# Comparison of system size for some optical interconnection architectures and the folded multi-facet architecture

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We compare system sizes for some optical interconnection architectures and introduce the folded multi-facet architecture which can potentially approach the smallest possible system size of *any* two-dimensional optical architecture.

## 1. Introduction

Optical interconnections are superior to resistive interconnections in terms of bandwidth, delay, packing density and energy over longer distances [1]. In this letter we compare the system size of some optical interconnection architectures and introduce the folded multi-facet holographic interconnection architecture, which has the potential to approach the minimum possible system size of *any* two-dimensional architecture in providing an arbitrary pattern of interconnections among a two-dimensional array of points.

We assume that $n/2$ pairwise interconnections are to be established among a collection of $n \gg 1$ points ($n/2$ to-be-connected source–detector pairs). For simplicity, the extension to fan-out is not considered. We also assume that the length of the longest interconnection is of the order of the linear extent of the system. The layout area (or volume) will be expressed as $nd^2$ (or $nd^3$). $d$ must be chosen large enough so that there is enough space to establish the desired interconnections. Of course, $d$ must also be large enough so that there is enough space for the devices; however, in this work we concentrate on the value of $d$ as set by communication requirements only. A significant parameter of such a layout is its *average interconnection length* $\bar{l}$, where $l$ denotes the distance of a particular connection and the overbar denotes averaging. This quantity is often expressed in the literature [2] as $\bar{l} = \kappa n^{q-1/2} d$ for a two-dimensional array of points. $\kappa$ is a coefficient which is often of the order of unity. $q$ is a measure of the connectivity of the system [2] and satisfies $1/2 \leqslant q \leqslant 1$. Many logic circuits are known to exhibit $q \sim 0.6$ whereas, for instance, neural networks may exhibit values of $q$ quite close to unity. Similarly, for a three-dimensional array of points, the average connection length may be expressed as $\kappa n^{q-2/3} d$ with $2/3 \leqslant q \leqslant 1$.

## 2. System size considerations

We now refer to table 1, which gives the system size for various situations. Order of magnitude accuracy is sufficient for the purpose of this paper. Thus, slowly varying logarithmic factors and factors such as 2, $\sqrt{2}$ etc. have been ignored for simplicity. $\lambda$ denotes the optical wavelength. $\mathscr{F}$ is a dimensionless factor which in principle can approach the order of unity, but may be quite larger in practice. Some of these results were originally derived for solid wires [3–5]. However, we have previously shown that such results also apply to optically communicating systems [6].

The best possible three-dimensional growth rate (column A) may be approached by using discrete fibers of diameter $\sim \mathscr{F}\lambda$. However, the resulting system size would nevertheless be large because of the relatively large value of $\mathscr{F}$. Similar comments apply to the case where the points to be connected are con-

Table 1
System size for some optical interconnection schemes for large $n$. Columns A and D give the minimum system size achievable with *any* three- or two-dimensional optical architecture, respectively. Column B gives the minimum for *any* architecture in which the points to be connected are constrained to lie on a plane but communication paths are allowed to leave the plane. Column C is for the reflective multi-facet architecture, and column E is for the folded multi-facet architecture.

| | A | B | C | D | E |
|---|---|---|---|---|---|
| Area | – | – | – | $\kappa^2 n^{2q} \mathscr{F}^2 \lambda^2$ | $\kappa^2 n^{2q} \mathscr{F}^2 \lambda^2$ |
| Volume | $\kappa^{3/2} n^{3q/2} \mathscr{F}^3 \lambda^3$ | $\kappa n^{q+1/2} \mathscr{F}^3 \lambda^3$ | $n^3 \mathscr{F}^3 \lambda^3$ | – | – |
| Linear extent | $\kappa^{1/2} n^{q/2} \mathscr{F} \lambda$ | $n^{1/2} \mathscr{F} \lambda$ | $n \mathscr{F} \lambda$ | $\kappa n^q \mathscr{F} \lambda$ | $\kappa n^q \mathscr{F} \lambda$ |

strained to lie on a plane (column B). Alternatively, it is possible to achieve this growth rate with a small value of $\mathscr{F}$ by using free space interconnections in conjunction with multiplexed holograms. However, this method not only results in poor diffraction efficiency, but also constrains the pattern of connections due to the ambiguity associated with the Bragg cone.

