Integration strategies for micro-optical systems

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ABSTRACT

A wide variety of integration strategies for micro-optical systems have been employed. Here we review some of these and comment on their relative strengths and weaknesses. In particular we compare approaches that are based on monolithic fabrication with those that make use of discrete components. As applications we consider free-space optical interconnects, telecommunications optical space switches and radiation mode interconnects for optical waveguides.

Keywords: Micro-optics, optical interconnects, alignment, planar optics, diffractive optics

1. INTRODUCTION

Micro-optical systems find application in many important areas of technology, including telecommunications, computer interconnects and biomedical sensing. Here we use 'micro-optical' to include any system in which light propagates as an unguided wave in at least part of the system, and where the optical beams have dimensions of microns to millimeters. Computer interconnects typically require parallel point-to-point links, and examples of such systems include intra-chip links[1], interchip links[2] and interboard systems[3,4], where light is relayed via either single channel microlenses or microlens image relays. However, a point-to-point link can also incorporate a complex remapping of the parallel data array, as demonstrated in reference [2] in order to perform information processing tasks. In telecommunications systems this ability to perform a remapping of a one or two dimensional array is taken further by incorporating micro-electromechanical systems (MEMS) technology mirrors to enable dynamic remapping. This can form the basis of an optical space switch [5,6] or dynamic wavelength add-drop multiplexer [7]. In all of the systems described above, there is a need to align one or more optical surfaces together, to high precision. A successful alignment and integration strategy is essential in order to reduce the size of optical components, to increase the functionality of optical microsystems and to deliver robust and reliable devices. Here we will review a range of approaches for the alignment and packaging of micro-optical systems and we will focus particularly on techniques which do not require monolithic fabrication. Free-space optics can also be employed as an integration technique for guided wave systems, and a number of researchers have demonstrated the use of surface outcoupling gratings to inject or extract light from waveguides [8,9]. We will also consider this approach and will describe the way that it can be used to realize extremely compact interconnects which are compatible with single mode waveguides.

2. INTEGRATION STRATEGIES FOR FREE-SPACE OPTICS

Many studies have been published on the accuracy requirements that are necessary for free-space optical interconnects [10-14]. Essentially the challenge is to hit a small detector with a beam that must be collimated over a long distance. Any angular error at the transmitter will very quickly cause the beam to miss the detector. Although tolerances can be improved by using (for example) clustered designs [15,16], field lenses [14,17] or Gaussian relays [18], typical lateral tolerances for interconnect distances of 10-100 cm are 10-100 μm, with angular tolerances of 10-500 arc minutes [14]. The interconnect system packaging is required to satisfy this tolerance.

The earliest free-space optical interconnect systems were packaged using discrete components and commercial mounts. Over time this approach gave way to the use of custom machined baseplates which allowed very complex systems to be

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constructed (see Figure 1(a)) [4,19,20]. However, whilst this approach was well suited to 'demonstrator' systems, it was not obvious whether it could be extended to a manufacturable system. Many of these systems required adjustable components such as Risley beam-steering prisms or steerable mirrors in order to compensate for machining tolerances or packaging errors of optoelectronic devices. One approach which avoided the need for these precisely machined systems was to design an interconnect which had a high inherent tolerance to misalignment (±1 mm and ±1° over 20 cm) by using expanded beams and redundant detectors [21]. However this was achieved at the expense of interconnect capacity.

To develop free-space interconnects beyond this point required the use of components that have a lithographically defined accuracy, rather than an accuracy determined by machining precision. One approach is to use LIGA (Lithographic Galvonoformung Abformung, or electroplating and molding), or other three-dimensional microfabrication or prototyping techniques. In these techniques the optical interconnect is fabricated from a single material which is then used as a master for mass-production in a moldable polymer via injection molding. An example of this is described in reference [1] where an optical bridge which interconnects two 2 x 8 arrays of optical channels over a distance of 5 mm is presented (see figure 1(b)). The element is approximately 5 x 6 x 2 mm in size and is fabricated in poly methylmethacrylate (PMMA) which is exposed to a proton beam. As the piece is moved through the beam in three-dimensions the necessary surfaces are formed as the proton beam modifies the cross-linking of the polymer. Exposed regions are removed in a subsequent development process. This approach is very powerful in that all of the optical surfaces are aligned to each other with an accuracy that is limited only by the precision of the positioning system that is used to move the work piece through the beam. Typically this process also yields optically smooth surfaces (down to 20 nm [1]). However there are limits in terms of the thickness of material that can be machined this way (due to absorption of the beam), the size of the total piece and also to the types of shapes that can be fabricated. However it has been shown that it is possible to fabricate 'lock and key' alignment features that allow several of these 3-D components to be assembled together.

