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# Advanced interconnect technologies

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**Abstract.** Advanced interconnect technologies play a prominent role in scaling up the performance of data center networks. Spatial Division Multiplexing (SDM) photonic interconnects have been suggested as means to overcome capacity upgrade requirements and enable disaggregation in future data centers. Here, Holographic Optical Elements (HOE) are proposed for SDM photonic interconnects. The proposed coupling scheme entails the use of holograms as fan out components for coupling light from a source to multicore fibers (MCF). The scheme is versatile and can be adopted to any SDM fiber core arrangement. Appropriate Computer-Generated Holograms (CGHs) are designed for two kind of MCF and the HOE interconnect is evaluated in terms of performance variations against system and fabrication related parameters. Furthermore, the interconnect design is optimized for loss-sensitive applications.

**Keywords:** optical interconnects, holographic optical elements; Spatial Division Multiplexing.

## 1 Introduction

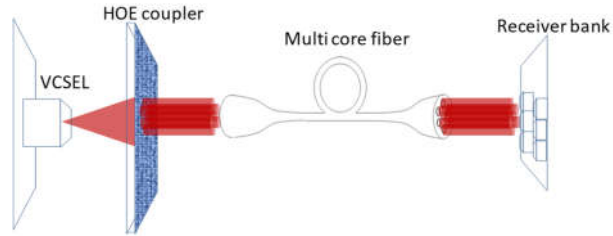
Information and Communications trends like Internet of Things (IoT) and Cloud Services have been formed to support emerging applications and consequently are driving the dramatic increase of the global Internet traffic. These new and emerging applications collect, store and process massive amounts of data, driving the requirement for large high-performance data centers. Advanced interconnect technologies play a prominent role in scaling up the network performance of data center segments that range from inter data-center links to short-reach rack-to-rack communication, even on-board and chip-to-chip connections [1], [2]. Photonic communication technologies have been long used in global optical networks and proposed to serve on and off-chip interconnects in data centers due to low power consumption and high bandwidth performance. Specifically, for rack-to-rack interconnection, vertical cavity surface emitting laser (VCSEL) based transmitters and multi-mode fiber have been the main candidate for 10Gb/s throughput server interconnection [2]-[3]. As scalability in terms of capacity is vital in data center environments, single mode fibers (SMF) and even MCF have been proposed, where capacity upgrades are guaranteed via various multiplexing techniques like wavelength and space division multiplexing (WDM) and SDM. SDM systems promise several link capacity upgrades with one fiber-

installation while reducing the amount of cable space required in data center networks [1]. Furthermore, the specific architecture is very much in line with the notion of disaggregation.

An important issue in this interconnect evolution is multiplexing of the laser signals to the MCF that will transport signals to several processors. Coupling of MCF to SMF (and vice versa) is technologically challenging and affects the interconnect's overall performance. In the literature, the component that couples light from an SMF to an MCF is termed as fan in/fan out component, coupler or even SDM multiplexer/demultiplexer (mux/demux). Here we use the term coupler as it is used in a broadcasting interconnect architecture. In SDM couplers, an additional degree of complexity is introduced by the fact that while SMF fibers are standardized, MCF are not and there is a plurality of MCF demonstrations that employ various arrangements of cores and number of cores. Hence, a plethora of coupling solutions have been explored and a few have been commercialized [4], while the interest in the field is ongoing. These have been specified for the various SDM fiber technologies namely, MCFs [5], few mode fiber and multimode fibers [6], Vortex Fiber Carrying Orbital Angular Momentum [7] and Hollow-Core Photonic Band Gap Fiber [8]. Coupling schemes can be categorized as fiber/waveguide based in the form of tapers and laser inscribed waveguides in transparent materials (e.g. glass) [9]-[10], free space that make use of lenses [11] and integrated methods where mux/demux operation is enabled by grating couplers integrated within a photonic chip [12]. Fiber/waveguide based schemes are compact solutions that offer the possibility for fiber connectors while the fabrication techniques used are fairly mastered. On the downside, the adiabatic transform from single to multicore (and vice versa) can be restrictive in terms minimum size of the device and also require sophisticated splicing technology. On top, in some cases it can be susceptible to crosstalk. Adaptation to any MCF core arrangement is not straightforward fabrication wise. Free space techniques on the other hand, rely on lens systems to image the cores of SMFs to the cores of the MCFs (and vice versa) and are scalable to any number of cores and arrangements. Additionally, losses and crosstalk are minimized. However, this is a bulky solution that does not favor integration.

