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Vertical cavity surface emitting lasers are ideally suited for high performance and low cost data transmission systems. Recent advances have yielded devices with low power efficiencies far greater than for in-plane lasers. This means that it is now possible to produce massively parallel two dimensional emitter arrays with acceptable heat generation. The low divergence circular optical emission enables the devices to be designed into low cost free space communication systems. Adding to the device characteristics has been the development of GaAs microlenses integrated directly into the substrate of bottom emitting Vertical Cavity Surface Emitting Lasers. These microlenses are used to collimate the emission from the lasers. This same microlens technology can also be adapted to InP based detector arrays for complete free-space communications links.

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TITLE:

LOW POWER VERTICAL-CAVITY LASERS WITH INTEGRATED MICROLENSES FOR FREE SPACE INTERCONNECTS

Phase I Final Report

SUBMITTED BY:

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1. Introduction

The purpose of the investigation was to look into developing Vertical Cavity Surface Emitting Lasers (VCSELs) with integrated microlenses for free space applications. As part of the Phase I investigation it was noted that many applications require the production and transmission of optical beams using standard diode lasers as the primary light sources. Typical diode lasers need temperature control for stable operation and external lenses for free space applications. VCSELs in comparison provide a unique solution to the cost, performance and packaging limitations of standard in-plane diode lasers.

VCSELs have inherent advantages over traditional in-plane lasers. They produce a single longitudinal circular mode that emits with low divergence for better free space coupling. The vertical geometries of the devices and the simplicity of fabrication makes VCSELs ideal for fabrication into one or two dimensional laser arrays. These arrays can be fabricated with integrated microlenses that serve to extend the practical distances of free space links. VCSELs can also be designed to operate over extended temperature ranges, and high speed VCSELs have been demonstrated at low bias. As a result, the devices have the potential to be used in many military and commercial applications.

High frequency VCSEL array packages have been produced by Optical Concepts that operate at more than 8 GHz at room temperature. Both top emitting and bottom emitting lasers arrays on 250 μm centers have been demonstrated. Both types of structures exhibit very low threshold currents. The VCSELs produced to date have not been optimized for high speed other than to minimize the device parasitics. In fact, they were optimized for high quantum efficiency. Lasers with higher mirror reflectivities would not saturate the gain as quickly, resulting in higher differential gain. Future optimization should result in even higher modulation efficiency and bandwidths as the modal volume is reduced, the reflectivities optimized and the thermal designs are improved. As an example of these further improvements, both UC Santa Barbara and Sandia National Labs have achieved greater than 16 GHz response in the last few months (Sandia results were presented in SPIE '96) using many of the enhancements described.

To achieve highly reliable laser packages, VCSELs have distinct advantages over in-plane lasers. They inherently operate with a limited temperature insensitivity, due to the availability of only one longitudinal mode. In a VCSEL, the spectral position of the gain peak is more sensitive to temperature changes than is the cavity mode. By offsetting the gain peak toward shorter wavelength, the threshold condition is increased due to the weaker gain into the cavity mode. As the devices temperature increases with bias, the gain peak becomes more in resonance with the cavity mode. As this occurs the height of the gain peak decreases resulting in a constant output power over a wide temperature range. VCSELs have been made that lased CW up to temperatures as high as 140°C. This high temperature operation eliminates the need for expensive cooling circuitry to meet the high end of the milspec temperature range. For the lower ambient operating temperatures, resistive heating could be utilized to heat the devices which would still result in a dramatic decrease in packaging costs compared to devices requiring thermoelectric cooling.

For high density free space communications, the drive currents of the devices become significant for thermal management. VCSELs have been demonstrated and reproduced by Sandia National Labs with 50% efficiencies. These results are as high as for in-plane lasers, however the VCSELs have a number of advantages over high efficiency in-plane lasers. The high efficiencies for the VCSELs were achieved at only a few milliamps, and the threshold currents of the devices were well under one milliamp. This can be compared with very high operating conditions necessary for high efficiency in-plane lasers. The best low power VCSEL devices produce hundreds of microwatts output power with input powers of only one milliwatt. This is a substantial improvement over in-plane laser technologies, especially when one considers that these devices can be readily made into two dimensional arrays.

Vertical cavity surface emitting lasers with their small beam divergence angle and separation of the laser from the surface are a breakthrough from a packaging perspective. The small divergence angle simplifies optical coupling since a lens with a low numerical aperture can be used. In comparison, in-plane lasers require a much higher numerical aperture for efficient free

space coupling. A backside emission VCSEL offers another great advantage in optical coupling. It can be fabricated with microlenses integrated directly onto the back of the substrate.

