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Misalignment corrections in optical interconnects

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Author
Song, Deqiang

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Misalignment corrections in optical interconnects

A dissertation submitted in partial satisfaction of the requirements for the degree

Doctor of Philosophy

in

Electrical Engineering (Photonics)

by

Deqiang Song

Committee in charge:

Prof. Sadik Esener, Chair
Prof. Joseph Ford
Prof. Andrew C. Kummel
Prof. Yu-Hwa Lo
Prof. Ramamohan Paturi

2006
The dissertation of Deqiang Song is approved, and it is acceptable in quality and form for publication on microfilm:

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Chair

University of California, San Diego

2006
For my wife, my son, my parents, and all my family
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Vita

1997  B.S. in Department of Precision Instrument, Tsinghua university, Beijing, P. R. China

1997-2001 Graduate Student Researcher, Department of Precision Instrument, Tsinghua university, Beijing, P. R. China

2001  M.S. in optical engineering, Department of Precision Instrument, Tsinghua university, Beijing, P. R. China

2001-2006 Graduate Student Researcher, ECE department, University of California, San Diego, CA

2004-2005 Graduate intern, SUN Microsystems, San Diego, CA

2006  Ph.D. in Electrical Engineering (Photonics), University of California, San Diego, CA

Publications


Deqiang Song, Matthias Gross, Sadik Esener, “Integration of precisely aligned lenslet arrays with waveguide arrays”, submitted to Optical Engineering, 2006


Deqiang Song, Haijiang Zhang, Veronica Gauss, Pengyue Wen, Sadik Esener, “Demonstration of all-optical flip-flops based on VCSOA pair”, to be submitted, 2006
ABSTRACT OF THE DISSERTATION

Misalignment correction in optical interconnects

by

Deqiang Song

Doctor of Philosophy in Electrical Engineering (Photonics)

University of California, San Diego, 2006

Professor Sadik C. Esener, Chair

Optical interconnects are considered a promising solution for long distance and high bitrate data transmissions, outperforming electrical interconnects in terms of loss and dispersion. Due to the bandwidth and distance advantage of optical interconnects, longer links have been implemented with optics. Recent studies show that optical interconnects have clear advantages even at very short distances – intra system interconnects. The biggest challenge for such optical interconnects is the alignment tolerance. Many free space optical components require very precise assembly and installation, and therefore the overall cost could be increased. This thesis studied the misalignment tolerance and possible alignment correction solutions for optical interconnects at backplane or board level.
First the alignment tolerance for free space couplers was simulated and the result indicated the most critical alignments occur between the VCSEL, waveguide and microlens arrays. An in-situ microlens array fabrication method was designed and experimentally demonstrated, with no observable misalignment with the waveguide array. At the receiver side, conical lens arrays were proposed to replace simple microlens arrays for a larger angular alignment tolerance. Multilayer simulation models in CodeV were built to optimized the refractive index and shape profiles of the conical lens arrays. Conical lenses fabricated with micro injection molding machine and fiber etching were characterized. Active component VCSOA was used to correct misalignment in optical connectors between the board and backplane. The alignment correction capability were characterized for both DC and AC (1GHz) optical signal. The speed and bandwidth of the VCSOA was measured and compared with a same structure VCSEL.

Based on the optical inverter being studied in our lab, an all-optical flip-flop was demonstrated using a pair of VCSOAs. This memory cell with random access ability can store one bit optical signal with set or reset beam. The operating conditions were studied to generate two stable states between the VCSOA pair. The entire functionality test was implemented with free space optical components.
1. Introduction

1.1 Background for optical interconnects

Optical interconnects are considered a promising solution for long distance and high bitrate data transmissions because they outperform electrical interconnects in terms of loss and dispersion \(^1\text{-}^{18}\). In a digital communication channel, low loss is crucial for power efficiency at the receiver side due to signal amplification and recovery; while low dispersion (especially at high frequency) can reduce the ISI (Inter Symbol Interference) and thus reduce the deterministic timing jitter. The timing jitter is critical in a high speed link faster than several Gbps (Giga bits per second) because it determines the requirements for power consumption of the CDR (Clock Data Recovery) circuitry and accuracy of data sampling. For these two reasons optical interconnects have intrinsic advantages in high bitrate and long distance data transfer \(^{19, 20}\).

Due to the bandwidth and distance advantage of optical interconnects, longer links are expected to be implemented with optics sooner than short links, which is in agreement with the historical evolution of optical data transfer \(^{19}\). In long distance communication, optical fiber communication has been ubiquitous for many years. For shorter links of hundreds of meters to tens of meters, such as rack-to-rack links, optics is now being introduced into commercial products \(^{5, 20, 21}\).

Recently studies \(^{10, 20, 22\text{-}24}\) have shown that optical interconnects have clear advantages even at very short distances, i.e., intra-system interconnects. Even for on chip interconnects optical solutions are promising candidates, especially combined with WDM (Wavelength Division Multiplexing) technology \(^{25}\), although WDM is not in the range of this thesis.
The focus of this thesis is on the next practical application for commercial products after rack to rack data transfer: optical interconnects for backplane applications. With the trend from long distances to short ones, the next step will be to provide optical solutions for backplane applications with a distance of about one meter. Hundreds to thousands of I/Os (Inputs/Outputs) with a speed of 10 Gpbs or beyond will be required to deliver the expected Terabit per second aggregate throughput for future high-end systems, such as servers, switch-routers and supercomputers [2, 12, 20, 21].

1.2 Architectures of optical interconnects

An optical link typically includes five parts: Tx (Transmitter), Tx coupler, transmission media, Rx (Receiver) coupler, and Rx. Most short distance optical interconnects are implemented in a multi channel architecture, and these channels are usually integrated into one dimensional or two dimensional arrays in order to increase the channel density and total aggregate throughput. Although single channel optical interconnects are used in some applications such as audio connection etc., this thesis will focus only on multi channel optical interconnects.

The Tx (in array) generates a signal light beam modulated with the data. In long haul optical interconnects (a.k.a. fiber optic communication links) the laser source is typically a DFB (Distributed Feedback) semiconductor laser and the signal is externally modulated onto the CW (continuous wave). The external modulators include EO (Electro Optical), EA (Electro Absorption), AO (Acoustic Optical), etc [26]. For short distance interconnects from rack to rack or inside the box, VCSELs (Vertical Cavity Surface Emitting Lasers) are the most prominent source. A crucial reason is that VCSELs can be easily integrated into one dimensional or two dimensional arrays because the emission surface is on the top of the wafer, and thus the channel number can be increased with little effort. Other advantages include low threshold current, low power consumption, individual
modulation, and simple operation \[27-29\]. Therefore in optical interconnects for backplane applications, VCSELs are the default light source. When VCSELs are used as the light source, direct modulation is usually employed for low cost and structural simplicity \[30, 31\]. In direct modulation, the current to a VCSEL is biased at a DC level slightly above the threshold, and a small AC current signal proportional to the data is added onto the DC bias current.

The Rx includes a photodetector and corresponding amplification and decision circuits. The photodetector is essentially an inversely biased PN or PIN (P-intrinsic-N) junction \[32\]. It senses the photons and generates photo current. This photo current is then amplified with a low noise TIA (Trans-Impedance Amplifier) and converted into a voltage signal \[28, 29, 33, 34\]. For bit detection this voltage is compared with a reference voltage for decision and a logic "0" or "1" is generated. Careful consideration must be given to the design of the Rx because of channel impairments the signal may experience during propagation (noise, crosstalk, misalignment). Additionally, high datarates require high bandwidth detectors with small detection areas thereby trading additional misalignment penalties for a reduced time constant. This will be discussed in details in later chapters.

The transmission channels between Tx and Rx include free space, optical fiber, or optical waveguides. Fiber based optical interconnects are typically used out of the rack, including long haul communication, metropolitan fiber net working, and rack-to-rack interconnects etc.. For backplane or shorter applications, waveguide is more preferred because of its compatibility with the PCB fabrication, as shown in Fig. 1.1 \[19\]. Usually optical waveguides, especially with materials like polymer, have higher losses than silica optical fiber. But for a distance as short as one meter, a rather low loss – 3dB – has been achieved \[19\]. In free space optics the light source array is imaged onto the detector array with free space optical components such as lenses and mirrors, as shown in Fig. 1.2 \[35\].
The light source array can be either one dimensional or two dimensional with little difference in the design for imaging. Therefore the channel density for free space optical interconnect is typically higher than that of waveguide or fiber based optical interconnects. The major challenges for free space optical interconnects are height, environment and misalignment tolerance.

![Fig. 1.1 Waveguide based optical interconnect](image1)

![Fig. 1.2 Free space optical interconnect](image2)

In addition to Tx, Rx, and optical channel the light needs to couple from the Tx into the optical channel and from the channel into the Rx. Many coupling mechanisms and methods have been studied and demonstrated, including free space coupler, butt coupling [36-40], evanescent field coupling [40], and holographic coupling [40, 41]. Our study focuses on the free space coupler because of its interchangeability, misalignment tolerance, and lack of physical contact [19]. The detailed study of this type of coupler is in chapter 2.
1.3 Merits of optical interconnects

Although high speed electrical interconnect are still the dominant solution for in box/rack applications, optics shows great potential to decrease loss and dispersion by the copper trace or cable due to long distance and high bit rate. This has been proven by the fact that optical fiber links have replaced copper cable in long haul communications. The critical distance where optical is better electrical interconnects will become shorter and shorter with the increase of data bit rate.

According to Yuceturk et al, optical interconnect will outperform electric (copper trace on FR4) in terms of loss and dispersion at 5 Gbps for a 40inch link, as shown in Fig. 1.3 [1].

![Fig. 1.3 Comparison of performance between electrical and optical interconnects](image)

In addition to loss and dispersion, another crucial issue in electrical interconnects also requires the employment of optical interconnect: off-chip I/O bandwidth [20, 23]. The latest ITRS (International Technology Roadmap for Semiconductors) indicates that the internal chip performance will keep increasing at a rate of about four times every three to four years. During the same period, however, the signal pins per chip will only increase
about two times and the bit rate per pin only 35\% \textsuperscript{[42]}. Thus the total off-chip I/O bandwidth increases only 2.7 times while the internal chip performance increases 4 times. After a decade, this difference will result in a three to one ratio between internal chip performance and off-chip I/O, which will make off-chip I/O an performance bottleneck and dramatically affect balanced system design \textsuperscript{[20, 43]}. To make matters worse, the actual improvement of off-chip bandwidth may be even lower in most cases since only a small number of pins can reach the maximum off-chip rate while many operate at a lower bit rate. Some other trends, for example packaging cost per chip increasing 5\% each year, also illustrate that many high performance chips will be increasingly limited by off-chip bandwidth. Optical interconnects are considered a good candidate to break this bottleneck \textsuperscript{[20, 42]}.

Compared with electrical interconnects, optical interconnects have the intrinsic advantages of high speed, low loss (with distance), low dispersion, high channel density, and high bandwidth. These advantages make optical interconnects viable candidates to be used at the backplane/midplane level for the advanced servers in the near future \textsuperscript{[20, 23]}.

1.4 Challenges of optical interconnects

Although optical interconnects have many advantages, there are also major challenges needing to be solved before optics are widely used in short distance commercial interconnects \textsuperscript{[2, 4, 6, 8, 20, 23]}.

The biggest challenge is the alignment tolerance \textsuperscript{[6, 11, 44]}. Many free space optical components require very precise assembly and installation thus increasing the overall cost. The cost penalty is even greater for packages which require active alignment of components. The most stringent alignment requirements are often imposed on the free-space and guided-wave coupling components, i.e., from VCSEL to waveguide, and from the waveguide to photodetector. A detailed analysis on the coupler misalignment
tolerance can be found in chapter 2. Chapter 2, 3 and 4 focus on practical solutions to increase alignment tolerance for couplers, receivers, and board-board connectors.

Besides the alignment challenge the O-E (Optical to Electrical) and E-O conversion components limit some of the performance. These devices are usually the limitation for speed, consumed power, reliability and integrability [2, 15, 16, 26, 30, 31]. For example, VCSELs are considered the best candidate of transmitters for short distance optical interconnects, for their unique advantages such as integration ability, threshold current, and power consumption, etc. However, the reliability of VCSELs has always been at question [45]. Unless there is some physical limit many device related issues can be solved or alleviated with the development of micro fabrication technology, which is driven by the tremendous and ever increasing CMOS (Complimentary Metal Oxide Semiconductor) market.

The device related limitations could be addressed and solved with help from other technologies, while the system level challenges could still require special effort.

1.5 Optical buffer and memory

Future optical interconnects may require optical switching to further enhance the performance and remove the O-E/E-O bottleneck. Currently, the study on optical switching is limited mostly to optical routers in long haul fiber communications. This technology, however, can provide a helpful resource and possibly a shortcut to optical switching for very short distance (meters) interconnects.