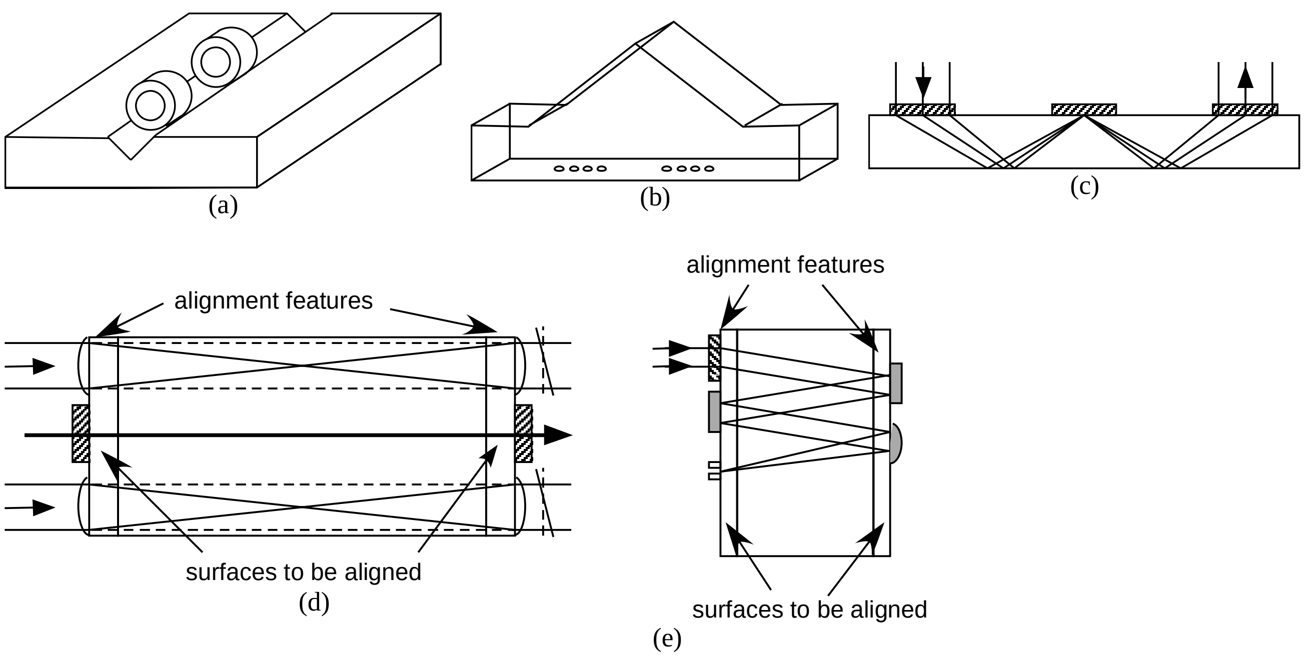

Figure 1. Examples of optical integration strategies. (a) Baseplate approach; (b) Component fabricated by 3-D micromachining (after [1]); (c) Planar optics component (after [22]); (d) Interferometrically aligned relay lenses (after [24]); (e) optically aligned component (after [27])

A second way to make use of lithographic precision in the assembly of optical interconnects is to use the 'planar optics' approach [22,23]. Here a thick (1-10 mm) transparent substrate is patterned with diffractive or refractive optical components on the top and the bottom, using standard microlithographic procedures and with a high precision mask aligner to ensure that features on the top surface are aligned to features on the bottom surface (see Figure 1(c)). This is a powerful approach that enables quite complex systems to be developed. Its chief limitations are that all the optical components are, by definition, off-axis, and that the maximum interconnect distance is limited by wafer size that can be supported by the microlithographic system that is employed. As with the 3-D micromachined elements, these components too could be reproduced in volume via LIGA techniques.