Optical Concepts has fabricated such microlenses onto GaAs substrates and has also put such lenses onto the backsides of VCSEL arrays, in collaboration with both UC Santa Barbara and Sandia National Labs. The addition of integrated microlenses greatly relaxes the tolerances for fiber coupling.

Vertical cavity surface emitting laser technology is maturing rapidly. By coupling ultra-low power requirements, high frequency operation and the potential of integrated microlenses, VCSELs are ready to be utilized in high density optical free space data links.

2. Phase I Objectives

The purpose of the phase I effort were to develop VCSEL packaging and fabrication technologies to accelerate the design of high density optical free space data links. The objectives of Phase I were:

1. Continue the development of integrated microlens technologies.

2. Optimize the vertical cavity lasers for low input powers.

3. Develop high yield, reliable mechanical and electrical connection technologies for the 1-D and 2-D arrays.

4. Based on our technological development, propose final designs for both low power VCSELs and free space data links using those VCSELs.

3. Phase I Results

The following subsections provide the results of the Phase I investigation. In the four key areas outlined above good progress has been made.
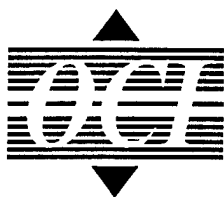
3.1 Microlens Development

The microlens development has continued with great success. It is now possible accurately and repeatably make microlenses with a prescribed radius of curvature in GaAs. This was made possible by taking careful measurements to develop control of the important etch rates. Work on InP microlenses has also begun with some good initial results. The InP microlenses are potentially useful for free space detectors.

The initial microlens fabrication was performed as shown in Figure 1. Initially cylinders of PMGI were defined photolithographically using conventional photoresist followed by a deep UV exposure to pattern the PMGI. Before reflowing the PMGI cylinders the PMGI was used as a self aligned mask to etch a small step into the GaAs. This small etch serves to constrain the PMGI during reflow to ensure a repeatable radius of curvature for the lens. The actual radius of curvature is based on the volume of material that is in the initial PMGI cylinder. After reflow the same amount of PMGI will then exist in a spherical cap that is constrained by the first GaAs etch. After reflow, PMGI microlenses were formed. The PMGI microlenses were then transferred into GaAs using a reactive ion etching (RIE) process. The RIE process itself changes the radius of curvature of the lenses since the etch rates of GaAs are different from PMGI. Figure 2 shows the relative etch rates using different etch parameters. Once the etch parameters are defined the transfer of the microlenses can be accomplished in a predictable and reproducible manner.

Figure 3 shows the radius of curvature of a number of lenses as a function of different lens diameters and initial PMGI thickness. The volume calculation coupled with the knowledge of the different etch rates between the GaAs and the PMGI are sufficient for designing the final GaAs microlenses. Once the GaAs lenses are complete back side metallization is added, at this point the microlenses appear as shown in Figure 4. The fabrication was accomplished so that three different sizes of VCSELs were fabricated along the horizontal axis, and three different sizes of microlenses were fabricated along the vertical axis (Figure 5). This was done to ensure that all combinations of microlenses and VCSELs would exist.

For the size of the VCSELs being made and the thickness of the GaAs substrate, it was estimated that the radius of curvature should be 400 μm for collimation of the output beam. Since there are

