used to mass-produce the systems thereby making the optics inexpensive.

Optical elements on the top and bottom surfaces of the substrate can also be aligned relative to each other with submicrometer precision by using a simple through-wafer alignment technique [44]. Due to the integration on a single substrate and the light propagating inside the substrate, mechanical and thermal stability are very good [45]. The systems are compact and require a considerably smaller volume than conventional optical systems. For example, an integrated system with dozens of optical elements was demonstrated on a substrate with a diameter of 25 mm and a thickness of 3 mm [46] (see Fig. 14).

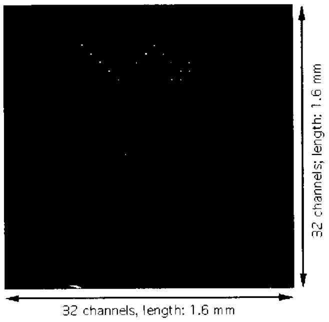


Fig. 11. Experimental result of the integrated system with 32×32 channels. 17 of the 1024 channels are illuminated in this picture. To indicate the physical size of the array, the lenslets were back-illuminated in the photograph. The channel separation is 50 μm in each direction.

B. Optical Imaging in Planar Optical Systems

For the implementation of high-density interconnections, it is necessary to use optical imaging which allows one to send many light signals through a single lens or system of lenses. For imaging purposes the folded optical setup of planar optics poses a problem because of aberrations. These are introduced by the angle that the folded optical axis forms with the substrate normal which typically ranges between 5° and 30°. However, by suitable design of the optics it is still possible to achieve good imaging properties and high interconnectivity. A specific approach is the use of a "hybrid imaging system" [47]. An integrated version is depicted in Fig. 10. Here a conventional imaging system is combined with microlens arrays that are positioned close to the input and output arrays. Each microlens provides collimation and focussing for a single optical channel. Thereby, the big imaging lenses need to have only relatively small numerical apertures that suffer less from aberrations. The concept of hybrid imaging was demonstrated with discrete [48] and integrated [49] optics. In the planar optical version, the imaging lenses were implemented as diffractive elements with slightly elliptical phase profiles to minimize aberrations. An experimental result is shown in Fig. 11. Seventeen of the 32×32 channels are illuminated while the others remain dark. The pixel spacing is 50 μm in each direction. Good crosstalk suppression between channels was measured ($>$ 23 dB). In this specific experiment, the lateral separation between the input and output areas on the substrate surface is 18.6 mm. The substrate thickness $h =$ 6 mm. The distance for the travel of the light inside the substrate is 97.7 mm. This corresponds to a delay time of 0.48 ns for the travel from the input to the output plane.

The system demonstrated in [49] implemented 1024 data channels. The maximum number of channels depends on various parameters such as substrate thockness h, the channel spacing, etc. For parameter values that were in the experiment, we estimate that several thousand chan-

Fig. 12. Surface-emitting microlaser chip integrated on planar optical substrate using the flip-chip bonding technique. The planar optics was designed to implement a simple interconnect which provides crossovers between pairs of input beams. For example, light from the third laser from the bottom is sent to the fourth output window as shown in the figure. Individual lasers are addressed by contacting metallic wires on the glass substrate with a probe. Ten channels with a lateral separation of 507 μm are implemented in this experiment.

nels could be implemented. Also interesting is the scaling behavior of the planar optical system. Based on simple considerations it is possible to show that the number of channels grows with h^2, or, as a function of the system volume V, with $V^{2/3}$ [49]. These relationships are typical for free-space optics. For comparison, we may consider that several layers of electronic or waveguide optical interconnects are stacked onto each other. In that case, the number of interconnections would only grow linearly with the number of layers and the thickness of the stack.

C. Hybrid Integration of Optoelectronic Chips

In order to build optoelectronic systems with a high functionality the integration of active functions has to be considered. Optoelectronic chips can be mounted on an optical substrate by using hybrid integration techniques such as flip-chip solder bump bonding [50]. This technique allows one to achieve a precision of a few micrometers or less in the lateral positioning of the chip relative to the substrate. Typical solder materials that are used are PbSn, AuSn, or In. A solder bump pitch of 50 μm and less has been achieved although issues such as the reliability of the connections remain an issue. The solder bump height is usually on the order of a few micrometers. Reflow of the solder bumps can be used to achieve submicrometer alignment precision [51]. As it was already mentioned above, the surface-mounting of the chips on the substrate might prove useful for handling during the manufacturing of a system as well as for cooling during operation and testing.