Evidently it is particularly difficult to establish a universal coupling scheme that accommodates all MCF variations. In the present contribution we address this with fan in/out holographic optical element (HOE) for coupling SMF to MCF. The proposed scheme (illustrated in Fig 1a) is essentially a free space optics scheme that carries all the pros of a lens system coupling while it relaxes the cons, as it is not as bulky solution as a bare lens system and also there is no requirement for optomechanics and prisms [13]. Relevant to the present work is the work of Calo and co-workers [14] and the more recent of Wilkinson et al [15] and [16]. In [14] a holographic coupler for coupling SMF to SMF was proposed. Deployment of the scheme was hindered by the technological advances of the rival coupling technology at the time where fiber-based connectivity was preferred. Nowadays this is reversed thanks to developments in fabrication and integration methods. In [15] a hologram is used for the mode coupling of multimode fibers, rather than core coupling in MCF proposed here. Furthermore [16] has proposed the use of microelectromechanical optical mirrors as switchable diffractive elements and the experimental investigation was merely

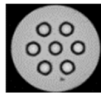
aiming at crosstalk investigation. Additionally, the implementation involved MEMs rather passive holograms. The latter approach is chosen as it favors small footprint and in addition it is more cost effective as the material assumed is fused silica.



(a)



(b)



(c)

|           | # of cores | Pitch size ( $l$ ) | SDM fiber diameter ( $D$ ) |
|-----------|------------|--------------------|----------------------------|
| LA [16]   | 8          | 50 $\mu$ m         | 250 $\mu$ m                |
| HPCS [17] | 7          | 40 $\mu$ m         | 250 $\mu$ m                |

(d)

**Fig. 1.** Block diagram of a broadcast short reach interconnect with a directly modulated VCSEL, HOE coupler a MCF and a bank of receivers. The interconnect utilizes either (b) multi-core SMF with linear arrays (LA) or (c) hexagonal close packed structure (HPCS) with the multi core fibre characteristics shown in (d).

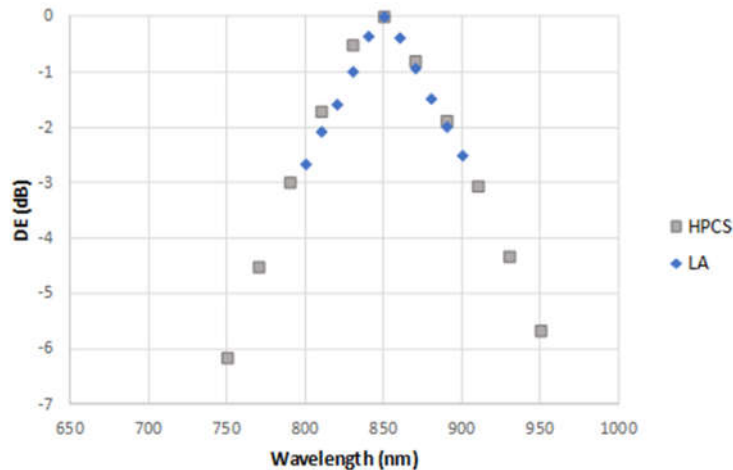
Here we choose to study binary phased HOEs on fused silica due to the ease of fabrication by standard microfabrication techniques. We perform for the first time to our knowledge, a systematic investigation on how the interconnect performance is affected by possible fabrication and system integration errors. We do this by simulating the performance of the broadcast SDM interconnects when specific parameters are detuned from optimal values.

## 2 SDM interconnect architecture

For the purposes of design and evaluation of the proposed HOE SDM couplers we consider the short reach broadcast interconnect scenario shown in Figure 1a). Broad-

cast interconnects investigation with respect to fanout, to provide multicast communication is one of the crucial demands of interconnects fabric for the future many-core systems [20]. Especially in short reach broadcast interconnect, minimal delay among multicasted signals may be of crucial importance for the operation of a data center. To simulate the operation of a short reach broadcast system: the output of a directly modulated single mode VCSEL is broadcasted to an array of photodetectors (i.e. multiple nodes) by means of a MCF. Coupling to the MCF fiber is achieved with the HOE SDM coupler under study. In short reach optical broadcast interconnects the requirement is that the high speed signal is transmitted to multiple nodes with reduced delay and jitter among the copies. The elaboration of short reach optical interconnects to include MCFs has already been considered [22]. MCFs offer the obvious advantage of massive data transport while for the short reach optical interconnects the requirement for optical amplification is relaxed. HOE SDM coupler is particularly suited for this application as it is inherently bit rate and time delay agnostic. An added bonus comes from the very use of VCSELS, rather than edge emitters with elliptical beam emission. Indeed, the circular characteristics of the VCSEL output simplifies the optical setup as no additional beam shaping optics are required for illuminating the HOE with a circular spot and guarantees the symmetry of the design. The interconnect operates at 850nm where both VCSEL and fibre cores support one mode. The miniaturization of the interconnect however imposes the incorporation of a lens at the output of HOE. The footprint of the overall setup can be reduced by means of a GRIN lens rather than a typical lens. The light that is broadcasted in all nodes it is then received by a bank of receivers that demodulate and process the signal.