OCI Microlens Fabrication

PMGI

GaAs

define
PMGI
cylinders

PMGI

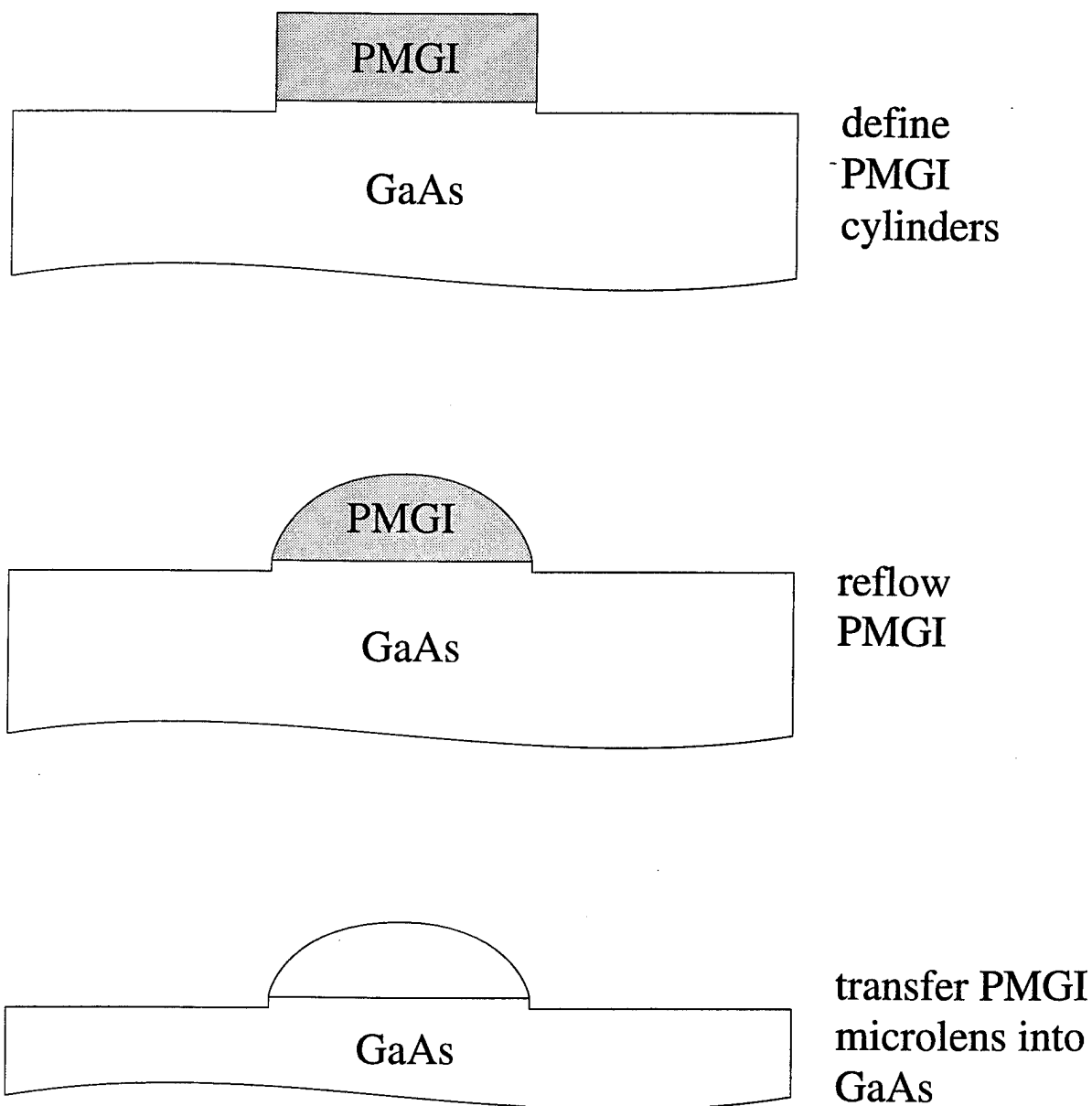GaAs

reflow
PMGI

GaAs

transfer PMGI
microlens into
