DESIGN OF AN OPTICAL DIGITAL COMPUTER

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Abstract A possible implementation of the design of a digital optical computer is presented. A general technique for *space-multiplexing* arrays of beams is described

Introduction

In this paper we describe a method for the implementation of a digital optical computer based on the architecture suggested by Murdocca [1]. A general discussion of the optical system is given by Prise et al [2]. The basic system configuration is that the signals in the computer are passed around as arrays of beams using free-space (as opposed to guided wave) optics. The logic is done by planar arrays of optical logic gates placed in the image plane of the optical system. Here the array of beams becomes an array of spots. Each spot corresponds to a logical bit.

Several regular interconnections between arrays of gates have been proposed. There are several networks which are all topologically equivalent to a perfect shuffle, whose optical implementation has been discussed. See for instance Jahns [3]. A simpler interconnection to implement optically is a split and shift. Murdocca [4] has shown how to implement arbitrary logic functions using this interconnect. The functionality of the system is added by blocking off some of the interconnection paths.

Devices

Before discussing the optical system we first have to make some assumptions about the devices. We assume the devices have the following properties. The signal output consists of the reflected power supply beam. We refer to these devices as reflection mode devices. The devices have two logical inputs. The two input signals do not have to be coincident with the power supply input. We wish to avoid the possibility of two signals being spatially coincident unless they are in opposite polarization since, unless all the path lengths in the system are held to interferometric precision, interference may result in a spurious logic signal. We anticipate devices such as these being produced using the SEED effect [5] and GaAs integrated circuit fabrication technology.

Optical Requirements

The purpose of the optical system connecting the arrays of gates is the following. An array of optical beams must be produced from a single power supply laser each having the same intensity. We will call this the power supply array. Our initial solution is to use binary phase gratings [6],[7]. This array of beams must be imaged onto the optical logic gate array. The reflected output must then be taken, put through an interconnect such as the split and shift with masks and then recombined on the next array of logic gates along with the power supply array for this device. We call these arrays the signal arrays since they contain the logic information.

The problem we concentrate on is having the array of logic gates in the focal plane of a single lens and feeding our array of power supply beams plus our arrays of signal beams onto the array of devices without losing power or sacrificing the resolution of the lens (which would mean we require larger devices and hence more power [2]) . Each individual signal or power supply must use, as near as possible, the whole aperture of the lens so that the resolution is not reduced. Since we are using reflective devices we also have the problem of extracting the reflected power supply array which provides the input signals to the next set of devices. The method we use may have general applications for free-space opto-electronic interconnects.

Split and Shift Implementation

Before describing how we do the above, we will briefly state how a simple split and shift interconnect can be implemented. Either put a birefringent plate in the output from the previous optical logic gate array, or simply use a polarization beamsplitter to split the output array, into two seperate beam images (beam arrays), shift one with respect to the other, and recombine with a polarization beamsplitter. Several different shifts are desirable between logic arrays [4]. The architecture requires that some of the paths are blocked. This can be done by re-imaging in two separate paths and placing a mask in the image plane. An alternative masking technique is to replace selected reflectors with absorbers in the image combinatation setup described in the next section. This second method is preferable since it will lead to a more compact system and it is the only one which can be used when a birefringent plate is used to perform the split and shift. Notice that the output of this interconnect is two signal arrays of opposite polarization but spatially coincident. The problem now is to combine these signal arrays with the power supply array as discussed above.

Beam combination using patterned reflectors

One means of combine two arrays onto the same polarization without either power loss or resolution loss, is to use polarization and patterned reflectors placed in the image plane of the system. The basic principle is shown in Figure 1, for combining the power

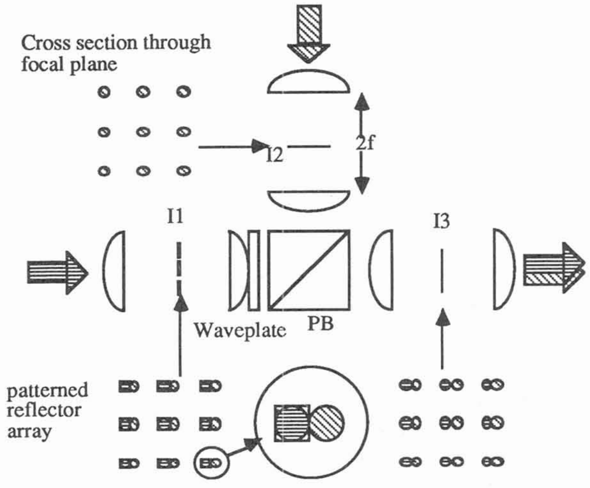

Figure 1: Method for space-multiplexing arrays of beams with no power or resolution loss.