One way of achieving an arbitrary pattern of interconnections among a planar array of points is to use the reflective multi-facet architecture [8] (illustrated in fig. 1a), or one of its variants [7,9]. However, due to diffraction considerations, the growth rate associated with this architecture (column C) is larger than the best possible (column B) [6], although the value of $\mathscr{F}$ involved can be of the order of unity. In fact, unless $q=1$, this growth rate is even worse than that achievable in two dimensions (column D).

The best possible growth rate for full two-dimensional layouts (column D) may be achieved by using waveguides with average effective line to line spacing of $\sim \mathscr{F}\lambda$. However, the value of $\mathscr{F}$ must be relatively large due to crosstalk and routing considerations.

## 3. The folded multi-facet architecture

We now consider the folded multi-facet architecture based on the substrate-mode holographic system [10,11] shown in fig. 1b. Such an imaging system will be used for each connection. In this manner we will be able to realize an arbitrary pattern of connections. (In certain situations involving a regular (perhaps space-invariant) pattern of connections, as in Fourier plane filtering, it is possible to send more than one data channel through the imaging system, leading to a simpler design [12].) This system is composed of two identical holographic optical elements (HOEs) which were recorded on the same plate. The first one, $\mathscr{H}_s$, collimates a coherent point source into a plane wave which is trapped inside the plate by total internal reflection. The second HOE, $\mathscr{H}_r$, focuses the collimated wave onto a detector. Since the holographic plate can be located very close to the source and the detector, and the light is guided inside the plate, this system can be very compact and easy to use. Unlike the reflective multi-facet architecture, here the path length of light is proportional to the distance $l$ between the source and the detector. In fact, since the total internal reflection condition must be satisfied, the proportionality constant is merely an obliquity factor not much greater than unity (such as $\sqrt{2}$). Thus, the path length of light may be taken approximately equal to $l$.

In order to achieve the least possible growth rate of system size, we will show below that, due to diffraction considerations, the area of both holograms should be chosen proportional to $l$. Unfortunately, since the distance $h$ between the device plane and the hologram plate and the $f$-number of the sources are constant, the area of $\mathscr{H}_s$ is fixed and cannot be chosen proportional to $l$.

Thus, in order to achieve the least possible growth rate of system size, we modify the architecture as follows: $h$, and hence $d_s$ and $d_r$ (the diameters of $\mathscr{H}_s$ and $\mathscr{H}_r$, respectively), are fixed for connections of all lengths and are preferably as small as possible. Two more holograms, $\mathscr{H}_a$ and $\mathscr{H}_b$, with diameters $d_a$ and $d_b$ are added. The route of the light from source to detector is shown in fig. 1c. $\mathscr{H}_a$ and $\mathscr{H}_b$ can be reflection holograms, or when the holographic emulsion is coated with a cover glass, transmission hol-