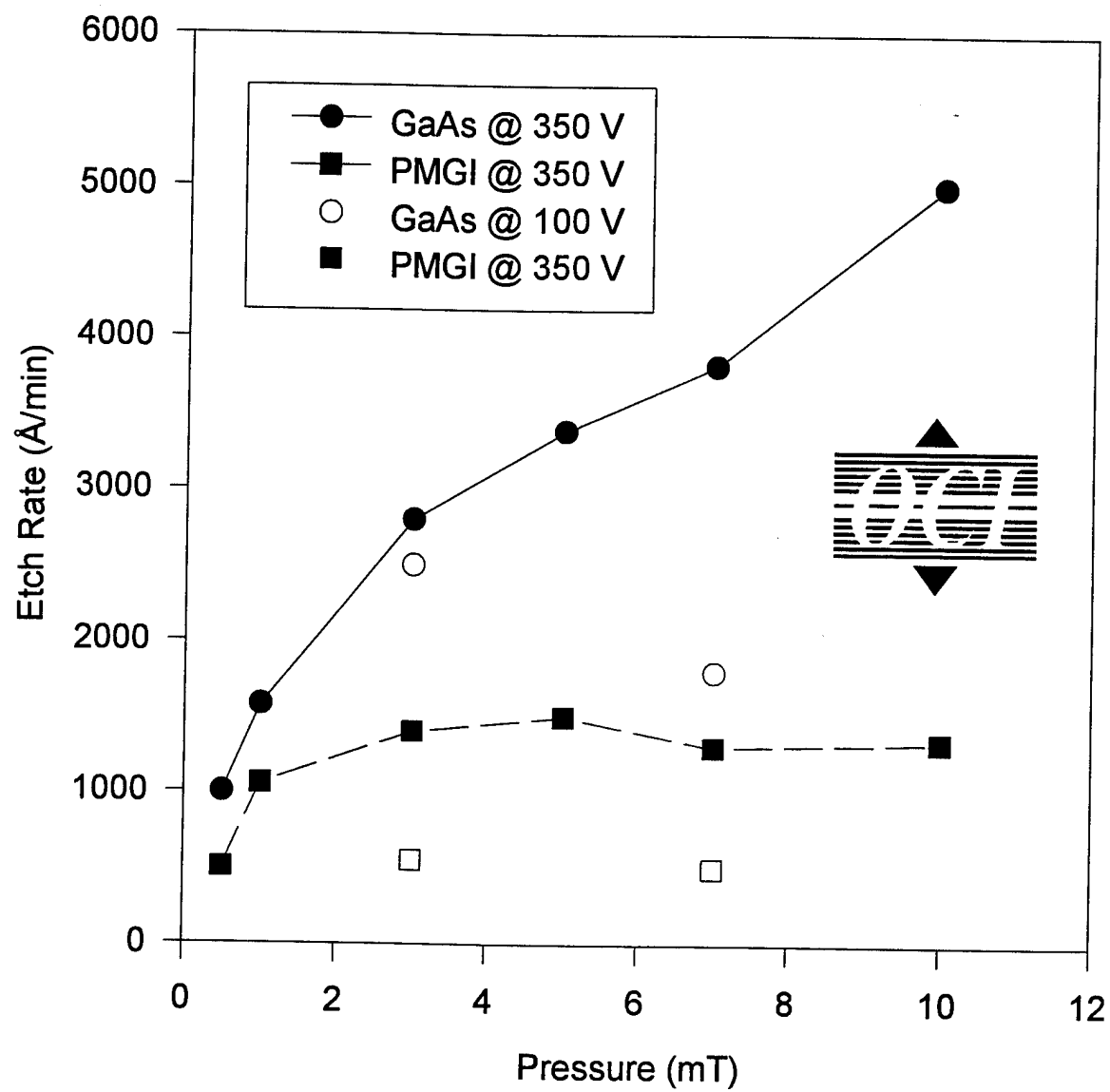GaAs

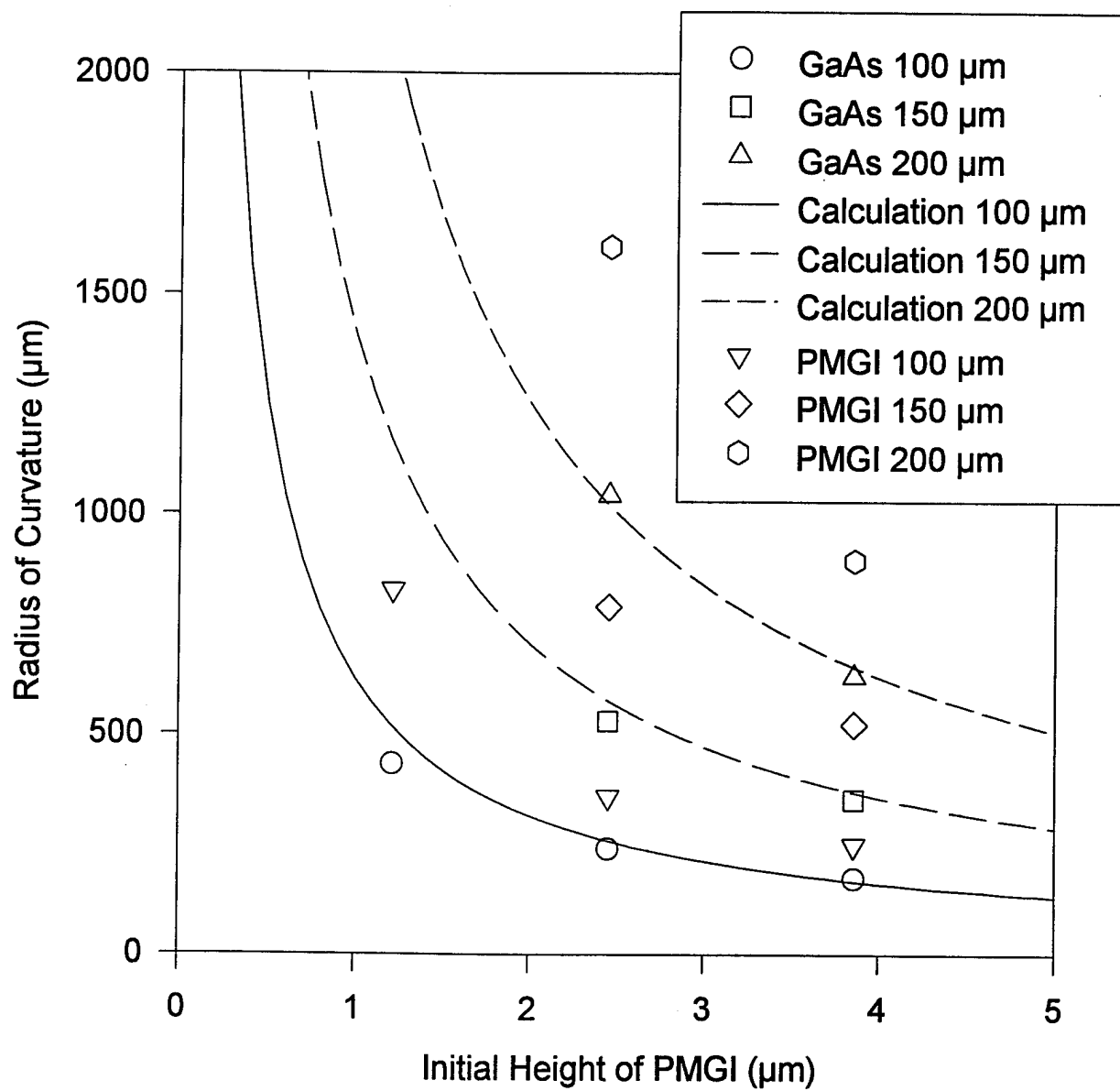**Figure 1**

Vertical Etch Rates in Cl$_2$ RIE

Figure 2

Radius of Curvature vs. Initial PMGI Height