Most of the proposed architectures process the packet header electronically [46] and make the routing/switching decisions using electronic control circuitry [47-50]. This approach can avoid the O-E/E-O conversion only for the data portion in the packet, but the header processing is still subject to the speed of the conversion. Since the optical data needs to wait for the header to be processed electrically a delay line must be employed.
These delay lines have been traditionally implemented simply with a length of fiber as done traditionally. Recent research indicates properly designed photonic crystals can slow light dramatically \cite{51-54}. For example, the silicon photonic crystal waveguide chip fabricated by IBM can actively control the amount of delay on the light \cite{55}. However, all these implementations can only delay or slow light, and they cannot store the light, i.e., the light cannot be directly accessed like RAM (Random Access Memory) in electronics.

Some researchers proposed a future all-optical network architecture for optical data packets to be routed quickly through all-optical nodes. \cite{56} In this scheme the packet header/label bits must be all-optically recognized and then the packet routed/switched transparently and with high throughput. \cite{57, 58} The all-optical label reading and packet routing has to be based on all-optical logic XOR gates and all-optical flip-flops, as shown in Fig. 1.4. \cite{56}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig1_4.png}
\caption{The architecture of a future all-optical packet router}
\end{figure}

All optical flip-flops are key devices in optical packet switching in the above architecture \cite{59}. They also provide the necessary all-optical latching functions for optical
routers in long haul fiber communications such as buffering, storage of decisions, and self-routing capabilities. During the last several years, there have been several demonstrations reported on implementing all optical flip-flops, [56, 60-66] including the bistable operation of laser cavities, external feedback with semiconductor optical amplifiers (SOAs), Mach-Zehnder interferometer based on SOA, and an SOA pair.

In Chapter 5 a new method to realize an optical flip-flop using a pair of vertical cavity semiconductor optical amplifiers (VCSOAs). VCSOAs have the advantages of high speed, high gain and low noise figure. Furthermore, the ability to fabricate large 2D arrays of VCSOAs enables the possibility for large scale integration.

1.6 References:


38. K. Tai, C. C. Wu and K. F. Huang, "Reliability studies of 0.85-μm VCSELs", 1994 Conference on Optical Fiber Communication - OFC'94. San Jose, CA


47. N. Wada, H. Harai and W. Chujo, "Multi-hop, 40 Gbit/s variable length photonic packet routing based on multi-wavelength label switching, waveband routing and label swapping", Optical Fiber Communications Conference (OFC). Anaheim, CA


2. In situ lenslet array fabrication on the edge of a waveguide array

As shown in chapter 1, optical interconnects have the advantages of high speed, high channel density and high aggregate throughput for sufficient long distance interconnections, compared with conventional electrical interconnects \[1, 2\]. However, the alignment tolerance for optical components often requires very precise assembly and installation, and therefore increases the overall cost. The most stringent alignment requirements are often imposed on the coupling components \[3\]. Typically for guided wave interconnects the misalignment penalty is incurred at the laser-waveguide and waveguide-detector coupling.

2.1 Misalignment tolerance for free space coupler

2.1.1 Simulation methods

Free space coupler is a typical structure to couple light using two microlenses integrated with the source and the receiver, respectively, as shown in Fig. 2.1. For the coupling between the VCSEL and waveguide, the source/detector aperture is about 10~20\(\mu\)m, the microlens diameter is about 250\(\mu\)m, and the coupling distance is about 4~7mm.

![Fig. 2.1 Free space coupler](image_url)

Several methods were used to simulate this structure:
1. Gaussian beam tracing

The beam is assumed to be a pure zero order Gaussian beam, and the ABCD matrix \[^4\] is used to model the beam propagation. The calculation is implemented in Matlab. Since the expression is rather complicated when considering high order modes from the VCSEL, only fundamental Gaussian mode was simulated using this method.

2. Ray tracing algorithm

Commercial software (both Zemax and CodeV) were used to implement the ray tracing. This approach has high computation speed and accurate result for large dimensions where beams can be represented as straight lines. However this method is not accurate enough for small dimension such as 10 µm because of the effect (for example, divergence) of Gaussian beam propagation.

3. Finite-Difference Time Domain (FDTD)

Commercial software is available for this algorithm, for example, FullWAVE, from RSoft, Inc.. This algorithm solves the Maxwell Equation without any approximation and the result is supposed to be very accurate. However, it takes a lot of computation power and the run time is too long for a device of several millimeters.

4. Finite-difference beam propagation (BMP)

BMP algorithm is realized in BeamPROP, from RSoft, Inc.. It solves the Maxwell equation with two major approximations - 1. System is time invariant. 2. The index of reflection of the structure does not have sudden change along the
propagation direction. This algorithm is widely used in waveguide structure simulations.

BeamPROP is a good compromise between computation power and accuracy for the dimensions of free space coupler. This method is used to study the misalignment tolerance for VCSEL-waveguide coupling, as shown in Fig. 2.2.

![Simulation structure for free space coupler, in BeamPROP (RSoft Inc.)](image)

2.1.2 Simulation result for misalignment tolerance for free space coupler

The lateral misalignment is studied between microlens and microlens. The free space coupler is configured to a 4F condition, i.e., VCSEL is at F (the focal length of microlens) away from the first microlens, the distance between two microlenses is 2F, and the waveguide is F away from the second microlens. The second microlens was laterally misaligned from the first one. The power loss due to misalignment was then simulated, as shown in Fig. 2.3.
Fig. 2.3 Loss due to lateral misalignment between microlens and microlens

Several VCSEL apertures were chosen to represent different source conditions from a diameter of 12µm to 35µm. The loss was simulated for lateral misalignment from 0 to 90µm. From the data we can see that the misalignment for 1dB loss is about 50µm. In precise installation of the microlens pair, usually the lateral precision can be limited to under 30~50µm. Therefore the free space coupler can tolerate the installation error and keep the coupling loss less than 1dB.

It can be concluded that the free space couplers have excellent misalignment tolerance to microlens-microlens misalignment.\cite{5}

The misalignment was also studied between VCSEL-microlens and microlens-waveguide coupling. VCSEL aperture of 16µm was chosen since it is the value used in most commercial VCSEL arrays. The lateral misalignment effects for both the VCSEL-microlens or microlens-waveguide were simulated and shown in Fig. 2.4.
From the simulation results, the VCSEL-microlens coupling has a tolerance of 12µm at 1dB loss, and 18µm for microlens-waveguide coupling. And both of them drop much faster with misalignment compared with microlens-microlens misalignment, which is shown as pink curve in Fig. 2.4.

So, although the free space coupler has excellent alignment tolerance between microlens-microlens, critical alignment is still required at the laser-lens and lens-waveguide and lens-detector interfaces \cite{6}. For this reason coupling lenses are often integrated directly with the laser source and the detector. It is also desirable to integrate the coupling lenses with the waveguides during fabrication. When this is possible, only lens-lens alignment that provides relax alignment tolerances is required during assembly or installation.

The integration of lenslet arrays with the VCSEL and detector arrays was studied and demonstrated by VCSEL and detector array manufacturers (for example, Honeywell Inc.)
Unfortunately waveguide-lenslet integration techniques usually involve aligning a waveguide array with a lenslet array until an optimal transmission pattern is observed, and fixing the two assembly with UV-curable glue. The alignment process is usually serial and expensive while the curing process often misaligns the system. This process becomes even more cumbersome if the waveguides are in a hard to reach location, for example if they are embedded in a printed circuit board (PCB) for backplane interconnects. It would be much more efficient and accurate if the lenslet array is integrated directly on the edge of the waveguide array.

In this chapter we present an in situ lenslet patterning and integration method using surface tension force. The lenslet array can be fabricated on the edge of a waveguide array and can be precisely aligned with the waveguide cores even when the waveguides are embedded in PCB.

### 2.2 Methods to fabricate a lenslet array on the edge of a waveguide array

The fabrication procedure for in situ lenslet array includes two steps. Step one is lenslet array in situ patterning, and step two is the lenslet fabrication on the patterned surface using surface tension force.

#### 2.2.1 In situ patterning for lenslet array

The procedure for in situ lenslet fabrication starts from the lenslet array patterning, as shown in Fig. 2.5. A glass wafer, which will hold the lenslets and is hydrophilic itself, is prepared with two layers, including a hydrophobic layer (RainX) on the wafer and a photoresist layer on top of the hydrophobic layer. The wafer is then glued on the edge surface of the waveguide array embedded in a published circuit board (PCB). A
customized exposure setup is built on a stage, as shown in the dashed frame in the figure. The stage can move two dimensionally until a best focused image on the CCD camera. The mask defines the pattern of the lenslet array, either one dimensional or two dimensional, and it is imaged onto the wafer surface through an objective lens. The CCD camera, through the same optics, captures an image of the wafer surface.

When light is coupled into the waveguide array from the far side, one can see the cores of the waveguide array, as well as the image of the mask with the CCD camera. In this case, the mask can be aligned easily with the cores of the waveguide array. For mass production the alignment could be automated with image processing techniques. After alignment, the mask pattern is transferred to the photoresist with UV illumination.

![Fig. 2.5 Configuration of hydrophilic / hydrophobic (H/H) patterning](image)

A prepared glass wafer is attached on the edge of a waveguide array. The mask for lenslet array is imaged onto the glass wafer. From CCD camera, one can see the images of the cores of the waveguide array, as well as the image of the mask. The mask can be aligned with the waveguide array easily.

2.2.2 Lenslet fabrication using surface tension force

After the wafer is exposed with the lenslet array pattern, the other processing is implemented in a clean room, as shown in Fig. 2.6. First the exposed photoresist is
developed, and then plasma etching is used to etch the hydrophobic layer and change the etched area to hydrophilic. After removing the photoresist, the wafer is hydrophilic / hydrophobic patterned. When dipped into a monomer solution a liquid lenslet array forms in the hydrophilic areas, due to surface tension force \[^{[8]}\]. Then UV light is used to polymerize the monomer and solidify the lenslet array.

![Fig. 2.6 Lenslet fabrication on hydrophilic / hydrophobic patterned surface](image)

Exposure and development creates the pattern of lenslet on photoresist. Plasma etching converts the areas unprotected by photoresist from hydrophobic into hydrophilic. Monomer solution only attaches on the hydrophilic area, and lenslet array is formed.

### 2.3 Experimental setup and fabrication process

A demonstration was conducted with a waveguide sample provided by IBM Zurich research lab. Microscopy cover slides were used as the glass wafer, which also works as a spacer between the lenslet array and the waveguide array. The experimental setup is shown as in Fig. 2.7. The mask, illuminated by collimated UV light, is imaged onto the wafer surface through a 4x objective lens. The image on the wafer surface is monitored by a CCD camera through the same objective lens. So are the waveguide cores which are illuminated by a visible laser diode from the back. The image of the mask can be aligned with the waveguide cores without moving the waveguide or the wafer.
The glass wafer was then exposed by the UV light through the mask and the objective lens. Then the waveguide unit including both the wafer and the waveguide (glued together) was taken into a fabrication lab for lenslet array fabrication. At the ITL (Integrated Technologies Laboratory) in UCSD, the wafer surface was first developed and cleaned. Then the unprotected areas of the hydrophobic (RainX) layer were etched in a plasma etcher (Technics PE-II-B Plasma Etcher). After photoresist removal (using Acetone) a hydrophilic / hydrophobic (H/H) patterned lenslet array was obtained on the wafer surface. By letting the monomer solution flow along the wafer surface, monomer stays at the hydrophilic areas, forming the desired lenslet array.

### 2.4 Characterization for the device fabricated

Using in situ lenslet array patterning, the alignment between the lenslet array and the waveguide array can be controlled precisely, by simply monitoring the lenslet pattern and waveguide cores simultaneously. In the experiment, no visible misalignment was observed from the CCD camera, as shown in Fig. 2.8(a). The structure of the lenslet array
on the sample waveguide array is illustrated in Fig. 2.8(b). The lenslet array was fabricated as a two dimensional array, which works for both one dimensional waveguide arrays (some lenslets are not used) and two dimensional waveguide arrays if available.

Fig. 2.8 Alignment and structure of the in situ fabricated lenslet. 
Fig. 2.8 (a) In situ lenslet array patterning, aligned with waveguide cores. In the figure, the big round dots are lenslet array pattern, and the small square red dots are waveguide cores. Fig. 2.8(b) shows the structure of a lenslet array fabricated on a waveguide array.

Fig. 2.9(a) shows the fabricated lenslet array and Fig. 2.9(b) is a detailed view of a single lenslet in Fig. 2.9(a). The roundness of a lenslet and the uniformity of the array were checked qualitatively, and both are within the acceptable range. Some polymer residue remains in the hydrophobic area, although it does not affect the functionality of the lenslet array.
For characterization, a multi mode fiber was used to couple the light into a single channel of the waveguide array from the far side. Then the diameter and divergence angle of the beam emerging from the integrated lenslet were measured. Far field patterns were measured and compared under three conditions: 1. No lenslet; 2. In situ fabricated lenslet; 3. Assembled commercial lenslet (from SUSS MicroOptics, Switzerland). The alignment of the assembled lenslet could be made perfect only for one of the lenslets but not for the entire array. We compare the results here for the best aligned lens. For the integrated solution all lenses were perfectly aligned. Fig. 2.10 shows the far field beam diameter and divergence angle for these three conditions.
Fig. 2.10 Far field beam diameters and convergence angle under three conditions
The beam diameters at different distance under four conditions were measured, and
the corresponding divergence angles were calculated.