In a recent experiment, flip-chip bonding was demonstrated as a useful technology for planar optics [52]. In that experiment, a one-dimensional array of VCSEL's was mounted on a quartz glass substrate into which an optical interconnect had been etched. Figure 12 shows a top view of the chip mounted on the substrate. Ten parallel channels were demonstrated with a channel separation of approximately 507 μm. Higher interconnection densities with more optical channels are feasible, for example by using the hybrid imaging system. The alignment precision between the VCSEL chip and the substrate was within ±2 μm. The solder bumps were 90 μm × 90 μm in area with a height of approximately 5 μm. The indium bumps were deposited on the substrate using electron beam evaporation and a liftoff technique.

D. Clock Distribution

Clock distribution on a chip, between chips, or between boards is an application that becomes increasinlgy difficult in electronics as signal speeds increase [2]. Since the transmission lengths in a clock distribution system are relatively large, the dissipated electrical power in the line drivers becomes significant at high speeds. Furthermore, timing jitter caused by active elements used in the distribution system for signal amplification can accumulate and result in clock skew between different outputs. Passive optical distribution of a clock signal does not suffer from these problems and may also be superior because of reduced power requirements [53].

Both, waveguide-optical and free-space optical clock distribution schemes have been discussed [54], [55]. As opposed to a waveguide implementation, a planar optical implementation can provide both the clock distribution and high-density interconnects. Furthermore, the coupling of the signals in and out of the substrate is easier and more efficient than the coupling in and out of a waveguide.

The basic building block of a planar optical clock distribution scheme is shown in Fig. 13(a) [46]. A cascade of N 1×2 beamsplitters is used to split up a signal into 2^N output beams. The beamsplitters are implemented as binary diffraction gratings designed to generate only two diffraction orders. Grating beamsplitters have been demonstrated with high diffraction efficiencies of more than 95% [46].

Figure 13(b) shows a large H-tree for clock distribution based on the use of the 1×4 system of Fig. 13(a). The maximum fanout of such a system is determined by power budget considerations and hence by the light efficiencies of the optical elements used in the systems. In particular, for systems in which the light travels large distances and many reflections are used, the reflectivity of the mirrors becomes significant [46]. It is estimated, that fanouts of 64 or more could be achieved for a distribution system between different chips. In an experimental demonstration, a planar optical signal distribution system with a fanout of 1×8 was shown (Fig. 14).

E. Optoelectronic Multichip Module Using Planar Optics

In this section, we would like to indicate the systems potential of planar optics. Based on different functions presented above, one could envision an optoelectronic multiprocessor as visualized in Fig. 15. Chips with optical input and output devices are mounted in a regular fashion onto a wafer-size substrate and interconnected optically. The chips might be implemented as all-GaAs chips with integrated optical and electronic functions as demonstrated with the FET-SEED's described earlier. Another possibility is the use of hybrid structures where the electronics is implemented in Si and the optical input/output functions in GaAs. Again, flip-chip bump bonding can be used to

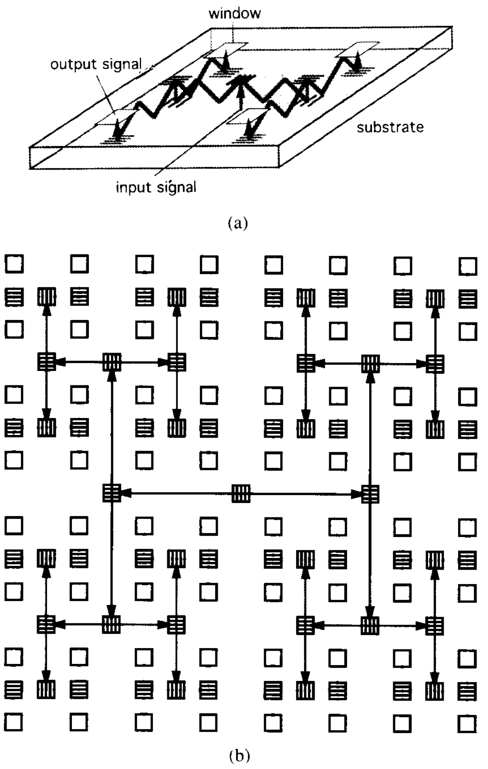


Fig. 13. (a) 1 × 4 signal distribution in a planar optical substrate using a cascade of beamsplitter gratings. (b) Top view of a 1 × 64 distribution system using a cascade of three 1 × 4 stages. The different shades of the light signals as they propagate from the center position to the output windows indicate the different stages.