Figure 3
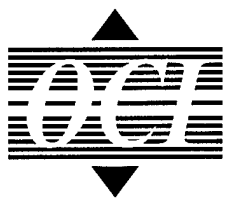
GaAs Microlenses

Figure 4
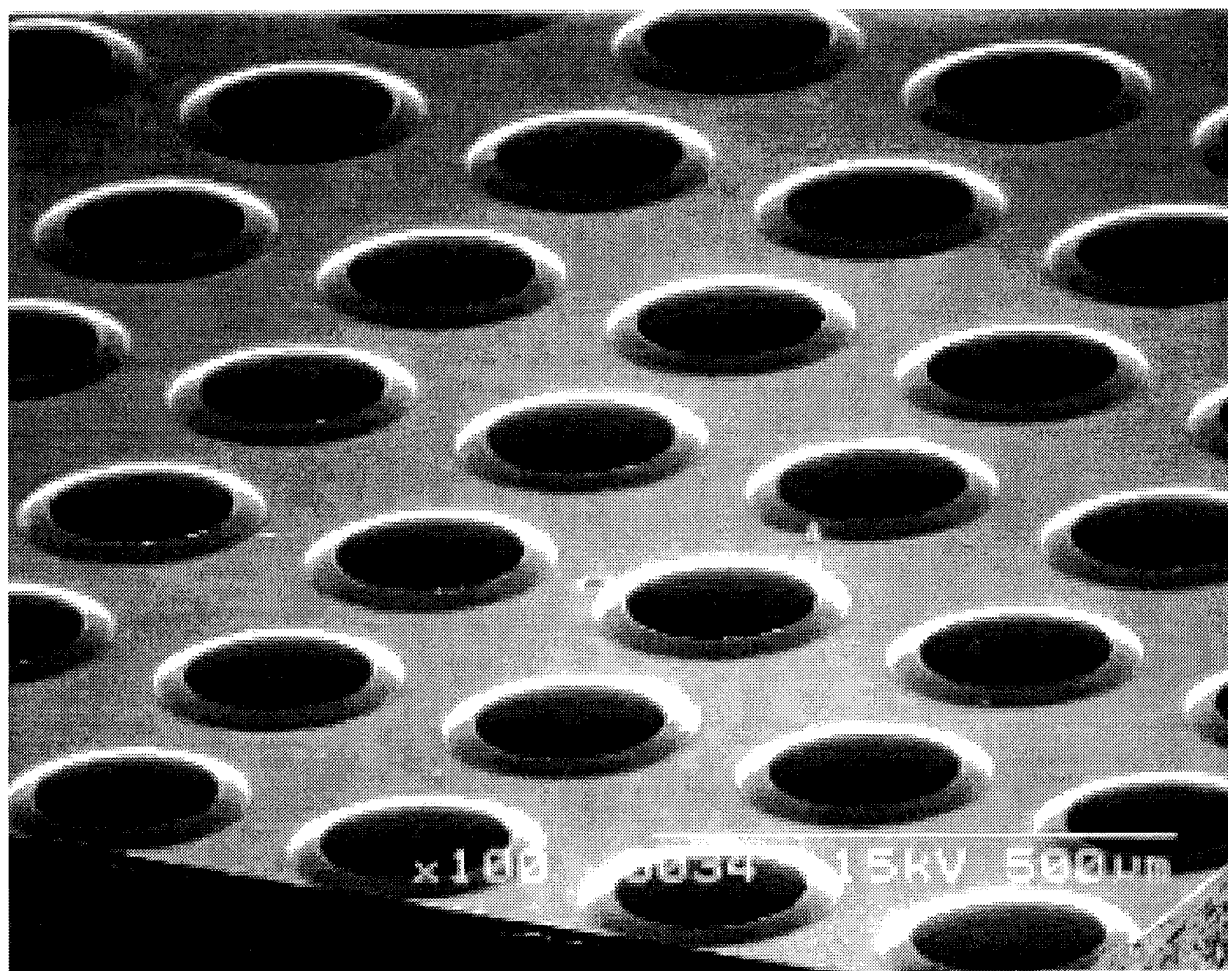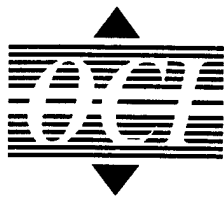
VCSEL Mask Layout