The in situ fabricated lenslet and the assembled lenslet have similar performance, in
terms of beam convergence. They both have much smaller divergence angles (3.29 deg.
and 3.49 deg.) than the case without lenslet (8.55 deg.).

2.5 Conclusion
In this chapter, we described and discussed a method to integrate a lenslet array on
the edge of an embedded waveguide array that was demonstrated experimentally. This
method can guarantee the alignment precision between lenslet array and waveguide array
with little alignment effort, and the integration technique can in principle be parallelized
and made suitable for mass production.

In the demonstration experiment, the lenslet array pattern was well aligned with the
waveguide cores, with no visible misalignment shown on the CCD camera. The
roundness of each single lenslet and the uniformity of the entire lenslet array were
qualitatively checked and they were all within the acceptable range showing negligible
non-uniformity. Far field beam divergence angle was quantitatively characterized. The result shows that an in situ fabricated lenslet array has similar performance with the best lenslet of an assembled commercial lenslet array in terms of divergence angle. They both have much smaller divergence angles (3.29 deg. and 3.49 deg.) than the case without lenslet (8.55 deg.).

Acknowledgement

This chapter will be published as "Integration of precisely aligned lenslet arrays with waveguide arrays", D. Song, D. Jorgesen, M. Gross, and S. Esener. The dissertation author will be the first author of this paper.

2.6 References:


3. Simulation and fabrication methods for micro gradient index conical lenses

3.1 Introduction

From chapter 1 we know that one of the advantages of optical interconnections is high bitrate. [1-4] Consequently photodetectors must be scaled down to reduce parasitic capacitance. The standard method to collect light for small photodetectors is to use a microlens before the photodetector to focus the light beam onto the detector. In this approach, the acceptance angle (only the light within this angle can be focused onto detector) of the microlens is about two or three degrees, under the assumption that the microlens diameter is 250 microns, detector diameter is 50 microns, and F-number of the microlens is 2. However in some applications, such as board-to-board optical interconnects and wireless optical communications, a larger acceptance angle is desired to increase the link distance to achieve looser misalignment tolerances. [5]

To get a larger acceptance angle, micro gradient index conical lens (MGCL) is a good alternative to the microlens, in terms of collecting light. An MGCL is a lens in a tapered shape made of gradient refractive index material. As shown in Fig. 3.1, the shape profile is generated by rotating a curve with equation \( y = R(z) \) around axis \( z \), and the refractive index at a certain location follows \( n(r, z) = f(r, R(z)) \), where \( R(z) \) is the radius of the cross section at position \( z \).

![Fig. 3.1 Gradient index conical lens (GRIN-CL)](image-url)
When \( R(z) \) is a straight line, this description degrades to a normal conical lens with gradient index (GRIN). Several studies have addressed the ray propagations in normal conical GRIN lenses, especially with gaussian or parabolic index profiles.\(^5\) For a normal conical GRIN lens with a parabolic index profile, the ray trajectories can be obtained analytically by solving the Eikonal equation.\(^5, 6\) The solution shows that the behavior of a ray in a normal conical lens is a sinusoidal in radius, decreasing as the ray moves toward the conical tip.\(^5\) This shows that the GRIN lens is capable of converging light.

In contrast, solid index conical lenses have a constant refractive index with a variable shape profile. Also known as an “optical concentrator”, solid index conical lenses have been studied for many years.\(^7-10\) An optimal shape profile for solid index conical lenses was solved as a compound parabolic concentrator (CPC). For any predetermined acceptance angle, a CPC can be designed, so that behind this CPC, the detector will collect all the rays entering the lens within the acceptance angle. The maximum acceptance angle for an ideal CPC is nearly 90°.\(^7\)

Although the CPC is an optimal solution for light funneling, it has a very stringent requirement on curvature profile fabrication. In micro optical systems, such as optical interconnects or fiber communication, the lens dimensions are on the order of tens to hundreds of micrometers, which makes the curvature requirement impractical to satisfy. In this paper, we combine the properties of both GRIN lens and optical concentrator and form a new structure. The resulting lens can be fabricated at small dimensions,\(^11\) although some sacrifice of acceptance angle is required. We investigate the effects of different shapes and several refractive index profiles, and implement the simulation for conical lenses using Code V.
3.2 Simulation methods for MGCL

The best simulator is determined by the dimension and shape of the device. MGCL has a 250μm entrance and a 50μm exit, and this is 294 and 59 times larger than the feature size of optical wave (0.8μm). In this dimension, geometrical optics is supposed to give the correct result. Although vector wave optics is a more rigid simulator (for example, FullWAVE from RSoft INC.), it is not practical to simulate a 2.5mm long device. For some scalar wave simulator (BeamPROP from RSoft INC.), which is more efficient than vector wave simulator, the side wall slope might break the slowly varying envelope approximation of the simulator.

Based on current commercial optical simulation software for ray tracing, GRIN lenses with a conical shape cannot be simulated directly, although several models can provide an approximate simulation. The three models are: Sequential surfaces model (SS model, as in Fig. 3.2a), nested cones model (NC model, as in Fig. 3.2b), and segmented nested cones model (SNC model, as in Fig. 3.2c).

![Fig. 3.2 Three available models for GRIN-CL](image)

The SS model simulates the conical lens by a series of sequential cylindrical layers with different diameters, where the index profile of each surface is defined according to the location of the surface. In the NC model, the conical lens is decomposed into a number of non-sequential surfaces, layered from axis to side boundary. The refractive indexes keep constant in each single surface, but change from surface to surface. The
SNC model is a combination of the SS model and the NC model. First the conical lens is cut into a number of segments longitudinally, similar with the SS model. Then each segment is modeled by the NC model.

The SS model works very well for paraxial beam propagations, while it has difficulty in dealing with reflections on the side boundary. The limitation of this model is that the side boundary of each thin cylindrical surface is always parallel to the cone axis, which is not true in reality. The NC model is suitable for side boundary reflection, and it can simulate high order curve cone surface. NC model works more accurate for beams with a large incident angle to the conical lens. For paraxial beam simulation using NC model, reflection could occur on the interface between adjacent cone layers because of grazing incidence. And the reflection is generally not included in the simulation, thus the simulation accuracy is affected. While with a larger incident angle, the reflection will reduce. The SNC model is an improved NC model. Since each segment has the property of an NC model, it has no difficulty in dealing with reflections at the boundary; since the whole conical lens consists of several segments, it has more flexibility and can represent almost any shape profile.

In order to build a MGCL in CODE V as accurately as possible, a large number of surfaces are used. Generally the surface number is several hundred. Due to the fact that these surfaces follow some common rules, we used a helper program (written in C++) to generate these surfaces in CODE V. After this model is built in CODE V, the acceptance angle can be measured.

3.3 Simulation Results

The purpose of our simulations is to investigate the acceptance angles of MGCLs with different refractive index and shape profiles for various diameters of the incoming light beam.
The parameters for the MGCL are as following. The basic refractive index is \( n_0 = 1.50 \). For gaussian index profiles, the refractive index change from the center to the boundary is \( \Delta n = 0.05 \), ie., the index at the center is \( 1.55 (= n_0 + \Delta n) \), and the index at the boundary is \( 1.518 (= n_0 + \Delta n \frac{1}{e}) \). The cone length is 2.5mm, and the diameter of the entry and exit surfaces are 250\( \mu \)m and 50\( \mu \)m respectively. The entry has the same diameter as a microlens, and the exit has the same dimension as a photo detector.

3.3.1 Comparison of solid index and gaussian index profiles

The transmission efficiency, defined as the percentage of the optical power received at the detector surface to the total incident optical power, is used to compare the different structures. The efficiency with different normalized diameters and at different incident angles is plotted in Fig. 3.3, where the normalized beam diameter is defined as the ratio of the diameter of the incident beam to that of the lens entrance.

![Comparison of Gaussian and solid index profiles](image)

**Fig. 3.3** Transmission efficiency of conical lenses for various normalized incident beam diameters
It is seen that for both index profiles, for a given beam diameter, the efficiency drops with increasing incident angles. From the results, we can see that the efficiency of a gaussian index profile lens falls off more slowly than that of a solid index profile lens. Specifically, when the normalized beam diameter is 0.5 (125μm), for a threshold of 50%, the acceptance angle for the gaussian index lens is more than 17°, and more than 13° for the solid index lens. In either case the acceptance angle is over four times larger than that with a simple microlens, which is about 3°. So we can conclude here that the gaussian index profile realizes an improvement in acceptance angle, as compared to a solid index profile.

3.3.2 Comparison of different shape profiles

Since the gaussian index profile has a larger acceptance angle than solid index profile, we further investigated the shape effects for conical lenses with a gaussian index profile. Three typical shapes are explored: normal, concave, and convex cones.

The normal cone has straight side walls, while the convex and concave cones are given an outward or inward curvature at the side walls. As shown in Fig. 3.4, these three different shape profiles have similar performance. In a close comparison at high efficiency level (>70), the concave cone shape has slightly smaller acceptance angle than the normal cone, while the convex has slightly bigger acceptance angle. Considering the fabrication difficulty, the normal cone shape is identified as the optimum because it is much easier to fabricate than cone lenses with curved shapes.
Comparison of various shape profiles

Fig. 3.4 Efficiency of gradient index cone lenses for various normalized incident beam diameters for three cone shapes

3.4 Fabrication and measurement

Among all the index profiles and shape profiles, solid index normal conical lenses can be fabricated the most accurately, so we choose this lens to experimentally verify the simulation result of acceptance angle. For a primary experiment, fiber etching is an efficient and flexible way to attain a solid index conical lens. We used 48% HF acid to etch a multimode fiber core with a 200μm diameter (FT-200-EMT, Thorlabs INC.). The fiber is dipped vertically into the etching solution, attached to a linear motion actuator, which is used to pull the fiber out from the etchant slowly in order to form a conical shape. The slope of the cone can be controlled by the pulling speed (e.g., a fast pulling generates a small slope on the fiber). By this means we obtain a tapered fiber with a desired slope, as shown in Fig. 3.5. After cutting the etched fiber at proper positions and polishing, it can work as a conical lens. The conical lens we fabricated has an entrance diameter of 200μm, an exit diameter of 60μm, and a length of 2mm. For mass production
of conical lens array, injection molding might be a better approach, considering the high precision and potentially low cost.

![Etched multimode fiber](image)

**Fig. 3.5 Etched multimode fiber**

In order to measure the acceptance angle of this conical lens, a rotating stage was used to provide angular movement, as shown in Fig. 3.6. The collimated incident laser beam has a beam diameter of 120μm, measured with a laser beam profiler (Digital BeamView Analyzer LASERCAM, Coherent INC.). The conical lens is located in the rotating center of the stage, followed by a pinhole and detector. The use of the pinhole is to block the light leaked from the side surface of the conical lens.

![Experimental setup](image)

**Fig. 3.6 Experimental setup**

The normalized optical power, defined by the ratio of received power to the maximum received power, is plotted against the incident angle, as shown in Fig. 3.7. When we choose 50% as the detection threshold, this conical lens provides an acceptance angle from -12° to +15°. This demonstrates that the acceptance angle of the conical lens
is significantly larger than that of a simple microlens (shown as a dashed line in Fig. 3.7). In this experiment, the full angle of $27^\circ$ is over 4 times larger than that of an equivalent microlens. For comparison, the simulation result for this cone lens is also shown in Fig. 3.7 (round symbols connected by dotted lines). It can be seen that the experimental acceptance angle is very close to the simulation result, except that the experimentally detected energy falls off more gradually with incident angle than the simulation result. A main reason for this difference is the reflection loss due to the fabrication defects. The number of reflections increases with the incident angle, thus the reflection loss takes more effect. This will make a gradual drop in efficiency. Another possible reason is that we used geometric ray tracing in the simulation, which assumes a uniform energy distribution on the whole beam cross section and all the rays are ideally collimated. But an actual beam has a gaussian energy distribution. Non-ideal collimation and diffraction may also contribute to the discrepancy. So in practice, the detected energy is more likely to drop gradually when increasing incident angles, instead of falling off suddenly after a critical incident angle, as in simulation.

![Correlation of simulation and experiment](image)

**Fig. 3.7** Normalized optical power at different incident angles
3.5 Conclusion

By using practical models (SS, NC, and SNC) to simulate micro gradient index conical lenses (MGCL) in CodeV, we verified that MGCL has a larger acceptance angle than a simple microlens. The shapes and refractive index profiles both have effects on the acceptance angles of MGCL. Conical lenses with a gaussian index profile have a larger acceptance angle than solid index profile lenses; convex, normal, and concave cones have similar acceptance angle, although convex cones slightly outperform at high efficiency level. Considering the fabrication, a normal cone with a gaussian index profile as appears to be the best solution for increasing acceptance angle in a practical micro optical system. A gaussian index normal MGCL can provide an acceptance angle of about $\pm 17^\circ$ for a 50% detection threshold.