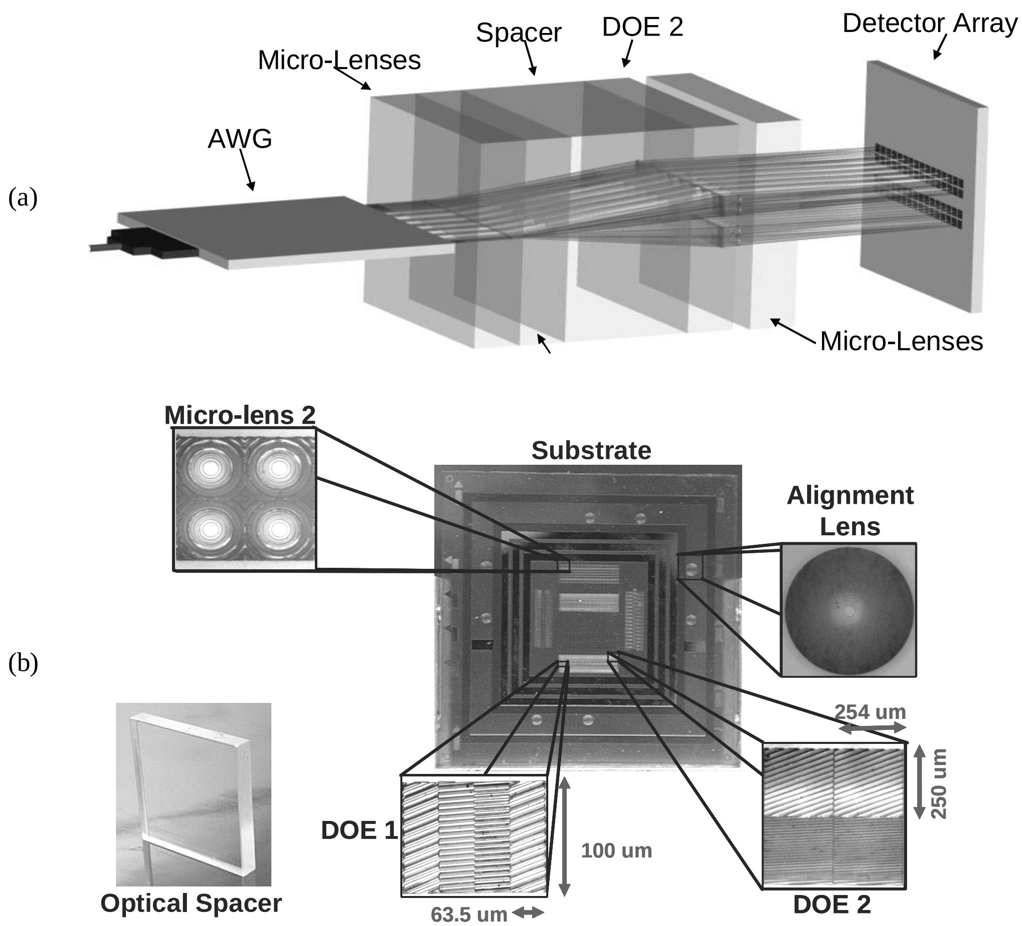

Figure 2. Multielement optical component that performs 1-D to 2-D optical channel reformatting. (a) Schematic design; (b) Layout of diffractive elements (DOE: diffractive optical element; AWG: array waveguide)