A $\quad$ 12xN $\longrightarrow$

alignment marks

B

C
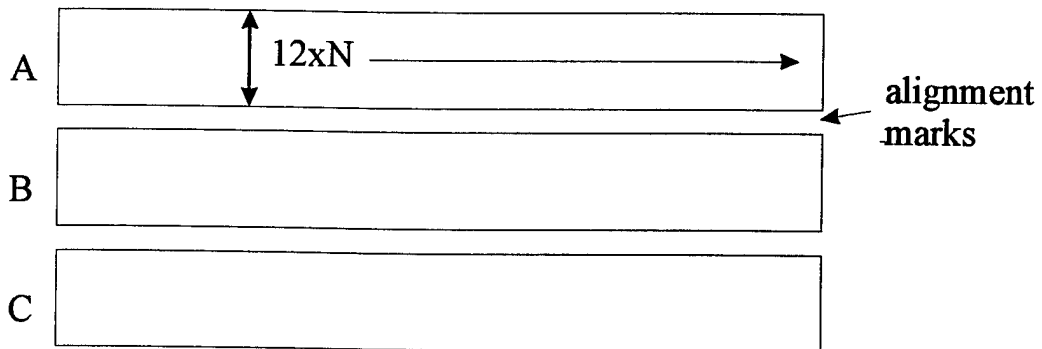
A, B & C represent different diameter microlenses

4x4 arrays
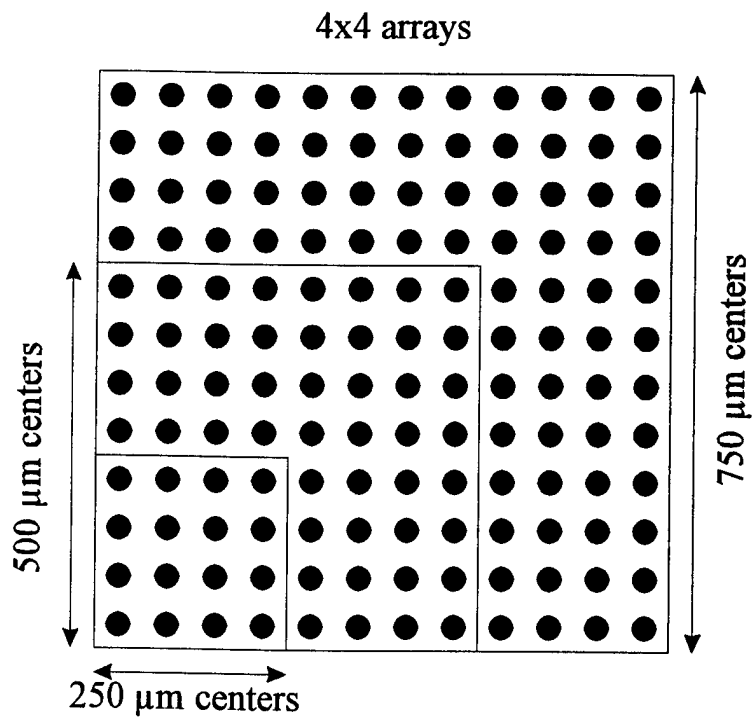
500 μm centers

750 μm centers

250 μm centers

Figure 5

three different sizes of microlenses made during the fabrication corresponding to three different radius of curvatures, the middle sized microlenses was designed to have a radius of curvature of 400 µm. After fabrication, the radius of curvature of the different microlenses was measured using a profile scanner. The resulting radius of curvature is shown in Figure 6, and the surface scan measurements are shown in Figure 7. Here the design and experiment were off by 47 µm in the radius of curvature measurement. This is a very close result and the process will only become more accurate through increased development.