A fabricated conical lens shows a -12 deg to +15 degree acceptance angle, similar to the simulation result of $\pm 14^\circ$ for this device. Under the same conditions, an ideal simple lens can only provide an acceptance angle of $3^\circ$. Thus, the MGCL is an attractive alternative to the simple microlens for increasing the acceptance angle.

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3.6 References:


4. Misalignment correction for optical interconnects using VCSOAs (Vertical Cavity Semiconductor Optical Amplifiers)

4.1 Introduction

In high speed signaling architectures for board-to-backplane or board-to-board applications, optical interconnects have the advantages of higher data rate, higher channel density and higher aggregate throughput than conventional electrical interconnects\(^1,\,2\). However, the alignment tolerance for optical components requires very precise assembly and installation, and therefore increases the overall cost. At the chip and board level, the relay lenses and coupling structures often require alignments\(^3\); while for board-to-backplane or board-to-board interconnections the connectors relaying light from board to backplane may have misalignment. This misalignment includes both lateral and angular uncertainties. Lateral shifts don't scale with interconnect distance, and small lateral errors can be corrected fairly simply by using a lenslet array in front of the detector or waveguide array. However the angular misalignment can cause a relatively large error that scales with the propagation distance. Devices and structures have been studied to correct angular misalignments, including parabolic mirror to transfer angular error to lateral error to compensate the angular error in board installation\(^4\), and MEMS controllable microlens to control the direction of beams from the VCSEL array (Vertical Cavity Surface Emitting Lasers)\(^5\).

In this chapter, we present a method to correct angular misalignment using an active device — a VCSOA (Vertical Cavity Semiconductor Optical Amplifier). A VCSOA has a structure similar to a VCSEL\(^6\). The signal light is coupled into the cavity through a DBR (Distributed Bragg Reflector) mirror. Inside the cavity, population inversion is
generated by optical or electrical pumping, and the stimulated emission amplifies the input optical signal. Compared with an edge emission SOA (Semiconductor Optical Amplifier), a VCSOA has a high quality factor resulting in large amplification and good suppression of spontaneous emission noise. By using a VCSOA, the optical signal can be amplified, reshaped and regenerated, and the signal to noise ratio can be improved by the nonlinearity of the device [7].

4.2 Methods for misalignment correction

Free space optical connectors, among which two typical structures are shown in Fig. 4.1, are preferred for board-to-backplane connections because of their low insertion force and high channel density. In structure (a), the light from the board-waveguide is collimated by a lenslet and then reflected by a mirror on the backplane. The beam is then converged by another lenslet on the backplane and coupled into the backplane-waveguide. Since the propagation beam is a collimated beam, this connection has excellent lateral misalignment tolerance [8]. Since the beam uses a large area of the mirror, the beam is rather insensitive to the mirror defects. However in this structure a relatively large mirror area is necessary to avoid beam clipping. In structure (b) the light is first focused on the mirror with the lenslet on the board, and then converged onto the backplane-waveguide with the lenslet on the backplane. Since only a small portion of the mirror is used to reflect the focused beam, this structure is quite sensitive to the mirror defects. However, a small mirror area and volume makes it easier to dynamically control the mirror to compensate for misalignment.
Fig. 4.1 Two typical structures to interconnect light between a board and the backplane
Structure (a) uses collimated beam propagation
Structure (b) uses focused beam propagation

The method to use an active device VCSOA is a hybrid of these two conventional structures. The detail configurations are shown in Fig. 4.2(a) and Fig. 4.2(b) for angular and lateral misalignment corrections, respectively. In the configuration shown in Fig. 4.2(a) the input beam has angular error because of board misalignment, and thus the beam is focused on the VCSOA with an incident angle uncertainty, as shown in dark and bright incident beams. When the VCSOA is biased barely below threshold (95% or 98% of threshold current, as in experiment), the input signal light increases the cavity gain and alters the VCSOA lasing condition. In lasing mode, the emitted light is always perpendicular to the cavity surface independent of the direction of the incident signal light. Therefore the output light has no angle uncertainty as the incident light does. This property of the VCSOA can be used for angle correction. In the configuration shown in Fig. 4.2(b) the incident light has a lateral misalignment instead of an angular error. To correct this misalignment the lenslet is configured to collimate the light out from the board-waveguide instead of converging it as in configuration (a). Another mini lens is used in the correction module (on the backplane) to transfer lateral shifts into angular errors. As in configuration (a) the output light is always in the same direction and location, independent of the incident signal light.
The misalignment correction ability is limited by the acceptance angle of the VCSOA. In the configuration of Fig. 4.2(a) the maximum corrected angle is the same as the acceptance angle of the VCSOA; while in Fig. 4.2(b) the lateral misalignment can be calculated from $\Delta x = f \cdot \Delta \alpha$, where $f$ is the focal length of the converging mini lens, and $\Delta \alpha$ is the acceptance angle of the VCSOA. Therefore the characterization of the misalignment correction capability is equivalent to a characterization of the VCSOA acceptance angle.

### 4.3 Angle correction ability of a VCSOA for DC signal

Since the capabilities for both angular and lateral misalignment corrections are determined by the same property of the VCSOA, characterization of the capability of either one can be used to determine the capability the other one. Considering the measurement precision and experiment difficulty, we characterized the correction ability
for lateral misalignment. The acceptance angle was then calculated from the lateral misalignment correction.

4.3.1 Experimental setup

The experimental setup is similar to a setup for measuring the gain of a VCSOA [6], as shown in Fig. 4.3. The signal light was generated by a tunable diode laser (DL-100, Toptica Photonics Inc.), and the polarization was adjusted with a half waveplate. Two 50:50 beam splitters were used to provide beams to monitor the wavelength and the power of the input beam, as well as the power and the direction of the output beam. In order to monitor the output beam direction, the beam profiles were captured by a CCD camera and the beam centers were calculated with Gaussian profile fitting. In the experiment, first the wavelength and polarization of the signal light were tuned to the optimal condition for maximal gain, usually above 40. Then some misalignment (angular misalignment to the VCSOA) was introduced by laterally shifting the beam splitter, as shown on the right in Fig. 4.3. The residual error in the corrected beam was measured from the images captured by the CCD camera.

![Fig. 4.3 Experimental setup to characterize the acceptance angle of VCSOA](image-url)
4.3.2 Results of angle correction ability for small DC signal

In the experiment, the VCSOA was biased at 6.66mA, which is 98% of threshold current, and the amplified spontaneous emission was around 2μW to 4μW. The input power from the tunable laser to the VCSOA was fixed at 1.03μW. When the input wavelength was tuned to 845.556nm, the output reached 50μW, obtaining the maximal gain of 50.

An objective lens with focal length 12mm was positioned in front of the VCSOA to converge the incident light to the VCSOA aperture of 20μm. The lateral misalignment scanned from -0.2mm to +0.2mm, which corresponds to angles from -2° to +2°, as shown in Fig. 4.4. The angles of the output beam were measured and are plotted with round dots in the same figure.

From the two measurements, it can be seen that the gain of the VCSOA drops with angular misalignment gradually. The 3dB gain acceptance angle is from -0.8° to +0.9° (total 1.7°) for both measurements. While the input angle changed from -2° to +2°, the output beam was almost in the same direction. Most of the output angles measured were near to 0°, with standard deviation of 0.06°. Equivalently, if configuration (b) is used to correct lateral misalignment, the correction ability will be ±15 · tan(Δα) = ±0.015f (total 0.03f), where f is the focal length of the lens before the VCSOA. For example, using an objective lens with focal length 12mm, ±0.18mm (total 0.36mm) lateral misalignment tolerance was obtained.
Acceptance angle of VCSOA

![Graph](image)

Fig. 4.4 Experimental result for the acceptance angle of a VCSOA and the angle change of the output beam: input is small DC signal

4.3.3 Effect of polarization and power on correction ability

The angle correction ability was also characterized as a function of polarization direction and input power levels, and the results are shown in Fig. 4.5. The angle tolerance for half maximal gain was measured and is shown in Table 4.1.

![Graphs](image)

(a) Fig. 4.5 Angle correction ability for different polarizations and input powers
(a) for all three polarization with input power of 1μW
(b) for all three polarization with input power of 2μW
Table 4.1 Angle correction capability under different working conditions (Degrees)

<table>
<thead>
<tr>
<th></th>
<th>Vertical P.</th>
<th>Horizontal P.</th>
<th>Circular P.</th>
<th>Average</th>
<th>Max. Diff.</th>
</tr>
</thead>
<tbody>
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<td>1μW input</td>
<td>3.0</td>
<td>3.3</td>
<td>3.5</td>
<td>3.27</td>
<td>8.3%</td>
</tr>
<tr>
<td>2μW input</td>
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<td>2.6</td>
<td>3.4</td>
<td>3.1</td>
<td>16%</td>
</tr>
<tr>
<td>Difference</td>
<td>4.8%</td>
<td>12%</td>
<td>1.4%</td>
<td></td>
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</tr>
</tbody>
</table>

From the results under different experimental conditions, it can be seen that the angle correction ability doesn't show much dependence on the polarization and input optical power. Therefore this correction method can be implemented with any polarized light beam at a low power level, without a considerable difference in terms of correction angle.

4.4 AC performance of angle correction

Section 4.3 describes the angle correction capability for DC input optical signal at 1μW optical power level. For practical use in interconnects, however, AC characterization is necessary to predict the performance of the device in real application, which mainly consists of high frequency components. In addition, for angular misalignment correction the typical input optical power is from tens to hundreds of micro watts, not as small as 1μW as in section 4.3. In this section the AC functioning of the correction ability is characterized with input optical power around 30μW.

4.4.1 Experimental setup for AC characterization

The experimental setup is different from the setup for DC measurement in section 4.3, as shown in Fig. 4.6. The major difference is that the signal light is generated by a VCSEL, with direct modulation, since the tunable laser cannot modulate the signal light at high frequency. The purpose of using direction modulation on the VCSEL is that the
high speed free space optical modulator at 850nm wavelength was not available. Most high speed modulators, greater than a couple giga hertz, operate at either 1550nm or 1300nm and are fiber coupled.

50:50 beam splitters were used to sample the beam to monitor the wavelength, power and the direction of the output beam, which was detected with a CCD camera. In the experiment the wavelength and polarization of the signal light were first tuned to get the maximal gain. Then misalignment was introduced by laterally shifting the beam splitter, as shown on the right of Fig. 4.6. AC optical power in the output beam was measured with a DCA (Digital Communication Analyzer) Agilent 86100B. The residual error of the direction in the corrected beam was measured from the images captured by the CCD camera. A photo of the experimental configuration is shown in Fig. 4.7.

Fig. 4.6 Experimental setup to measure the AC performance of angle correction ability for VCSOA at AC power level 30μW
Fig. 4.7 Photo of the experimental setup to measure the AC performance of VCSOA

Besides the optical bench setup, the AC characterization can be viewed from another perspective. According to the information flow, the system can be described with a signal block diagram, as shown in Fig. 4.8.

![Signal Block Diagram]

**Fig. 4.8 The signal block diagram to measure VCOSA angle correction ability**

The driving current of the VCSEL is modulated by the high speed RF (Radio Frequency) signal, at the speed of Gigahertz, using a bias-T. A VCSEL with a diameter of 8μm was used as the light source instead of a 20μm VCSEL on the same die because of its lower RIN (Relative Intensity Noise) noise and better beam profile. The bias-T combines the DC current from the current source and the AC signal from the RF signal...
generator. The DC bias current and RF power (or AC current, considering the load resistance is a constant for a small AC signal) can be tuned to get the best ER (Extinction Ratio). The best ER is measured from the DCA waveform, when the wave bottom reaches zero while the wave peak stays at a reasonable power level, for example, 50μW, as shown on the left of Fig. 4.9(a). Then the output from the VCSOA is also measured with the DCA, shown on the right of Fig. 4.9(b).

![Fig. 4.9 Waveform of the input and output of the VCSOA for angle correction](image)

(a) Input waveform      (b) Output waveform

The peak value and bottom value of the input and output optical power can be read from the waveforms, and then the AC peak-peak input / output can be calculated. These values need to be calibrated to remove the effects of beam splitters and fiber coupler efficiency, etc..

4.4.2 Angle correction ability of VCSOA for AC signal

The AC performance characterization includes two figures of merit. One is angle correction ability at high speed, the other is the bandwidth of VCSOA. In this subsection, we discuss the angle correction ability at 1GHz, and the bandwidth or transfer function in the next. As with measurement of DC signal angle correction, the beam splitter is translated laterally. Thus the input angle to the VCSOA can be scanned by:

\[ \Delta \theta = \frac{\Delta x}{f}, \]
where $\Delta x$ is the lateral shift and $f$ is the focal length of the objective lens.

With incident angle increase, the output power from the VCSOA shows a drop with angle, as shown as red dots in Fig. 4.10. Notice the input power is constant, as shown with blank red squares. The angles generating 3dB maximal output are measured as -4.2 deg. and +5.2deg., with a total 9.4deg. At the same time, the angle of the output beams are also measured, as shown by the blue dots. This angle is calculated from the centroids of the beam profiles. The values are close to zero, meaning that the output beam has very little lateral shifts after the objective lens. It also indicates the output (amplified) beam from VCSOA maintains the emission angle, independent of the angle of the input beam, meaning the input angle misalignment was corrected. VCSOA can therefore be used for angle misalignment correction, with a tolerance angle of 9.4 deg. for 1GHz sinusoidal signal.
Fig. 4.10 Angle misalignment correction using VCSOA: AC input signal at 1GHz. The lower images show the output from VCSOA maintain the beam angle, and the angle misalignment in the input beam was corrected.