supply array with a single signal array. The critical elements is the patterned mirror I1. These consist of arrays of reflectors. Each of the arrows represents an array of beams which corresponds to an array of spots in the image planes. In Figure 1 we show how to combine two arrays of beams losslessly without losing any of the optical system resolution. The combination is done by interleaving two counterpropagating arrays of beams in an image plane where the arrays of beams are discrete spots. The patterned reflector is arranged such that one set of beams is reflected and the other transmitted. It consists of an array of reflectors, each of which has the same dimensions as the spot size, with the same spacing as the spots in an individual array. We now have the two interleaved arrays of beams propagating in the same direction. In order to avoid these arrays propagating back along the same path as that taken by the reflected array, we use the polarization beamsplitter and a $\lambda/4$ plate. The collimated beams are incident on a polarization beamsplitter with the polarization such that they are completely reflected. They are then focussed down into the plane of the patterned reflector. They are aligned such that the individual spots are all reflected. In Figure 1 we have shown what the image looks like at the focal planes of the different lenses.

The $\lambda/4$ plate is placed between the polarization beamsplitter and the lens. The beams, on reflection back through the lens, are collimated and, this time, are transmitted through the beamsplitter. The array of beams transmitted through the patterned reflectors is arranged to have a polarization such that it is transmitted through the beamsplitter. Thus we have now obtained two arrays of beams which, when focussed down, give us two interleaved arrays of spots. The interesting thing is that both these arrays now have the same polarization and the size of each spot is limited by the full aperture of the system. We can take these arrays and combine with another array of signals by using the same system again. We can continue doing this until we have filled up the entire field of the lens. This ability to "space-multiplex" arrays of beams to an arbitrary extent may prove very useful for all types of free space optical interconnections.

We still have the other polarization channel which we can use to losslessly combine the output another array of beams (in this case the other signal beam array).

Input/Output Module for an Optical Computer

In Figure 2 we describe how this principle can be used to build a compact optical input/output system which could be used as a module in an optical computer. The power supply beams are provided by a single laser and a Dammann grating. Since we do not have two arrays of working devices, our input signal beam is provided by another laser and binary phase grating. In a real system our signal would consist of two arrays in opposite polarization obtained by taking the output from the previous optical logic gate array and putting it through a split and shift interconnect as described in section 4.

In our experiments we have used patterned reflectors to simulate the devices. These masks have reflectors of dimensions $10\mu m \times 20\mu m$ separated by $80\mu m$. The reflectors are on a glass substrate about 2mm thick (for shorter focal length lenses this means we would have to use lenses corrected for spherical aberration). The structure is transparent between reflectors. These patterned reflectors

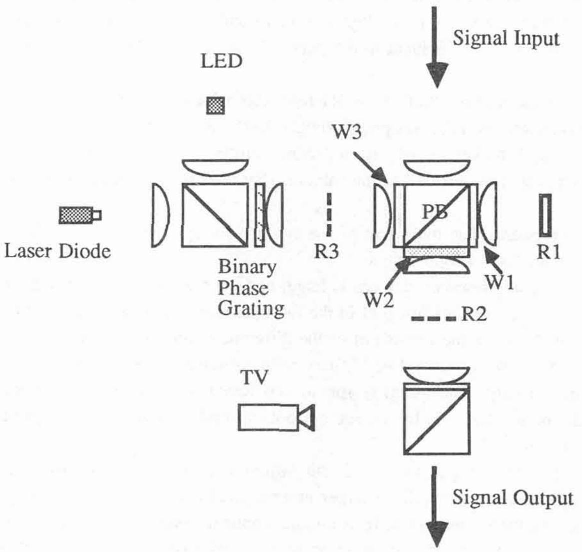

Figure 2: Experimental optical input/output module for a digital optical computer.