The proposed HOE SDM couplers are specified for two typical examples of MCFs previously considered for use with integrated silicon photonic transceivers namely MCFs with linear arrangement (LA) of core arrays [22] and hexagonal close packed structure (HPCS) [23]. Any type of multi core fibres can be used [14], as shown in Fig.1 b and c.



**Fig. 2.** Relative diffraction efficiency with respect to the source wavelength for two CGH coupler designs. Both LA and HPCS CGH designed at /for 850nm.

## 2.1 SDM coupler design

In the following we design the Computer-Generated Holograms (CGHs) for the HOEs couplers for LA and HPCS arrangements in context of the short interconnect scenario (Fig 1a). The evaluation gauge in all cases is the diffraction efficiency (DE)  $\eta$ , a measure of how much optical power is diffracted into designated spots compared to the power incident onto the diffractive element. Here it is calculated as the ratio of the diffracted irradiance integrated in the designated spot areas (intensity) over the beam intensity behind the HOE. Diffraction efficiency  $\eta$  is directly related to the insertion loss of the element and the actual optical power diffracted into one of the targeted N fibre cores (N=7 or 8) depending on the configuration). Considering loss from the optical system to be approximately 5% and the 1 x N splitting loss the insertion loss of the fan-out is [24]

$$\text{Loss}=0.05 \eta/N \quad (1)$$

Evidently as loss depends on the number of cores N of the multi core fibre, it is avoided as a figure of merit in comparisons between the two HOE coupler that correspond to Fig. 1 b) and c). For the design of the CGHs and analysis of the HOE optical interconnects we use the commercially available software VirtualLab by LightTrans [25]. For the computation, an advanced iterative Fourier-transform algorithm (IFTA) is used. The iterative Fourier transform algorithm in VirtualLab, enables the HOE design for the targeted beam pattern. The IFTA consists of the following steps, after the generation of an appropriate transmission field. The software creates an optimized output field phase and optimizes the specific merit functions with respect to the specifications. Here DE, uniformity error  $\epsilon$  and signal to noise ratio have been used. The HOE is analyzed and light distributions in target plane is calculated. Light distribution is modified in order to fulfill all constraints and element parameters are calculated with light back propagation. The multi step algorithm result is validated and the optimum HOE design is used for the simulation of the short reach optical interconnect.

For the simulation the following are considered: the optical interconnect modelled here assumes one single mode VCSEL source at 850nm [2]. The VCSEL beam output is a circular Gaussian beam with 600 $\mu$ m diameter. The required beam size can be modified by means of a collimating lens if necessary. The HOE is placed at the output of the VCSEL. The rectangular HOE is placed in a 2f [14]. At a possible HOE coupler design the lens could be replaced by a GRIN element. For all the calculations presented here  $f=10$ mm. The HOEs are designed as binary phase CGHs. For each HOEs this translates to an optimal pixel size. This translates into 13.27  $\mu$ m (LA) and 15.17  $\mu$ m (HPCS). Judicious HOE design can result to non-trivial savings in fabrication time and costs. It is noted that the proposed design can be readily extended to longer wavelengths e.g. 1525nm as it will be indeed done here. Given that the CGH

pixel size [26],[14] is related to the reconstruction wavelength i.e. the operation wavelength of the interconnect, choice of longer wavelength relaxes pixel size requirements for optimal reconstruction.