The three photos in Fig. 4.10 show the output beam intensity, profile, and locations for different incident angles. They verify that the VCSOA can amplify the beam within 9.4deg. incident angle while maintaining the output beam location unchanged.

The acceptance angle measured for AC signal is much larger than the DC measurement before i.e., 9.4deg total for AC and 1.7deg total for DC. This doesn't necessarily mean a different response for AC and DC. Instead, it comes from the tradeoff between gain and angle correction ability. In DC measurement, the incident power is quite low, at about 1μW; while in AC measurement, the incident power is about 30μW. From previous studies in our lab [6-7], we know the gain will decrease for higher input
powers. In the experiment the peak gain is 48 for 1μW DC input, and 7 for 30μW AC input. When the gain decreases it is not as sensitive to mechanical alignment.

4.4.3 Frequency transfer function for VCSOA

To characterize the bandwidth of the VCSOA the input optical power to the VCSOA needs to be consistent, which actually means two conditions: 1. the Extinction ratio should be relatively high, i.e., the bottom of the waveform is close to zero; 2. The AC peak-peak optical power should be kept, at least roughly, at a nearly constant value. Since the directly modulated VCSEL has varying modulation efficiency with frequency, we need to manually tune the RF electrical power to make the AC output from the VCSEL can reach zero, to satisfy the extinction ratio condition. The VCSEL output is attenuated to a certain level to keep the AC peak-peak value roughly a constant to satisfy the second condition. After these two conditions were met, the optical input and output of the VCSOA were measured with the DCA and the gain vs. frequency was plotted. The AC signal gain $G_{AC}$ is defined as the:

$$G_{AC} = \frac{(P_{out-Max} - P_{out-Min})}{(P_{in-Max} - P_{in-Min})},$$

where $P_{out-Max}$, $P_{out-Min}$, $P_{in-Max}$, and $P_{in-Min}$ represent the maximum and minimum power in the output and input waveforms, respectively. The gain $G_{AC}$ is plotted in Fig. 4.11. The RF input power was tuned from -18dBm to +5dBm so that the AC peak-peak power from the VCSEL was kept within a small range from 60μW to 100μW.
Fig. 4.11 AC gain of VCSOA at different input frequencies
(a) AC gain vs. Frequency
(b) The tuning condition to get a constant AC optical input to the VCSOA

From the result, we can see that the AC gain is relatively flat within a frequency range from 100MHz to 1.5GHz. There is no any evidence showing frequency dependent drop within this range. The frequency transfer function was not characterized at any speed higher than 1.5GHz because it would be difficult to rule out all the electronic parasitic effects caused by the packaging of the VCSOAs when working at speed above 10GHz.

To our best understanding, there could be two major mechanisms limiting the speed of the VCSOA: the first is the carrier (excited electron) life time, and the second the photon life time. The carrier life time is on the order of nano-seconds, and this limits most direct-modulated VCSELs, with a 3dB efficiency near 1GHz. For example, a VCSEL with the same structure as the VCSOA we used was measured to have a 3dB cut off frequency between 1.0GHz and 1.1GHz, as shown in Fig. 4.12. Since the VCSOA does not show any frequency dependency from 0.1GHz to 1.5GHz (while the VCSEL does), we have good reason to believe the speed of the VCSOA could be limited by the other mechanism, which is photon life time, meaning higher operation rates are possible.
4.4.4 Bandwidth measurement using optical component analyzer

The transfer function of the VCSOA was also measured using optical component analyzer. The configuration for this measurement is shown at the bottom of Fig. 4.13. The RF signal is generated from the optical component analyzer. It is combined together with the DC bias current using a bias-T and then used to drive the VCSEL. The optical signal out of the VCSEL and the optical signal from the VCSOA are both measured with the optical component analyzer, as shown on the left in Fig. 4.13. The measured optical power density from the VCSEL and the VCSOA can be denoted as $H_1(f)$ and $H_2(f)$, respectively. Thus the transfer function of the VCSOA can be derived from:

$$H_{VCSOA} = H_2(f) - H_1(f), \text{ in dB scale}$$

The result is shown on the right in Fig. 4.13. In this measurement, the RF power was chosen as -15dBm, which is the power level for most frequencies according to the test in the last sub section. The frequency response measured this way agrees well with the result when the transfer function of the VCSOA was measured using a direct method. This result further verifies that the VCSOA doesn't have frequency dependency up to 2GHz. By comparing the frequency response of the VCSOA with that of the VCSEL, it
can be concluded that the speed of the VCSOA is limited by a different mechanism than the VCSEL.

![Optical power density](image1)

**Fig. 4.13 Bandwidth measurement of VCSOA using optical component analyzer.** On the upper left is the measured transfer function for $H_1$(VCSEL) and $H_2$(VCSEL+VCSOA); On the upper right is the transfer function derived for VCSOA; At the bottom is the block diagram for the experimental setup.

Although this method is simpler to implement, we prefer the method in which the frequency is manually scanned. The reason is the measurement precision. In the second approach (optical component analyzer), the RF electrical input power is kept constant. However, because of VCSEL modulation efficiency (Fig. 4.12), the input optical power to the VCSOA (the output from the VCSEL) is not a constant. At some frequency point, for example 0.86GHz shown in Fig. 4.13, the optical input power to the VCSOA is very low. Thus the output measurement at this point is also low, and the accuracy at this frequency is limited by the sensitivity of the instrument. The method in section 4.4.3 is different though: we change the RF input power and keep the input to the VCSOA...
roughly constant so the measurement at all frequencies will have similar accuracy. By controlling the input to the VCSOA at a relatively high power level (AC optical power), the output can be measured more accurately than the indirect measurement using the optical component analyzer.

4.5 Future improvement and conclusion

For the configurations in Fig. 4.2 non-polarized beam splitters were used to split the input and output beams. In this case there is 3dB power loss for input beam and another 3dB loss for the output beam. This lost power could cause crosstalk or feedback which further affects the overall performance. We propose an improved structure to avoid this 6dB loss. As shown in Fig. 4.14 by using a polarized beam splitter and a quarter waveplate the input and output can be separated without power loss. The input beam is s-polarized and is reflected by the PBS (Polarized Beam Splitter), entering the VCSOA after the quarter waveplate. When the output beam comes into the PBS it has passed the quarter waveplate twice and so it is rotated to p-polarization. The p-polarization output will go through the PBS without reflection or loss. In this configuration the correction module can gain 6dB optical power compared with the configurations in Fig. 4.2. This approach, however, requires the VCSOA to have identical wavelength-gain responses for both s- and p- polarizations.
In this chapter a method was designed to correct optical misalignment between a board and backplane using an active device - the VCSOA. Unlike misalignment correction using passive devices, using a VCSOA can amplify, reshape and regenerate the optical signal at high speed and also improve the signal to noise ratio. Angular or lateral misalignment can be corrected using the designed module. The correction ability is determined by the acceptance angle of the VCSOA, which was characterized to be 1.7° full angle at 3dB gain drop, for 1μW DC signal. The lateral misalignment correction ability is 0.03f, where f is the focal length of the mini lens to converge the input light onto the VCSOA. For AC signal of 30μW at 1GHz, the angle correction ability is 9.4 deg. full angle and the lateral correction ability is 0.16f. The bandwidth of the VCSOA was verified larger than 2GHz, which implies the speed of the VCSOA is limited by a different mechanism than a VCSEL with the same device structure.

From the measurement and characterization in this chapter, VCSOAs have good misalignment correction ability for optical interconnects, especially for board-backplane free space optical connectors. VCSOAs usually have relative strict operation requirements on temperature and bias current, and the output beam from VCSOAs need
to be regulated to a nominal power level. In practical applications, feedback control might be needed to maintain stable operation conditions for VCSOAs. When the operation conditions for VCSOAs are addressed and engineered, VCSOAs are excellent candidate for misalignment correction in optical interconnects.

Acknowledgement

This chapter will be published as "Misalignment correction for optical connecters using VCSOAs", D. Song, H. Zhang, M. Gross, and S. Esener. The dissertation author will be the first author of this paper.

4.6 References:


5. Optical flip-flop based on VCSOAs

5.1 Introduction

Future optical interconnects may require an optical switching function to further enhance the performance and remove the O-E/E-O bottleneck. All-optical label reading and packet routing has to be based on all-optical logic XOR gates and all-optical flip-flops [1-10]. All-optical flip-flops provide the necessary latching functions for optical routers in long haul fiber communications, such as buffering, storage of decisions, and self-routing capabilities. During the past several years, there have been many implementations of optical flip-flops demonstrated, [11-16] including the bistable operation of laser cavities, external feedback with semiconductor optical amplifiers (SOAs), and Mach-Zehnder interferometers based on SOAs, or SOA pairs.

In this chapter, a novel method to realize an all-optical flip-flop using a pair of vertical cavity semiconductor optical amplifiers (VCSOAs) will be reported. VCSOAs have the advantages of high speed, high gain, and low noise figures. A VCSOA is a surface emitting device, so it is intrinsically easier to integrate into two dimensional arrays. Since it uses a multiple quantum well active region, the size of a single device can be scaled down and could eventually fit the requirement for large capacity optical memory.

5.2 Methods and principles

Similar with the implementation of the electrical flip-flop, a VCSOA based all-optical flip-flop (VCOFF) is based on a pair of VCSOAs acting as optical inverters. A VCSOA has a similar structure with a VCSEL (Vertical Cavity Surface Emitting Laser), but it is electrically biased under threshold. The input beam is injected into the cavity and is
amplified with stimulated emission, so the cavity acts as an optical amplifier. VCSOAs exhibit strong bistability and cross gain modulation (XGM) effects, even at relatively low power levels (e.g., $\mu$W). \cite{17, 18} By combining bistability and XGM, an optical inverter with a sharp transfer curve was demonstrated in our group. \cite{19}

5.2.1 Electrical flip-flop from inverters

In electronics, two inverters can form a flip-flop with positive feedback, as shown in Fig. 5.1. \cite{20} Each inverter has an identical transfer curve as shown in Fig. 5.1(b). Since $V_{o1} = V_{i2}$ and $V_{o2} = V_{i1}$, one of the transfer curves is rotated (plotted with switched x and y axes). The working condition (status of voltage) for these two inverters is shown at the right bottom in Fig. 5.1. Although there are 3 points (A, B, and C) that are valid for both inverters, only A and B are stable. C is a metastable operation point. \cite{20} Since both operation points A and B are stable, the state can change from A to B or vise versa, due to an external set or reset signal. Thus the memory function is implemented.

![Fig. 5.1 Electrical flip-flop with two inverters](image)

In order to make this configuration work properly, it is necessary that the inverter has a transition slope larger than 1 (or smaller than -1 with the minus sign indicating inversion). Otherwise only one operation condition is stable and there is no memory.
5.2.2 Optical inverters and optical flip-flop

From the theory of the electrical flip-flop we can see that two conditions are necessary for the two inverters to form a flip-flop: 1. the output is an inversion of the input; 2. the slope of the inversion transition is larger than unity.

In the inverter demonstrated in our group [19], the first condition is realized with XGM: since two beams injected into the same cavity are amplified using the same pool of carriers, the gain of one beam will be modulated by the intensity of the other beam. The cross gain modulation has a negative coefficient because of gain competition, and so the inversion function can be implemented using XGM. The second condition (slope) is realized with optical bistability in the VCSOA. Optical bistability enables the gain to have a sudden jump with the input optical power, as shown in Fig. 5.2(a). [17, 18] Thus if the input signal has a gain jump, the inverted output will have a sudden drop in intensity, as demonstrated in Fig. 5.2(b). [19]

![Fig. 5.2](image)

(a) Optical bistability in VCSOA [Wen] and (b) optical inverter using VCSOA [19]

Therefore if two of such inverters are cascaded together, as with the electrical flip-flop, an optical flip-flop can be formed.
5.3 Experimental setup

The optical flip-flop is set up as two cascaded inverters, as schematically shown in Fig. 5.3. Two VCSOAs act as two inverters and they are coupled using the beam-splitters between them. VCSOA1 is aligned with tunable laser 1, and amplifies the CW (continuous wave) s-polarized signal from tunable laser 1. If there is also a probe beam (p-polarization) that comes into VCSOA1, then because of cross gain modulation, the amplified CW beam s- will be modulated according to the probe signal p-. If the probe signal has strong bistability, the output s- is an inverted signal with a sharp transition region. This output s- will be the probe signal for VCSOA2, and similarly, VCSOA2 will use the s- probe signal to invert the CW beam p- from tunable laser 2. This p- output from VCSOA2 is then fed-back as the probe to VCSOA1. Consequently, a positive feedback loop is created and the state is latched between the two VCSOAs. The output $Q$ and $\bar{Q}$ can be detected as indicated in Fig. 5.3. Note that when we mention s- and p-polarizations, they not only mean two different polarization directions, but can also mean different wavelengths as well. Details on wavelength and power levels will be discussed in later sections.