were fabricated using an Electron Beam Exposure System which is commonly used to fabricate the masks for VLSI processing.
The central element is the polarization beamsplitter. The power supply array comes from the laser to the right. The signal input is obtained from another laser and binary phase grating. The lasers are operating at $852nm$. Arrays consisting of 289 beams are generated from each laser diode using binary phase gratings [7]. These gratings have a period of $520\mu m$. All the lenses shown have a focal length of $5cm$. The only thing not shown is that we use a zoom lens system after the binary phase grating. This allows us to slightly magnify the binary phase grating to match it exactly to our device array size.
The light emitting diode is used to illuminate both the devices and the arrays of reflectors in the different image planes. A light emitting diode operating at the same wavelength as the laser diode was used to avoid any problems due to dispersion between the illumination light and the signal or power supply light. The illumination light is fed into the system using a polarization beamsplitter.
The alignment is carried out as follows. The reflector array representing the devices (R1) is positioned 5cm from lens L1. The image of this reflector array is focussed on the TV camera. This reflector array is now replaced with a mirror. The input power supply array of beams is now focussed onto R1. Then by replacing the patterned array of reflectors, and using the zoom lens, the spacing between the spots in this array can be adjusted so it exactly matches the reflector array spacing.
Patterned reflector R2 is then brought into focus. If R1 and R2 are not exactly one focal length away from the respective lenses or the focal lengths are not exactly equal, these arrays of reflectors will appear to have different spacings. In this case this was not a problem. Further study is necessary to see whether this becomes a serious problem with different focal length lenses. Reflector R3 and R4 are also brought into focus. All of the reflectors arrays can be translated in both a horizontal and vertical direction with micrometers. We found the focus could be adjusted simply by manually sliding the reflector holder back and forward along the rods. The rotation of everything can also be set by manually sliding the reflectors in their mounts. We found it straightforward to align all the reflector arrays and the arrays of beams so that they would appear coincident on the video camera.
To set up the desired signal paths, we want one polarization of the split and shifted signal input to go straight through the beamsplitter, be reflected off R2, go back through W2 and be reflected onto the device array. The other polarization must be reflected through W3, back off R3 and transmitted through the beamsplitter onto the device array. In order to block off some of the signal paths which we wish to do for our split and shift interconnect, we have another fabrication stage where some of the reflectors are made absorbing, perhaps by depositing polysilicon.
The power supply input must be transmitted through R3 and W3, then transmitted through the beamsplitter and onto the device array. The reflected power supply which is the output must then be reflected back through W1, reflected off the beamsplitter, through W2 and R2, and is the output signal array.
The above was acheived by first aligning all the reflector arrays so they appeared coincident on the cameras. We then shift arrays R2 and R3 so they are half overlapping with array R1. By adjusting the position of the input signal array, which is split into two

at the beamsplitter, so that it is incident on this overlapping area both polarizations now take the required paths. This appears on the camera as if these arrays (which are coincident) dissappear. The alignment of the signal beams reflected of R3 can be checked simply by moving R2. The only way to check on the alignment of the other signal beam is to place another camera behind R1 and shift R1 slightly to see if all the beams are coincident in the plane of the devices. We did this initailly but we found this check was unnecessary.

The power supply array was lined up onto the half of the R1 reflectors which were not overlapping with the reflectors R3 and R2. So on the television camera we can see the reflected power supply which is the output.

So that we could use the total output power to put into an interconnection stage, we use a waveplate / polarization beamsplitter combination to vary the portion of the light directed to the camera. (By rotating the waveplate the reflectivity of the beamsplitter can be varied).

We found the alignment straight forward. The main part of the system is very compact. In this case the beamsplitter is only $1cm^3$. Ideally we would like to use smaller focal length lenses.

The problem we have is that the spacing between devices is large, and we are limited by fabrication to binary phase gratings with a certain minimum period size. The innaccuracies inherent in the fabrication of the binary phase grating [7] mean that as we make the period size smaller the differences between the intensities of the different beams become larger. We found we could make a grating to produce a 17×17 array of beams with a period of $520\mu m$ with sufficient accuracy to obtain beams with a maximum intensity spread of 30% of the minimum intensity. The intensity spread was found both experimentally and by numerical simulation to go approximately inversely with the period size and by the square root of number of beams one trys to generate. We limit ourselves to a minimum grating period of $520\mu m$.

This period gives a spot spacing, in the image plane, of about $80\mu m$ with a $f = 5cm$ lens. We can get around this problem by demagnifying the grating but this means we require a larger grating and hence larger illuminating optics. At some point this will become impractictable. In this experiment we use a $1cm$ aperture optical system. If we have a Gaussian input beam, in order to lose less than 1% of the light at the aperture, the gaussian beam waist parameter must be less than $3.33mm$. When these beams are focused down onto our device $\sim 5\%$ of the power will miss the device. This is undesirable, but can only be changed by having a smaller period grating and a shorter focal length lens (which is a problem because of the limitations of binary phase gratings), or demagnifying a binary phase grating illuminated with a larger beam (which is a problem because we require larger aperture optics which will take up more space and will cost more) or, best of all, simply making the devices closer together.

Conclusions

In conclusion we have described a method for combining arrays of beams without losing power or optical resolution which may have useful applications in optical computing and for opto-electronic interconnections. We have experimentally demonstrated a particular application of this method and pointed out some of the system tradeoffs which have to be made.

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