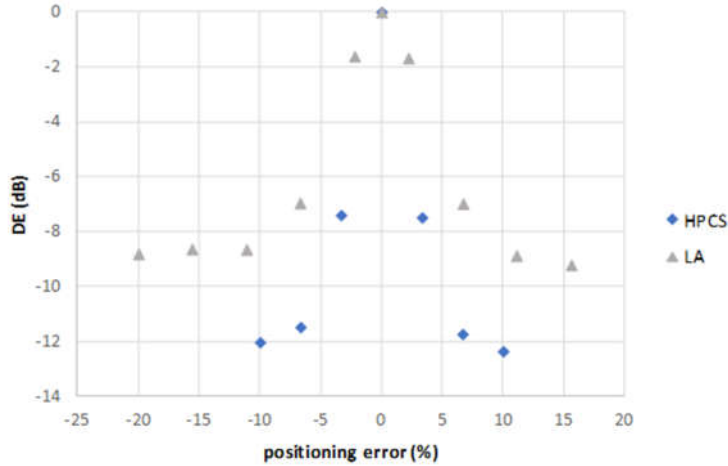
## 2.2 Fabrication Tolerance Simulation

Once the optimal designs have been achieved, a simulation setup is used to evaluate the HOE couplers that were designed. A tolerance analysis is performed in terms of a) wavelength b) MCF position and c) fabrication errors. The rectangular HOE is assumed to be fabricated on fused silica and comprises 280 pixels for the HPCS and 320 pixels for the LA case. The lens in all cases is considered circular with diameter of 25.4 mm. The DE and uniformity errors are used as figures of merit. Plots are shown in dB, with respect to the highest achieved value, i.e. relative diffraction efficiency. Highest DE is 75.5% for the LA and 76.42% for the HPCS optimal designs. Relative figures are used as different HOE designs yield slightly different values as the scope of the paper is to evaluate and compare the tolerance to changes and not the actual designs.

Fig. 2 shows the relative DE versus source wavelength for CGHs that are used in a LA and HPCS couplers. Specifically, the DE is designated with respect to the maximum value (in dB) to evaluate the DE variation when source wavelength is detuned with respect to the wavelength used for the design of the HOE (i.e. 850nm). Setting the system threshold for maximum tolerable DE deviation to 1 dB, the LA HOE coupler is wavelength agnostic over a span of 50nm while the HPCS over a span of 60nm. Thus, both cases are suitable for SDM WDM. Notably the HPCS is more robust to wavelength variations with respect to LA. This however is an artifact of the geometry of the HPCC core arrangement, which includes the 0th order of diffraction in the output reconstruction. As the operation wavelength is detuned with respect to the design wavelength, part of the VCSEL power that illuminates the HOE remains undiffracted. In the case of LA, the undiffracted light, i.e. light that is directed to the zero-order is lost, as the zero order does not coincide with a core. Hence wavelength variation will be translated into increased coupling loss. In the case of HPCS the undiffracted light increases the power that is incident to one of the cores, hence it is translated into uniformity error [24].

The effects of errors in positioning the SDM fiber with respect to the HOE are explored in Fig. 3 for the same cases as in Fig. 2. In interconnects like the one shown in Fig.1, SDM fibre is assumed to be placed at distance  $f=10\text{mm}$  from the lens in order to achieve the maximum DE. In order to model the effect of misaligning the fibre with respect to its optimal position on the focal point, the fibre position deviates from the optimal position on the z-axis as a percentage of  $f=10\text{mm}$ . Specifically, if the coordinate of the SDM fiber facet is  $z$  with respect to the lens facet (where  $z=0$ ), then the positioning error is defined as  $((z-10)/10)\%$ . Fig. 3 shows the relative diffraction efficiency versus positioning error for CGHs that are used in LA and HPCS couplers. The linear features of the LA arrangement yield some tolerance to the integration process. Although it is evident that in both cases the systems require precision with

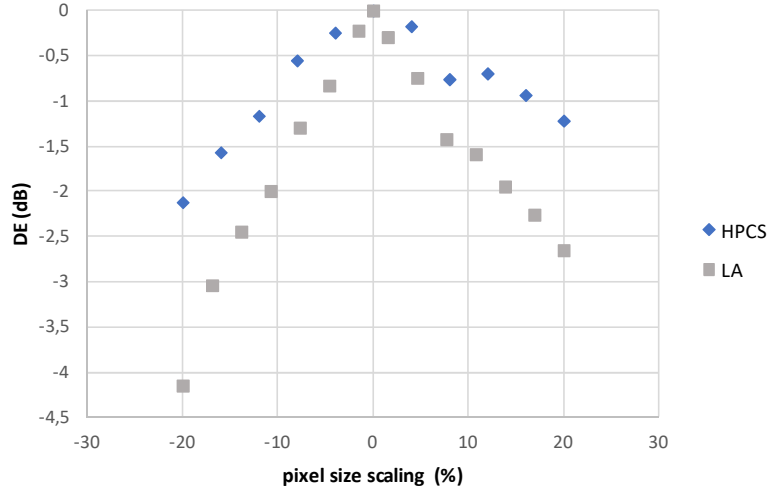
respect to the positioning of the lens, the LA configurations allows more flexibility to possible integration misalignments along the z-axis.