![Schematically experimental setup for the optical flip-flop based on VCSOAs](image-url)
The real experimental setup has many more components than those shown in Fig. 5.3. A more accurate representation is shown in Fig. 5.4, and a photo is shown in Fig. 5.5. However, it should be noted that none of these figures include all the components used in the experimental setup. The components which have been omitted (e.g., power meters, wavelength meters, additional beam splitters, current and temperature controllers for the lasers and VCSOAs, irises, etc.), are not necessary for understanding the functionality of the flip-flop.

Isolators are necessary in front of the tunable lasers to avoid feedback. Spatial filters are used to filter out the higher order modes of the laser beam and reshape the beam to a fundamental Gaussian mode. A couple beam splitters are used to provide and combine...
the Set/Reset beam with the pump beam. Two polarizers are used in each pump path - one to tune the polarization and the other to tune the intensity.

The two polarization beams between NBS1 and NBS2 are split and recombined using PBS1 and PBS2. There are two reasons to split the two polarization components. First, in the output of inverter 1 (VCSOA1), there are two polarizations present, but only the s-component is desired. The s-component is the inverted p-input signal. The other output polarization p-component is simply an amplification of the input signal p-, and we are not interested in this component for our application. Thus we split the two polarizations and use an isolator to block the p-component. Specifically, ISO4 will block the p-component from VCSOA1, and ISO3 will block the s-component from VCSOA2. The second reason to split the two polarizations is that, as we will see in later sections, the input and pump optical power levels to each VCSOA need to be individually controlled to make the inverters work at optimal conditions. Thus, the two polarizations need to be split and individually controlled since they are inputs to different VCSOAs. The polarizers P5 and P6 in front of the isolators are used to modify the beam intensity.

Half wave plates are used after the isolators and in front of VCSOAs. The basic function of a half wave plate is to change the polarization direction. For a linearly polarized beam, the polarization direction after a half wave plate will be a flip of the original direction around the fast axis of the wave plate. The half wave plates in front of the VCSOAs are tuned close to zero degree (fast axis is vertical), when the intrinsic polarizations (max gain) of the VCSOA are horizontal and vertical. But if the intrinsic polarizations are not 0 deg. and 90 deg., we need to rotate either the polarizations or the
VCSOA mount. Using a half wave plate to rotate the polarizations saves the work of rotating the VCSOA mount.

The half wave plates after the isolators are used to correct the polarization rotation due to the isolators. Most isolators use a polarizer-Faraday Rotator-polarizer structure. The output then has a 45 degree polarization rotation from the original direction. Thus it needs to be rotated back to avoid the loss when combining with another polarization on the PBS. These two half wave plates after the isolators are adjusted to 22.5 deg. to modify the polarization by 45 deg..

![Fig. 5.5 Photo of the experimental setup for optical flip-flop based on VCSOAs](image)

Fig. 5.5 is a ninety degree rotation from schematic setup Fig. 5.4. The two tunable lasers are not shown on the photo, but are on the left side. The two VCSOAs are shown on the right side of the photo, as labeled.
5.4 Operation conditions

The demonstration of VCOFF (VCSOA-based Optical Flip-Flop) in free space encountered three major challenges: Optical alignment, VCSOA characterization, and operation conditions.

5.4.1 Optical alignment

A natural way to plan the alignment is as follows: Align the VCSOA loop first (i.e., align the two VCSOAs to each other). Next, align the two tunable lasers with the two VCSOAs, respectively. However, the beams from the tunable lasers usually need to be filtered to get the fundamental Gaussian mode. So in practice, the two tunable lasers are usually aligned with each other (as well as the optical table) first, and then their respective spatial filters are aligned. Finally, the other optical components are aligned. Under this constraint, however, it is hard to guarantee that the two VCSOAs are aligned with the two tunable lasers at the same time.

Therefore, the optical alignment needs to solve two issues: 1) It needs to provide enough degrees of freedom to manipulate the beams from the tunable lasers and the VCSOAs, and 2) It needs to provide the means to trade off between signal gain and pump gain, since they may not be optimized at the same time.

The first issue was solved by pre-aligning all the NBSs (Non-polarized beam splitter) and PBSs. After the beam splitters are aligned roughly, slight tuning doesn't affect the transmitted beam but will control the reflected beam. Specifically, the procedure is as follows: 1) Align the two VCSOAs (via stages) with the two tunable lasers, respectively, to achieve maximum gain for each pump beam. 2) Tune NBS1 and NBS2 to align the beam out from VCSOA2 with VCSOA1, for maximum p- signal gain. 3) Tune PBS1,
PBS2, M1 and M2 to align the beam out from VCSOA1 with VCSOA2, for maximum s-signal gain. This method typically provides enough gain for the signals and pumps for both VCSOAs, and the optical alignment is also adequate, although it is not optimized.

In step #2 and #3 above, the stages should not be tuned for maximum signal gain. From our experience, after we get maximum signal gain from step #2 and #3, the gain can be further improved if we tune the VCSOA stages as well. However, the VCSOA stages are already aligned with the two tunable lasers for maximum pump gain. So we can trade some signal gain for pump gain. The issue is then: what is the best tradeoff point? From the following subsection we will see that the signal needs to be tuned to a gain-sensitive operation point to get better performance for an inverter, (e.g., with respect to extinction ratio). Therefore, one more step must be appended to the alignment process to get better performance: Slightly tune the VCSOA stages to further optimize the signal gains for s- and p- respectively, while making sure there is no apparent gain drop for the pump beams.

5.4.2 VCSOA characterization

In order to make two cascaded VCSOAs work together properly, elaborate characterization is necessary for both VCSOAs. The most important characteristics include threshold current, IPPS (Intrinsic Polarization Peak Separation), intensity bistability, wavelength bistability, etc..

The bistability property is of great importance in determining the operation conditions. For a certain input optical power, the bistability occurs at a specific wavelength detuning, as shown in Fig. 5.6. Similarly, for different wavelength detuning, the intensity bistability occurs at different input optical power, as shown in Fig. 5.6(b). So the wavelength detuning is actually uniquely determined by the desired input optical power, and the relationship between the wavelength detuning and input optical power can be characterized as in Fig. 5.7 for both VCSOAs.
Fig. 5.6 Bistability observed in wavelength and intensity
(a) Wavelength bistability for VCSOA1 (V#33)
(b) Intensity bistability for VCSOA2 (V#31)

Fig. 5.7 The relationship between wavelength detuning (for bistability) and input optical power

As we will see in the next sub section, the IPPS will ultimately determine the wavelength detuning and optical power levels necessary for the two VCSOAs to operate as a flip-flop. The IPPS is measured by directing a beam with a small optical power (1μW used) into the VCSOA and measuring the gain-wavelength curve for different
polarizations. For intrinsic polarizations, there should be only one peak for each polarization in the gain-wavelength curve. If not at the intrinsic polarization, a second (usually smaller) peak may be observed at the location of the other intrinsic polarization. For the two intrinsic polarizations, the gain is then measured with wavelength. The wavelength separation between the two gain maxima of the intrinsic polarizations corresponds to the IPPS, as shown in Fig. 5.8.

![Graph showing IPPS](image)

**Fig. 5.8 IPPS = 38pm for VCSOA2 (Intrinsic Polarization Peak Separation)**

The sign of the IPPS indicates the order of the two wavelength (positive means P- is to the right of S-), following the definition:

\[
IPPS = \lambda_{(P)} - \lambda_{(S)} \tag{Eq. 5.1}
\]

where the parenthesis around P and S denote that the two polarizations are close to the exact P and S polarizations, although they are not usually pure vertical or horizontal.
5.4.3 Operation condition

To the best of our knowledge, the optical inverter's transition slope is determined by the bistability on the input signal. Here the "input signal" is relative to the "pump", which is also amplified and provides the output of the inverter. The pump needs to be amplified with a high gain to obtain a high extinction ratio.

A first necessary condition is to make the input beam see the bistability. Thus the high input optical power sees a higher gain than the low input, so that the inverted output could have a transition slope larger than unity. For a certain signal optical power, for example, 10μW, the wavelength for a strong bistability is located at the edge of the curve for 10μW, as shown in Fig. 5.6(a), which is 841.605nm. This is 18pm larger (detuning) than the intrinsic wavelength (841.587), as shown in both Fig. 5.6(a) and Fig. 5.7. The pump power, however, usually is much lower than the signal power, from the equation:

\[ P_{signal} = P_{pump} \cdot G_{pump} \cdot G_{loop} \]  \hspace{1cm} (Eq. 5.2)

where \( P_{signal} \) and \( P_{pump} \) are the signal (high) and pump power; \( G_{pump} \) and \( G_{loop} \) are the pump gain and loop gain (gain of optical path from VCSOA1 to VCSOA2). A typical set of values are: \( G_{pump}=25 \), \( G_{loop}=0.2 \), \( P_{signal}=10\mu W \), then \( P_{pump}=2\mu W \).

The wavelength of the pump needs to be tuned to obtain the maximum gain when the signal is absent. It is known that the bistability is much weaker without signal beam, which has much higher power than the pump beam. Besides, the wavelength of the pump need to be tuned far from the bistability peak to obtain a stable high gain (Fig. 5.6a). Thus the detuning of the pump wavelength can be small compared with the detuning for signal wavelength. Therefore in the first order model, it is assumed the pump detuning is zero.
The necessary wavelength detuning condition is illustrated in Fig. 5.9. In Fig. 5.9(a), the input signal is detuned $D_s$ from the intrinsic peak $S$ for strong bistability at 10$\mu$W. The pump and the output are at the same $P$-wavelength for a high gain. The pump has no detuning according to the assumption made above. Thus both the wavelength of the signal and pump (output) are determined from the IPPS of VCSOA1. These input and output correspond to the output (pump) and input for VCSOA2. So for VCSOA2 in Fig. 5.9b, the input and output wavelengths are determined from VCSOA1. Similarly, the input signal and pump of VCSOA2 need to satisfy detuning conditions as well, i.e., some fixed detuning for the signal, and no detuning for pump. So from Fig. 5.9, it can be seen that VCSOA2 is required to have an IPPS satisfying:

$$D_s + D_p = IPPS_1 - IPPS_2$$  \hspace{1cm} (Eq. 5.3)

where $D_s$ and $D_p$ are the required wavelength detuning for $S$ and $P$ components (for VCSOA1 and VCSOA2), respectively, and IPPS1 and IPPS2 are the IPPS of the two VCSOAs, respectively.
The right side of Equation 5.3, \((\text{IPPS1} - \text{IPPS2})\), is defined as the "detuning budget", which gives a total wavelength detuning limit for two known VCSOAs. Based on the properties of input power vs. detuning (Fig. 5.7), and the detuning budget for two VCSOAs, the power level can be solved graphically as shown in Fig. 5.10.
Fig. 5.10 Solution of operation condition, i.e., wavelength detuning and signal power

The solution is obtained through the following: A. Flip one of the two detuning-input power curves in Fig. 5.7, for example, VCSOA2, as shown in Fig. 5.10; B. Move this curve up by the detuning budget (IPPS1-IPPS2); C. Find the cross point of the two curves, as shown in Fig. 5.10, Pin=12μW, D_s=18pm, D_p=27pm. This is the operation condition for the VCSOAs with the detuning properties shown in Fig. 5.7.

If we have the freedom to design or choose the IPPS or detuning properties of the VCSOAs, then we get the freedom to set the input optical power. This is quite important, since the input optical power is proportional to the output optical power.

The graphic solving procedure is actually to solve the equation:

$$D_3 = IPPS1 - IPPS2 - D_p$$ which is identical to Eq. 5.3.

For a more precise model, the detuning of the pump needs to be considered. Then the equation is Eq.5.4, from the analysis in Fig. 5.11.
Fig. 5.11 Operation condition for wavelength detuning considering the pump detuning

\[ D_{s1} - D_{s2} + IPPS2 + D_{p2} - D_{p1} = IPPS1 \quad \text{or} \]

\[ D_{s1} + D_{p2} - D_{p1} - D_{s2} = IPPS1 - IPPS2 \quad \text{(Eq. 5.4)} \]

With the detuning properties from Fig. 5.7, the operation condition (or the closest) can be obtained with a numerical search around the first order solution obtained from Fig. 5.10.
5.5 Experimental demonstration

Under the experimental conditions listed below, the two optical inverters latched and formed two stable states, as shown in Fig. 5.12.

![Graph showing two optical inverters](image)

**Fig. 5.12 Two optical inverters latched and formed an optical flip-flop**

Experimental conditions:

VCSOA1 (V#33): $I_b=6.430\,mA$, $T=26.2\, ^\circ C$, $\frac{1}{2} \lambda$: -6.2 deg., $V=1.6885\,V$

VCSOA2 (V#31): $I_b=6.430\,mA$, $T=13.3\,K\Omega=18^\circ C$, $\frac{1}{2} \lambda$: -8.5 deg.