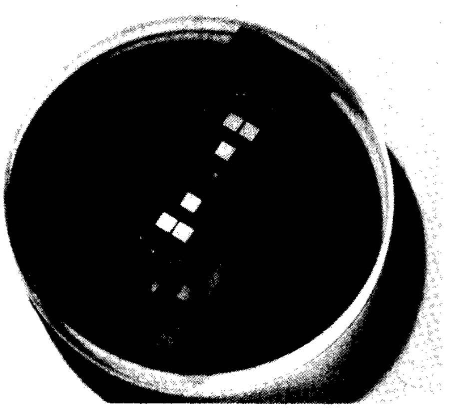


Fig. 14. Photograph of a planar optical clock distribution experiment with 8 outputs. The substrate thickness in this experiment is 3 mm, the diameter is 25 mm. Etched into the top surface and coated with a metallic layer are beamsplitter gratings and lenses. Square-shaped output windows can be recognized in the upper right and lower left of the substrate.

integrate the two chips. The system shown in Fig. 15 might be useful, for example, to implement an MIMD processor with a mesh architecture and parallel interconnections between nearest neighbors [56]. Interconnections with 1000 or more channels can be provided using the concept of hybrid imaging. The signal distribution system described in the previous section can be useful to provide a clock signal or other broadcasting functions. Time delays for the data transmission between neighboring chips might be on the order of a few tenths of a nanosecond which would allow for a clock speed of 1 GHz or more.

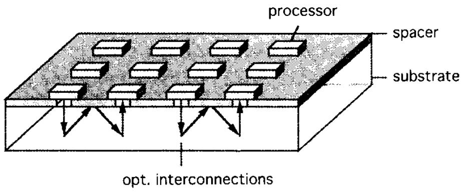


Fig. 15. Scheme of an optoelectronic multichip processor using planar optical interconnections for communications and clock distribution.

F. Thermal and Packaging Considerations

A specific aspect of integration is the thermal management. Particularly if large device arrays of 32 × 32 channels are used, the power dissipated on a single chip may be on the order of several watts. Efficient ways of removing the heat have to be included in the overall packaging scheme for the interconnects. A specific approach to accomplish this in the planar optics scheme was described recently [57]. A wafer between the planar optical substrate and the chips serves two purposes (see Fig. 10): first, it acts as a spacer to provide the required distance between the emitters and detectors and the lenses used for collimation and focusing, respectively. Second, it is used to spread the heat generated in the chips. A silicon wafer might serve this purpose. The windows required to transmit the light signals can be etched into the Si by using well-known micromachining techniques [58]. In order to integrate the Si onto the glass wafer thermal anodic bonding might be used [59]. It is important to use materials with a good thermal match such as, for example, Si and pyrex glass. The optoelectronic chips can be mounted onto the Si using flip-chip bonding as discussed earlier. The use of pyrex as the material for the passive optics, however, poses another problem. Pyrex is not well suited for conventional reactive ion etching. Hence, other techniques such as, for example, ion-beam milling or chemically assisted ion-beam etching have to be considered for making the optics.

As for the heat removal itself, various techniques can be considered. However, the cheapest and simplest heat sinks, air cooling and radiation, are both limited to fluxes well below 0.1 W/cm^2 and therefore probably not adequate. Liquid and thermoelectric cooling systems typically allow heat fluxes up to 10–100 W/cm^2. Heat removal in excess of 1300 W/cm^2 has been demonstrated using microchannels etched into Si [60]. Generally speaking, the problem is to spread the dissipated heat over a sufficiently large area so that the heat can be removed by a convenient sink such as the Si or diamond layer that was mentioned earlier. For this reason, the use of highly conducting synthetic diamond films could become interesting provided the layers can be made thick enough [61].

V. CONCLUSION AND OUTLOOK

Free-space optics achieves naturally what is very difficult for electronics and waveguide optics; namely, the use of the third spatial dimension. By using the third dimension, one can achieve a higher interconnection density and thereby comply with Rent's rule [62] that requires a certain number of pins for a given number of gates on a chip. Furthermore, the use of the third dimension may allow system designers the possibility to optimize the layout of a specific system by placing interconnections pins at arbitrary positions on a chip.

Planar optics is a systems technology for free-space optics that is compatible with IC manufacturing which emphasizes the importance of packaging. Areas of applications are digital optical computers, free-space optical switching systems, optical interconnections for electronic computers, optical backplanes and buses [63]–[66]. Other potential applications include pickup heads for optical data storage [67], integrated optical sensors [68], and compact analog optical correlators [69].

A relatively new technology like planar optics still requires several issues to be solved in detail. These include, for example, issues related to the fabrication of the micro-optical components, the design of specific interconnections, and, maybe most importantly, low-cost implementations of planar optical interconnections. Another topic that was already mentioned is the problem of thermal management. Despite the difficulties that still have to be overcome, we currently do not see any fundamental "walls" that would prevent planar optical interconnections from becoming a reality. The payoff would be high. As compared to conventional optomechanics, planar optics has a chance to fit into the world of integrated circuits. It offers higher interconnection densities and more compact implementations than integrated waveguide optics. Finally, it allows one to take advantage of the features that optical signal transmission offers over electronic transmission.

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