A related approach is to fabricate the various optical components separately and then use optical alignment techniques to ensure precise assembly. The first example of this technique was the use of interferometric alignment lenses for the alignment of optical relays [24] (see Figure 1(d)). The diffractive lenses at the edges of the relay lenses create interference between the zero-order and first order beams, resulting in fringes that are only flattened when the lenses are precisely aligned. The lenses are glued to a spacer after alignment. This approach can deliver alignment tolerances of 1-5 microns for device plane separations of 30 mm [24]. This concept has been extended to include off-axis alignment gratings and lenses which can provide alignment information about all 6 degrees of freedom [25] and most recently to designs that provide diagnostic information on the state of alignment (via the creation of focused beams on targets) which could be used for automated assembly[26,27] (see Figure 1 (e)). An example of a component assembled using these techniques is shown in Figure 2. This particular device is designed to reformat a 1-D array of 64 channels on a 62.5 μm pitch (each of which is a unique wavelength in a dense wavelength division multiplexing (DWDM) optical telecommunications system) into a 2-D array of 16 x 4 beams on a 250 μm pitch. The reformatting is done by the use of beam-deflecting gratings which must be aligned together to high precision. This device could again be replicated via molding after initial assembly. This approach combines the accuracy of lithography with the flexibility of discrete components, but can result in complex designs and mask sets.

A final approach that must be mentioned is the use of integrated micromechanical elements to provide realignment after assembly. This approach is already used in the assembly of some commercial telecommunications switches which are based on beam-steering micromirrors. Obviously this approach is less attractive if the mirrors are not already required as part of the system. However a similar approach is to incorporate built-in micro-machined actuators to reposition components such as optical fibres [28], microlenses [29] or micromirrors [30] after assembly in order to minimize insertion loss. Once alignment has been achieved the moving components can then be locked into place with a suitable adhesive.

3. INTEGRATION STRATEGIES FOR GUIDED WAVE DEVICES

At first sight it may not seem meaningful to discuss integration strategies for guided wave devices such as planar waveguides, as these are already considered to be an integrated technology. However here we will consider to integration-related aspects of this technology which require free-space micro-optics: the coupling of light from free-space to and from guided wave devices and the coupling of light vertically between guided wave devices. Grating couplers have been investigated for a number of years as a technique for coupling light between free-space and waveguides [8,31] (see Fig. 3). They have the advantage that that the lateral alignment tolerance between the incident beam and the waveguide can be more relaxed than in the case of butt-coupling or focusing into the end of the waveguide. The gratings can be fabricated lithographically as part of the waveguide fabrication process and this approach has been used successfully to realize low-cost optical sensing systems[32]. The simple periodic grating can be modified in order to include focusing [9] or beam-splitting [33] functionality, which greatly increases the input and output options. However one of the major challenges of this field is to develop techniques for quantitatively modeling the coupling efficiency. The coupling strength of guided modes to and from radiation modes becomes very difficult to determine for all but simple periodic gratings. The concept of radiation mode coupling can be extended to consider the use of grating couplers for the vertical integration of waveguides[17,34-38] (see Figure 4.). We have investigated the use of strong gratings to couple light between semiconductor waveguides (which could support optical amplifiers for example) and low loss silica, silicon or glass waveguides [39]. Insertion losses of around 3dB for Si-InGaAsP coupling have been achieved in simulation, and further improvements should be possible with optimized gratings.

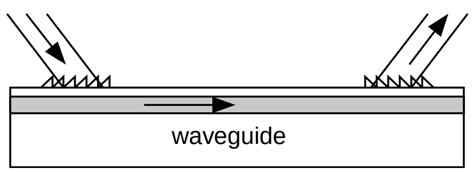

Figure 3. Simple grating coupler

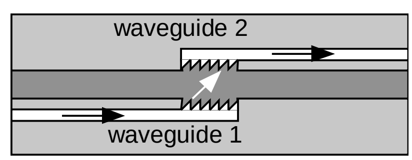

Figure 4. Vertical integration of waveguides

4. CONCLUSIONS

A wide variety of different approaches for the integration of micro-optics have been investigated over the years. Many strategies can be employed in order to ensure that the required alignment tolerances can be achieved. However, if micro-optics is to be widely used, these strategies should be directed towards assembly processes that will scale to low cost, high yield, volume fabrication. Techniques which yield single monolithic assemblies (such as the proton or X-ray LIGA, or planar optics) are attractive for this reason, in that the fabricated elements can then be used as masters for injection molding. However approaches which permit automated assembly, such as the optical alignment features described above, may also have a role to play since they provide a method of aligning discrete components which may not be amenable to molding.

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