Tunable laser (DL100, TuiOptics): $I_b=60\,mA$, $T=20.2^\circ C$, $\lambda=841.550\,nm$

Tunable laser (Velocity 6313, New focus):

$I_b=35.6\,mA$, $T=20.5^\circ C$, $P_{out}=10.0\,mW$, $\lambda=841.575\,nm$, Pizo=42.4\%

Powermeters: Output of VCSOA1 (close to VCSOA2): #4425@840nm

Output of VCSOA2 (close to VCSOA1): #3305@840nm

Power levels: pump to VCSOA1 = 6.32\,\mu W (S-); pump to VCSOA2=5.36\,\mu W (P-);

Output levels:

Output of VCSOA1: $H=23.1$, $V_H=26.8$, $L=10.8$, $V_L=6.5$, (unit: \mu W)
Output of VCSOA2: H=34.5, VH=37.5, L=11.2, VL=5.1, (unit: μW)

The functionality test is shown in Fig. 5.13.

![Fig. 5.13 The functionality test for an optical flip-flop based on VCSOAs](image)

The functionality test shows that the output $Q$ and the inversion $\overline{Q}$ have two steady states, and are always complementary. With the Set signal, the $Q$ is set to high. With the Reset signal, the $\overline{Q}$ is set to high. When $Q$ is already high, the Set signal doesn't change the state; when $\overline{Q}$ is high, the Reset signal doesn't change the state.

**5.6 Summary**

In this chapter, a new method to build all optical flip-flops using VCSOAs was designed and experimentally demonstrated. VCSOAs have the advantages of high speed, high gain, and low noise figures. VCSOAs have an intrinsic two dimensional integration...
ability and great potential to be scaled down to fit the requirement for large capacity optical memory. The analysis presented here gives a practical method to calculate the operation condition from a given VCSOA pair, or to determine the necessary VCSOAs from a pre-determined operation condition. Experimental demonstration shows the two VCSOAs used can latch with each other and form an all optical flip-flop. The high/low state of the flip-flop can be changed using the optical Set/Reset signal.

5.7 Appendix: Integration considerations

To integrate VCOFF, it would be necessary to use VCSOA arrays. With the understanding on wavelength and detuning for maximum bistabilities and gains discussed before, two critical questions need to be answered first.

1. How to use two identical VCSOAs to form a flip-flop?
2. How to compensate the nonuniformity among the VCSOAs in the array?

5.7.1 VCOFF using two identical VCSOAs

It is assumed that the IPPS of a VCSOA array can be controlled through fabrication and packaging. An example number is IPPS=20pm, as shown in Fig. 5.14 VCSOA1. The VCSOA2 has an identical structure as VCSOA1, which is usually true for devices in an array. A half wave plate can be used in front of the VCSOA2, and thus the s- becomes p- and p- becomes s-. Note that only the polarizations (s- and p-) are changed, and the wavelength and gain stay the same, as shown in the figure. With a proper intensity setting, the signal, pump, and the output can all be set at an identical wavelength, where the signal exhibits a strong bistability and the pump meets the high gain requirement.

Therefore when the VCSOA array is used for VCOFF, micro half wave plates need to be integrated onto every other VCSOA in the array, so that the wavelength detuning condition can be satisfied.
5.7.2 Compensate the nonuniformity among the VCSOAs on an array

The VCSOAs on an array are usually not uniform, which can affect the threshold current, wavelength, gain etc.. The wavelength is especially important for VCSOAs to work with a high gain, and therefore as a high performance inverter. As shown in Fig. 5.15, the nonuniformity of a one-dimensional VCSOA array can be separated into two components. One component of the nonuniformity is a gradual change in some given parameter (e.g., intrinsic wavelength). For example, it may be found that the intrinsic wavelength of the VCSOAs increases from the left side to the right side. This gradual change is linear or close to linear most of the time. Thus two point-heaters can generate a temperature gradient across the array and it can compensate the gradual nonuniformity of the array. Once this gradual portion is corrected, the residual nonuniformity is relatively
small among different VCSOAs, and it could be further compensated with individually controlled bias current.

![Diagram of VCSOA array](image)

**Fig. 5.15 A proposal to compensate the nonlinearity for VCSOA array**

It was mentioned that a non-zero IPPS is desired to form VCOFF using identical VCSOAs. However, a well grown symmetric VCSOA cavity probably provides identical peak wavelength for both polarizations, i.e., IPPS=0, unless special design and fabrication efforts are made to make the cavity asymmetric. Well-controlled fabrication of the VCSOA array will ultimately result in a low cost solution to obtain the required uniform IPPS. But before the technology reaches this point, an engineering solution could be possible to realize it. As shown in Fig. 5.15, the VCSOA die is glued on a piezoelectric transducer and is stretched along the longitudinal direction. The stress generated at the two ends of the array will be evenly distributed among all the VCSOAs. Then all the VCSOAs get the same asymmetric stress between the two polarization
directions. Therefore by controlling the piezoelectric transducer, the IPPS for all the VCSOAs can be tuned to the required condition.

Acknowledgement

This chapter will be published as "Demonstration of all-optical flip-flops based on VCSOA pair", D. Song, H. Zhang, V. Gauss, P. Wen, and S. Esener. The dissertation author will be the first author of this paper.

5.8 References:


6. N. Wada, H. Harai and W. Chujo, "Multi-hop, 40 Gbit/s variable length photonic packet routing based on multi-wavelength label switching, waveband routing and
label swapping", Optical Fiber Communications Conference (OFC). Anaheim, CA


19. H. Zhang, P. Wen and S. Esener, "Demonstration of all-optical inverter based on Vertical Cavity Semiconductor Optical Amplifiers (VCSOAs)", To be published,


21. H. Zhang and S. Esener, "Bistability and cross-gain modulation in VCSOA", To be published,
6. Summary and Future directions

For sufficiently long distances and high bitrate, optical interconnects will outperform electrical interconnects in terms of loss and dispersion. Due to the bandwidth and distance advantages of optical interconnects, optics is now being introduced into commercial products for links longer than hundreds or tens of meters. With the trend from long distances to short ones, the next step will be to provide optical solutions for backplane applications with a distance of about one meter.

This thesis analyzes the major challenges and possible solutions for an optical interconnect system for backplane level applications. It includes the following: (1) an analysis and solution to misalignment at the transmitter-to-free-space coupler, (2) improvements in the angular tolerance at the receiver using a conical lens, (3) the misalignment correction for optical connectors using active devices (VCSOAs), and (4) a promising way to realize optical RAM with strong integration ability. In the appendix, a theoretical model to analyze the optical crosstalk is also established and some numerical results are presented.

6.1 Summary

In chapter 2, we simulated the misalignment tolerance for the free space coupler using BeamPROP. The result shows excellent alignment tolerance between microlens and microlens, which is crucial for installation. It also shows critical alignment tolerance at the laser-lens, lens-waveguide, and lens-detector interfaces. For this reason coupling lenses need to be integrated directly with the laser source and the detector. It is also desirable to integrate the coupling lenses with the waveguides during fabrication.
Also in chapter 2, we outlined a method to integrate a lenslet array on the edge of an embedded waveguide array, and showed how it was demonstrated experimentally. This method can guarantee the alignment precision between lenslet array and waveguide array with little alignment effort, and the integration technique can in principle be automated and thus made suitable for mass production. In the demonstration experiment, the lenslet array pattern was well aligned with the waveguide cores, with no visible misalignment shown on the CCD camera. The roundness of each single lenslet and the uniformity of the entire lenslet array were qualitatively checked and they were all within the acceptable range showing negligible non-uniformity. The far field beam divergence angle was also quantitatively characterized. The results showed that an in situ fabricated lenslet array has a similar performance to the best lenslet of an assembled commercial lenslet array, and they both have much smaller divergence angles (3.29 deg. and 3.49 deg.) than the case without the lenslet (8.55 deg.).

In chapter 3, the possibility and performance of using a conical lens to increase the angular tolerance was simulated and experimentally demonstrated. By using practical models (SS, NC, and SNC) to simulate Micro Gradient Index Conical Lenses (MGCL) in CodeV, we verified that MGCL has a larger acceptance angle than a simple microlens. The shapes and refractive index profiles both have effects on the acceptance angles of MGCL. Conical lenses with a gaussian index profile have a larger acceptance angle than solid index profile lenses. Convex, normal, and concave cones have similar acceptance angle, although convex cones slightly outperform at high efficiency level. Considering the fabrication, a normal cone with a gaussian index profile appears to be the best solution for increasing acceptance angle in a practical micro-optical system. A gaussian index normal MGCL can provide an acceptance angle of about $\pm 17^\circ$ for a 50% detection threshold. A fabricated conical lens shows a -12 deg to +15 degree acceptance angle, similar to the simulation result of $\pm 14^\circ$ for this device. Under the same conditions, an
ideal simple lens can only provide an acceptance angle of 3°. Thus, the MGCL is an attractive alternative to the simple microlens for increasing the acceptance angle.

In chapter 4, a method was discussed to correct the optical misalignment between a board and the backplane using an active device (VCSOA). Compared with misalignment correction using passive devices, using VCSOAs can amplify, reshape and regenerate the optical signal at high speed, and also improve the signal to noise ratio. Angular or lateral misalignment can be corrected using the designed module. The correction ability is determined by the acceptance angle of the VCSOA, which was characterized to be 1.7° full angle at 3dB gain drop, for 1μW DC signal. The lateral misalignment correction ability is 0.03f, where f is the focal length of the mini lens to converge the input light onto the VCSOA. For an AC signal of 30μW at 1GHz, the angle correction ability is 9.4 deg. full angle and the lateral correction ability is 0.16f. The bandwidth of the VCSOA was verified to be larger than 2GHz, which implies the speed of a VCSOA is limited by a different mechanism from a VCSEL with the same device structure.

In chapter 5, a new method to build all optical flip-flops using VCSOAs was presented. VCSOAs have the advantages of high speed, high gain, and low noise figure. VCSOAs are easily integrated into two-dimensional arrays and have great potential to be scaled down to fit the requirement for large capacity optical memory. The analysis presented here gives a practical method to calculate the operating condition from a predetermined VCSOA pair; or to determine the necessary VCSOAs from a predetermined operating condition. Experimental results showed that the two VCSOAs used can latch with each other and form an all optical flip-flop. The high/low state of the flip-flop can be changed using the optical Set/Reset signal. At the end of chapter 5, some analysis and possible solutions are proposed for integration of VCSOA-based optical flip-flops.
6.2 Future research work

Optical interconnects have some unique advantages and are promising in future server and high performance computers. However, integration is still one of the biggest challenges to commercialization. In this dissertation, a few VCSOA-based applications were mentioned, including alignment correction for optical connectors and an all-optical flip-flop. These two approaches are both based on discrete VCSOA devices. They have to be integrated to really become attractive. Fortunately both of these integration issues are being investigated or studied in other programs.

Another open question is the speed of VCSOA-based devices. Although in chapter 4 some preliminary tests were performed to measure the speed, more thorough studies are necessary to exactly characterize the bandwidth of the VCSOA. This has to be done before the VCSOA is finally widely accepted in industry.

VCSOA-based all-optical flip-flops are very promising devices for applications such as optical storage, routing, and all-optical logic. There are great opportunities to integrate and commercialize them, once the speed of the flip-flop is characterized. In our first functionality test, the speed was not characterized in detail, but our observations showed some complicated mechanisms which may limit the speed. For example, there could be some low frequency oscillations from the bistability of the two VCSOAs. Lastly, the operating condition could be studied in more details to further optimize the device.
A. Analysis of optical crosstalk for a waveguide based optical interconnect system

A.1 Introduction

In multi channel optical interconnect systems, there is often some optical power leakage from one channel to the other channels,\[^{1,2}\] which is referred to as inter channel crosstalk. This crosstalk not only decreases the power in the desired channel, but also increases the noise floor in the other channels. Thus the performance of the interconnect system, including EO/EC (eye opening/eye closure), BER (bit error rate) etc., will be degraded. In this paper, an analytical model is established to investigate the crosstalk in a waveguide based optical link. The results indicate that the system performance is impacted by the link loss, waveguide scattering, and the dominant noise.

A.2 Crosstalk analysis for the optical interconnect system

The crosstalk analysis is based on an interconnect architecture presented by Berger et al. IBM on LEOS 2004\[^3\]. In this setup waveguide is chosen as the primary propagation media for this optical interconnect system. The transmitter is a 1 by 12 VCSEL (Vertical Cavity Surface Emitting Laser) array with a pitch of 250 μm, working at a wavelength of 850 nm. The source beams are coupled into a waveguide array through a microlens free space coupler, which can provides misalignment tolerance and interchangeability. After propagation in waveguide, the light coming out from the waveguide is coupled onto a photodiode array through another microlens free space coupler.

Since the crosstalk is caused by various mechanisms in different parts of this interconnect system, the entire optical link is decomposed into three parts: VCSEL-
waveguide free space coupler, optical waveguide, and waveguide-photodiode free space coupler.