**Fig. 3.** Relative diffraction efficiency with respect positioning error of the output fibre for two CGH designed for LA and HPCS systems. The positioning error is given as a percentage of the focal length  $f=10\text{mm}$ .

Fabrication tolerances of the CGH for coupling to LA and HPCS fibers are assessed in Fig 4. Errors in the fabrication process can cause HOE construction with non optimal pixel size, or the pixel size that stemmed from the optimisation process cannot be achieved with the accuracy of the fabrication methods. These fabrication errors are simulated by scaling the pixel size of the CGH. In Fig.5 the relative diffraction efficiency is calculated with respect to pixel scaling. Evidently both designs are highly tolerant to pixel size scaling. The HPCS design seems more tolerant to pixel size deviations with respect to the optimal one. Expectantly the wider pattern of the LA multi core fiber requires finer optimum pixel size ( $15.17\mu\text{m}$  in the case of HPCS and  $13.27\mu\text{m}$  in the case of LA). The symmetrical HPCS pattern is very relaxed to fabrication errors although even in the case of the LA, a  $\pm 10\%$  error in the pixel size does not deteriorate the DE significantly. In the case of HPCS, pixel size scaling of  $\pm 10\%$  which corresponds to variation of  $1.5\mu\text{m}$  can be tolerated before the DE deteriorates further from the 1 dB threshold.



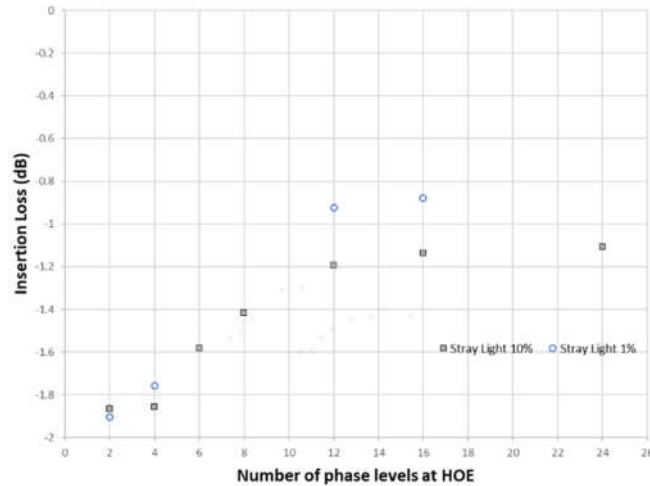


**Fig. 4.** Relative diffraction efficiency with respect to pixel size scaling for two CGH each designed for the optimal pixel size.

### 3 Losses in SDM interconnects

The designs of the previous section have focused on binary CGH structures that can be fabricated with low cost fabrication techniques. Here we elaborate the designs of Section II to study multi-phase CGHs that can be fabricated with more sophisticated fabricating techniques aiming at the minimization of losses. In this way we investigate the suitability of the proposed cross-connects for loss-sensitive applications like quantum communications [17], [18]. To this end we consider the interconnect of in Fig. 1 (a) that deploys the MCF of Fig. 1 (c) and long wavelength VCSELs operating at 1525 nm. This is a popular wavelength for quantum communication networks. The diffraction efficiency and hence insertion losses can be greatly enhanced if multiphase rather than binary CGHs are used as shown in Fig. 5 [27]. The losses can be optimized further if the design accounts for the cost function of stray light, i.e. light scattered in space rather than contributing to the reconstruction of the desired pattern. The comparative analysis of the optimization process for two lowest possible stray light values (10% and 1% respectively) is shown in Fig. 5, where insertion losses are calculated.

Evidently the multiphase HOE based interconnects outperform binary HOEs exhibiting a very good performance with optimized insertion losses as low as 0.8 dB for stray light optimization constraint of 1%, lower than the state-of-art optical couplers for MCFs [4].



**Fig. 5.** Insertion loss for various CGH designs for HPCS with varying number of phase levels in the HOE.

## 4 Conclusions

Holographic elements were explored as a robust solution for high capacity SDM photonic interconnects based on multi core fibers. To this end, appropriate CGHs were designed for SDM multicore fibers with linear and hexagonal core arrangement, two commonly used MCF in literature. The performance analysis of the proposed HOE SDM interconnects in terms of diffraction efficiency variations with wavelength, positioning error and fabrication misfits concluded that both configurations (LA and HPCS) perform well and are tolerant to potential system integration and alignment errors as well as fabrication errors. These results along with the versatility of the proposed scheme suggest the suitability of HOE interconnects for SDM applications. The proposed scheme can be further optimized to address stringent loss requirements in SDM interconnect scenarios.

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