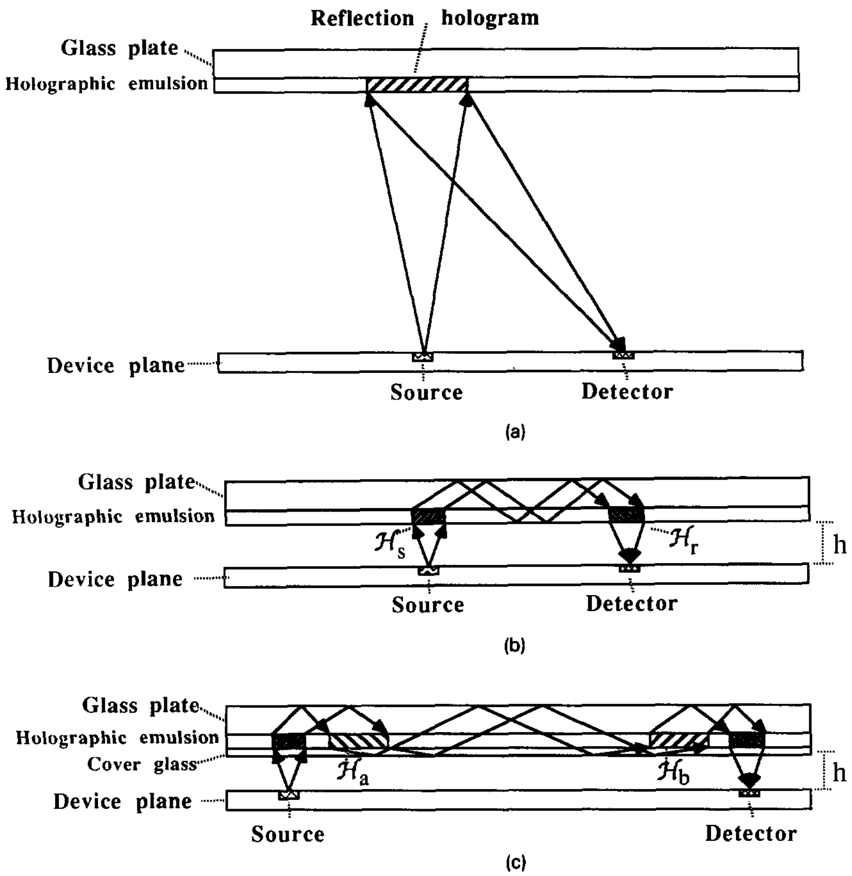


Fig. 1. Holographic optical interconnection architectures. Only one source–detector pair and its associated facet(s) are shown for clarity. (a) The reflective multi-facet architecture. (b) The folded multi-facet architecture in its most primitive form. (c) A modified version, which achieves the best possible growth rate of system size in two dimensions.

ograms. Unlike the area of $\mathcal{H}_s$ in fig. 1b, the areas of $\mathcal{H}_a$ and $\mathcal{H}_b$ are not fixed by the $f$-number of the sources and can be chosen in a manner so as to minimize total system size, as quantitatively discussed below.

To calculate the minimum value of $d$, we equate the total area occupied by the holograms associated with the $n/2$ interconnections to the total available area $nd^2$,

$$(n/2)\overline{[d_s^2+d_r^2+d_a^2(l)+d_b^2(l)]}=nd^2\,, \tag{1}$$

where $d_b(l)=\mathcal{F}\lambda l/d_a(l)$. $\mathcal{F}$ can approach the order of unity for diffraction-limited operation. The overbar denotes averaging over all connections. $d$ may be minimized by choosing $d_a^2(l)=d_b^2(l)=\mathcal{F}\lambda l$. That is, we use larger facets for longer interconnections. With $d_s=d_r$ we obtain

$$d^2=d_s^2=\mathcal{F}\lambda\kappa n^{q-1/2}d\,, \tag{2}$$

which approximately leads to a system linear extent of

$$n^{1/2}d\simeq n^{1/2}d_s+\kappa n^q\mathcal{F}\lambda\,, \tag{3}$$

which becomes, for $q>1/2$ and large $n$,

$$n^{1/3}d\simeq\kappa n^q\mathcal{F}\lambda\,. \tag{4}$$

Since the value of $\mathcal{F}$ need not be much greater than unity [10], the folded multi-facet architecture can approach the best possible system size achievable by any two-dimensional system.

The interconnection scheme presented is similar to the use of waveguides in that each interconnection consumes area proportional to its length. Whereas guiding (i.e. focusing) takes place in a distributed manner along the length of a waveguide, in our architecture it is concentrated at the end points.

Although passage through four holograms is necessary, the overall diffraction efficiency can still be over 80% if thick phase holograms with individual diffraction efficiencies of $\sim 95\%$ are utilized. To prevent reflection from the glass–gelatin surface, the average refractive indices of these materials must be equal.

Several design issues must be addressed during practical implementation of our architecture, some of which we briefly mention. Let $\beta$ denote the angle the optical rays bouncing inside the glass plate make with the normal. $\beta$ must exceed $\sim 43°$ so as to satisfy the total internal reflection condition. Another issue is that, as they undergo several bounces, the rays impinge on holograms which belong to other connections. In order to avoid crosstalk, $\beta$ should differ from the Bragg angle of the hologram impinged upon. Since the holograms have very high obliquity, they are very angle sensitive. By proper selection of very thick emulsion and comparatively low depth of modulation, we may ensure that the hologram efficiency falls to nearly zero when $\beta$ differs more then $\pm 1–2°$ from the Bragg angle. Since there is considerable flexibility in choosing $\beta$, with careful design the light rays will impinge only at their destination holograms at the proper Bragg angle. It does not seem that the design problem of choosing $\beta$ approximately for each interconnection is more formidable than that of routing solid wires of waveguides.

## 4. Conclusion

In conclusion, the folded multi-facet architecture (which is essentially a "free-space" architecture) allows near diffraction-limited operation and can potentially approach the smallest possible system size of any two-dimensional system. This is difficult to achieve with waveguides, which must usually be packed at an effective line-to-line spacing much greater than $\sim \lambda$.

A practical implementation of an architecture allowing an arbitrary pattern of connections, with growth rate equal to the best possible in three dimensions and a value of $\mathscr{F}$ not much greater than unity is still to be discovered.

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