A.2.1 Crosstalk in free space couplers

In 4f free space couplers, the crosstalk is mainly generated from lens clipping, beam divergence and misalignment. We assume channel 0 is the desired channel, thus beam divergence will result in an inter-channel crosstalk through lens clipping (light deflection from channel ±4, as shown in the example setup in left of Fig. A.1). Similarly, misalignment, especially microlens-microlens misalignment, will result in crosstalk to channel ±1, as shown in the right of Fig. 1, assuming small misalignment.

![Crosstalk caused by divergence (left) and lens-lens misalignment (right) in a free space coupler](image)

Therefore, in a free space coupler, if all channels are lighted, the crosstalk occurs in channel 0 only consists of four parts, in the example shown above from channel ±1, and channel ±4. The power received in channel 0 is:

\[
E_{0r}(1) = 1 - \gamma + N + aE_4 + aE_{-4} + bE_1 + bE_{-1}
\]

(Eq. A.1)

\[
E_{0r}(0) = N + aE_4 + aE_{-4} + bE_1 + bE_{-1}
\]

(Eq. A.2)
where $\gamma$ is the loss of signal power; $N$ is Gaussian noise of the signal, with zero mean and variance $\sigma$; $E_4$, $E_{-4}$, $E_1$, and $E_{-1}$ are the transmitted power from the $\pm 4$ and $\pm 1$ channels respectively, each of them can be either 0 or 1, with probability of 0.5; $a$ and $b$ are the crosstalk coefficients, depending on the beam divergence and misalignment.

The error probability $p_{0|1}$, the probability that 0 is detected while 1 is transmitted, can be expressed as:

$$p_{0|1} = \frac{1}{2^4} \sum_{i=0}^{1} \sum_{j=0}^{1} \sum_{k=0}^{1} \sum_{n=0}^{1} Q\left(\frac{1-\gamma + ai + aj + bk + bn - T}{\sigma}\right),$$  \hspace{1cm} \text{(Eq. A.3)}

where $Q(\rho)$ denotes the probability that $N(0,1)$ takes a value larger than $\rho$, with $N(0,1)$ a normal distribution with zero mean and unit variance, while $T$ denotes the decision threshold.

In most optical interconnect systems, we can assume a low noise and therefore the crosstalk dominates. And because the $Q(\rho)$ function decreases exponentially with $\rho$, among all the $Q(\rho)$ terms in $p_{0|1}$, only one term with minimal $\rho$ is dominant. Then we get,

$$p_{0|1} \approx \frac{1}{2^4} Q\left(\frac{1-\gamma - 2a - 2b - T}{\sigma}\right),$$  \hspace{1cm} \text{(Eq. A.4)}

and the total error probability is:

$$p_e = p_{3|0} + p_{0|1} \approx \frac{1}{2^4} Q\left(\frac{T - 2a - 2b}{\sigma}\right) + \frac{1}{2^4} Q\left(\frac{1-\gamma - 2a - 2b - T}{\sigma}\right)$$  \hspace{1cm} \text{(Eq. A.5)}

For a minimal total error probability, the optimal threshold $T$ is chosen to make two $Q(\rho)$ terms equal, i.e., $T = \frac{1-\gamma}{2} + a + b$. A worst case is that the lost power doesn’t
escape the system, and it totally contributes to crosstalk. Thus we have $2(a + b) = \gamma$, and then

$$p_c \equiv \frac{1}{2^3} Q\left(\frac{1-2\gamma}{2\sigma}\right), \quad (\text{Eq. A.6})$$

This result indicates that the free space coupler attenuates the optical signal with a factor of $(1-2\gamma)$, while it doesn’t induce extra noise.

### A.2.2 Crosstalk in optical waveguide

Two major sources of loss exist in polymer multimode optical waveguides. One comes from the material absorption, and the other is the scattering on the interface between the core and cladding. The material absorption results in attenuation to both signal and noise, and it doesn’t hurt SNR; while the scattering not only brings the signal attenuation, but also introduces crosstalk.

The scattered light doesn’t propagate along specific directions like the crosstalk in a free space coupler. From a simulated field distribution (with BeamPROP, RSoft INC.), as shown in Fig. A.2, we can see that after a sufficiently long distance propagation in the waveguide (30cm in simulation), the scattered power is almost equally distributed into all the other channels (even noise floor around the original channel).

![Computed Transverse Field Profile at Z=0000000](image)

**Fig. A.2 Field distribution of the scattered optical power**
Therefore, every channel will receive some scattered power from all the other channels. Thus the total crosstalk is a summation of all the power in the other channels multiplied by a crosstalk coefficient. When the number of channels in the system is large (>16), the total crosstalk can be well approximated by a Gaussian random process $N(\mu_{\text{sca}}, \sigma_{\text{sca}})$, according to the central limit theorem. The mean value $\mu_{\text{sca}}$ and variance $\sigma_{\text{sca}}$ are given as:

\[
\mu_{\text{sca}} = \frac{1}{M} \sum_{i=1}^{M} (c \cdot \mu_{\text{ch-i}}) = \frac{1}{2} c
\]  

(Eq. A.7)

\[
\sigma_{\text{sca}} = \frac{1}{M} \sqrt{\sum_{i=1}^{M} (c \cdot \sigma_{\text{ch-i}})^2} = \frac{c}{2\sqrt{M}}
\]  

(Eq. A.8)

where $c$ is the scattering coefficient, indicating how much optical power is scattered from one channel to another channel; $M$ is the total channel number; $\mu_{\text{ch-i}}$ and $\sigma_{\text{ch-i}}$ are the mean values and variance for the $i$-th channel. As suggested above we assume the scattered power is equally distributed into other channels. Then we get:

\[
P_e = Q\left(\frac{1 - \gamma_{\text{abs}} - \gamma_{\text{sca}} - \mu_{\text{sca}}}{\sqrt{\sigma^2 + \sigma_{\text{sca}}^2}}\right) = Q\left(\frac{1 - \gamma_{\text{abs}} - \gamma_{\text{sca}} - \frac{c}{2}}{\sqrt{\sigma^2 + \frac{c^2}{4M}}}\right)
\]  

(Eq. A.9)

\[
\text{SNR}_{eq-sca} = \frac{(1 - \gamma_{\text{sca}} - \mu_{\text{sca}})^2}{\sigma^2 + \sigma_{\text{sca}}^2}
\]  

(Eq. A.10)

where $\gamma_{\text{abs}}$ is the loss due to material absorption, and $\gamma_{\text{sca}}$ is the loss due to scattering.

\[
\sigma_{\text{sca}} = \sigma_{WG-E} = \frac{\eta P_{\text{WGloss}}}{2\sqrt{M}} \left(\frac{W_{\text{Core}}}{W_{\text{Pitch}}}\right)^2
\]  

(Eq. A.11)
where $\sigma_{WG-E}$ is waveguide noise, which is measured in current; $R$ is the responsivity of the photodiode; $\eta$ is the crosstalk ratio; $P_{WGlost}$ is the optical power lost in waveguide; $W_{Core}$ is the core width of the waveguide; $W_{Pitch}$ is the Pitch size of waveguide array.

The $\eta$ indicates how much of the lost power in the waveguide is transferred into crosstalk. It is a small number (e.g. 5%) for absorption dominant waveguide, and it can be large if the dominant loss in the waveguide is from the boundary scattering. The square term $\left(\frac{W_{Core}}{W_{Pitch}}\right)^2$ means only the crosstalk power in the waveguide core region will be picked up by the receiver. The square root $M$, $\sqrt{M}$, comes from the summation of $M$ random variables. When $M$ random variables are summed together, the total variance is the $\sqrt{M}$ multiplied with a single one.

A.2.3 Noise from other sources and total noise of the system

Noise in transmitter (VCSEL) is usually dominated by RIN (Relative Intensity Noise), which is described as:

$$\langle i_i^2 \rangle = I_{RIN} (\Re P_S)^2 B$$

(Eq. A.12)

where $I_{RIN}$ is the normalized bandwidth integral, which is -128dB/Hz for VCSEL arrays from Honeywell, Inc.; $R$ is the responsivity of photodiode; $P_S$ is the received signal power; and $B$ is the bandwidth.

Noise in the receiver, however, consists of several terms:

$$\langle i_r^2 \rangle \approx \frac{4kT}{R_f} \alpha_i B + 2q(3R P_S + I_d) \alpha_i B + 4kT \frac{(2\pi C_T)^2}{g_m} f_c \alpha_f B^2 + 4kT \frac{(2\pi C_T)^2}{g_m} \alpha_2 B^3$$

(Eq. A.13)
where $\alpha_2$, $\alpha_3$, $\alpha_f$ are normalized bandwidth integral, they are about 0.6, 0.09, and 0.2, respectively; $R_f$ is the feedback resistance, typically around 40K$\Omega$ for high gain; $I_d$ is the dark current of the photodiode; $f^*$ is the excess channel noise factor for short channel transistor; $C_T, g_m$ are the input capacitance and transconductance of the transistor; $f_c$ is the corner frequency for 1/f noise.

The four terms on the right side of Eq. A.13 are the thermal noise, shot noise, 1/f noise and FET gate noise, respectively.

The total signal and noise level depends on the gains (or loss) and additive noise of all the stages of the system. For a three stage system shown as in Fig. A.3,

System block diagram and the total SNR is:

\[
\begin{align*}
S_0 & \rightarrow \text{Coupler} \rightarrow \text{Waveguide} \rightarrow \text{Coupler} \rightarrow \text{Receiver} \\
G_1, P_{n1} & \quad G_2, P_{n2} \quad G_3, P_{n3}
\end{align*}
\]

\[
SNR_{tot} = \frac{(S_0 G_1 G_2 G_3 R)^2}{(P_{n0} G_1 G_2 G_3 R)^2 + (P_{n2} G_3 R)^2 + P_{TN} + P_{SN}}
\]

Fig. A.3 System block diagram and total signal to noise ratio

where $R$ is the responsivity of the photodetector, $P_{TN}$ and $P_{SN}$ are the thermal noise and shot noise from the receiver, respectively.

**A.3 Numerical results**

We then calculated all the noises according to the equations above under the following conditions, and the calculated result is shown in Fig. A.4.
BitRate=10Gbps; RIN = -130dB/Hz; Feedback R=10KΩ; Other optical loss =-5dB; waveguide loss = -5dB for 1 meter long; waveguide core/pitch = 35/50µm; Crosstalk ratio η = 0.2; Channel number = 32.

From the result, we can see the total noise is dominated by the FET gate noise when the Tx optical power is below 2.5dBm (or 1.8mW); and it is dominated by RIN for Tx above 2.5dBm. It is noticed that the waveguide noise (coming from scattering crosstalk) has the same trend as the RIN noise, since both of them are proportional to the square of the transmitter optical power. We then further compared the RIN noise and waveguide noise in detail, as shown in Fig. A.5, with the conditions as:

BitRate=10Gbps; RIN = -130dB/Hz; TX optical power = 2mW; Other optical loss =-5dB; Crosstalk ratio = 0.2; Channel number = 32

Fig. A.4 Comparison of difference noises in waveguide based optical interconnects
We can see from the plot that the RIN noise and waveguide noise have different dependency with the waveguide loss. The RIN noise decreases with the waveguide loss; while the waveguide noise increases. At about 6dB waveguide loss, RIN noise and waveguide noise have the same magnitude. Below 6dB, RIN noise dominates all the other noises and above 6dB, waveguide noise dominates. It is noted that this waveguide noise is for a denser waveguide optical interconnect, with core/cladding ratio 0.7. A typical core/cladding ratio is 50µm/250µm=0.2 in most of present demonstrations, and the denser 35µm/50µm core/cladding ratio is for next generation optical interconnect in IBM research lab.

Waveguide noise is usually neglected in the design of optical interconnects, and it is true most of the time. However, under certain conditions, waveguide noise does dominates all the other noises. The following is an example condition under which the waveguide noise dominates:
BitRate = 10Gbps; TX optical power > 2mW; WG loss > 6dB; 20% of WG loss to
crosstalk; Core/Cladding = 35µm/50µm; Channel M=32; RIN = -130dB/Hz (VCSEL);
Responsivity = 0.5mA/mW; CMOS process = 0.18µm; FET short channel Γ = 2; FET
gate capacitance = 60fF; FET gm = 100 µS/um; NMOS gate width = 0.18µm; PMOS
gate width = 1.0µm.

A.4 Conclusion

An analytical model is established to analyze and model the crosstalk in multi-
channel waveguides and free space coupler. The crosstalk in multi waveguide channels is
equivalent to an additive Gaussian noise, denoted as waveguide noise. The waveguide
noise level strongly related to waveguide core/cladding ratio, waveguide loss, and
crosstalk ratio. It can become dominant for higher channel densities, higher optical
power, and higher waveguide roughness. In free space coupler the crosstalk is equivalent
to a power loss, and it doesn't generate Gaussian noise.

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North Carolina, USA, 2005. The dissertation author is the first author of this paper.

A.5 References:

1. D. V. Plant and A. G. Kirk, "Optical interconnects at the chip and board level:
   challenges and solutions", Proceedings of the IEEE, 88, pp806-18,

2. N. S. Petrovic, C. J. O'Brien and A. D. Rakic, "Analysis of free-space optical
   interconnect misalignment tolerance in the presence of multimode VCSEL