To show what effect an error of approximately 50 µm in the radius of curvature will have on the output beam, theoretical Gaussian mode propagation studies were performed. For a VCSEL of approximately 8 µm diameter, the divergence angle of the beam will vary with the radius of curvature of the microlens according to Figure 8 Here one can see that if the microlens radius of curvature is off by 50 µm, the largest effect this will have on the beam divergence angle is to increase the angle from 2.97° to 3.22° a variation of 8.5%.

3.2 Low Power VCSEL Development

The VCSEL development has continued with increased success. We have demonstrated the lowest thresholds (<0.5 mA) from VCSELs made without the oxide-apertured process. These structures were purely single mode and should be high speed. They have been tested with wide open eye diagrams at 1 Gbps, which was the limit of the package being used (Figure 9). These etched post devices operated single lateral mode as can be seen in the far field plot shown in Figure 10. This is a necessary property for VCSELs used with integrated microlenses for reasons that are discussed in section 3.4.2.

Initial oxide-apertured device have also been made. As reported elsewhere, the threshold currents of the devices are very low, but they operate in multi-lateral modes. This is due to the lack of the mode selective loss that exists inherently in an etched post device. These devices have very high performance and their development cannot be neglected.
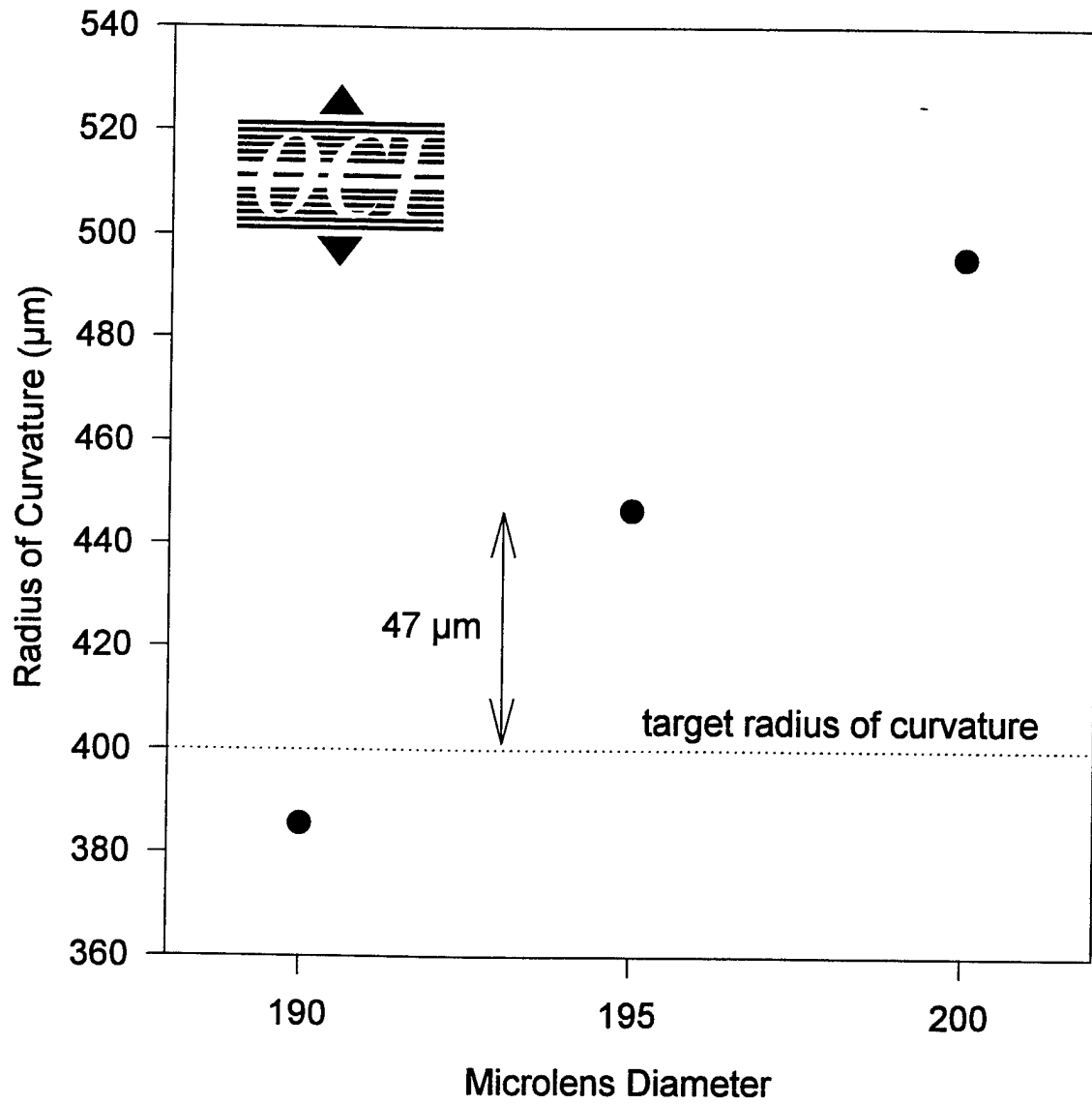
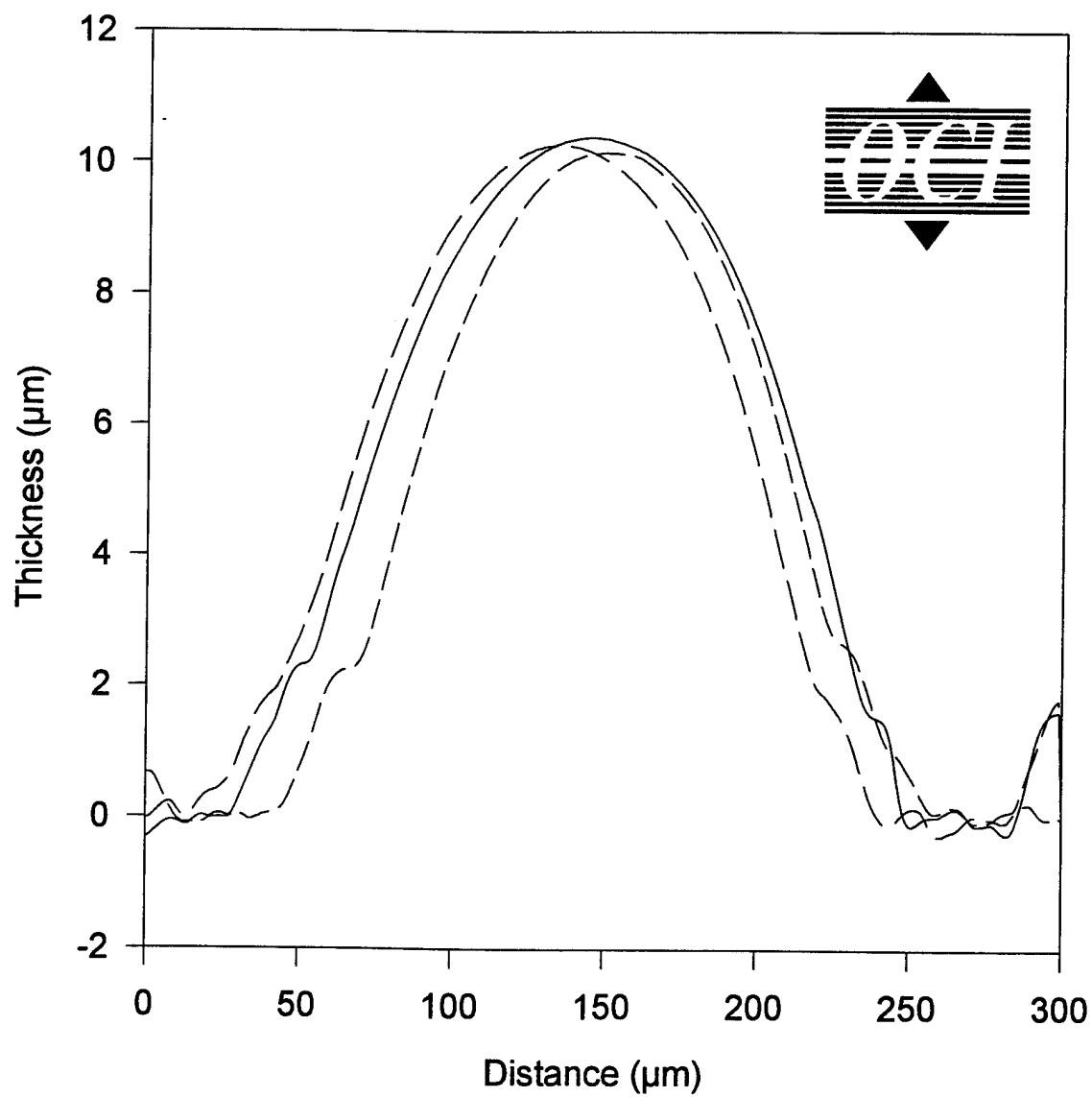# Microlens Fabrication Accuracy

Figure 6

Surface Scan of Microlenses

Figure 7

Radius of Curvature vs. Divergence Angle
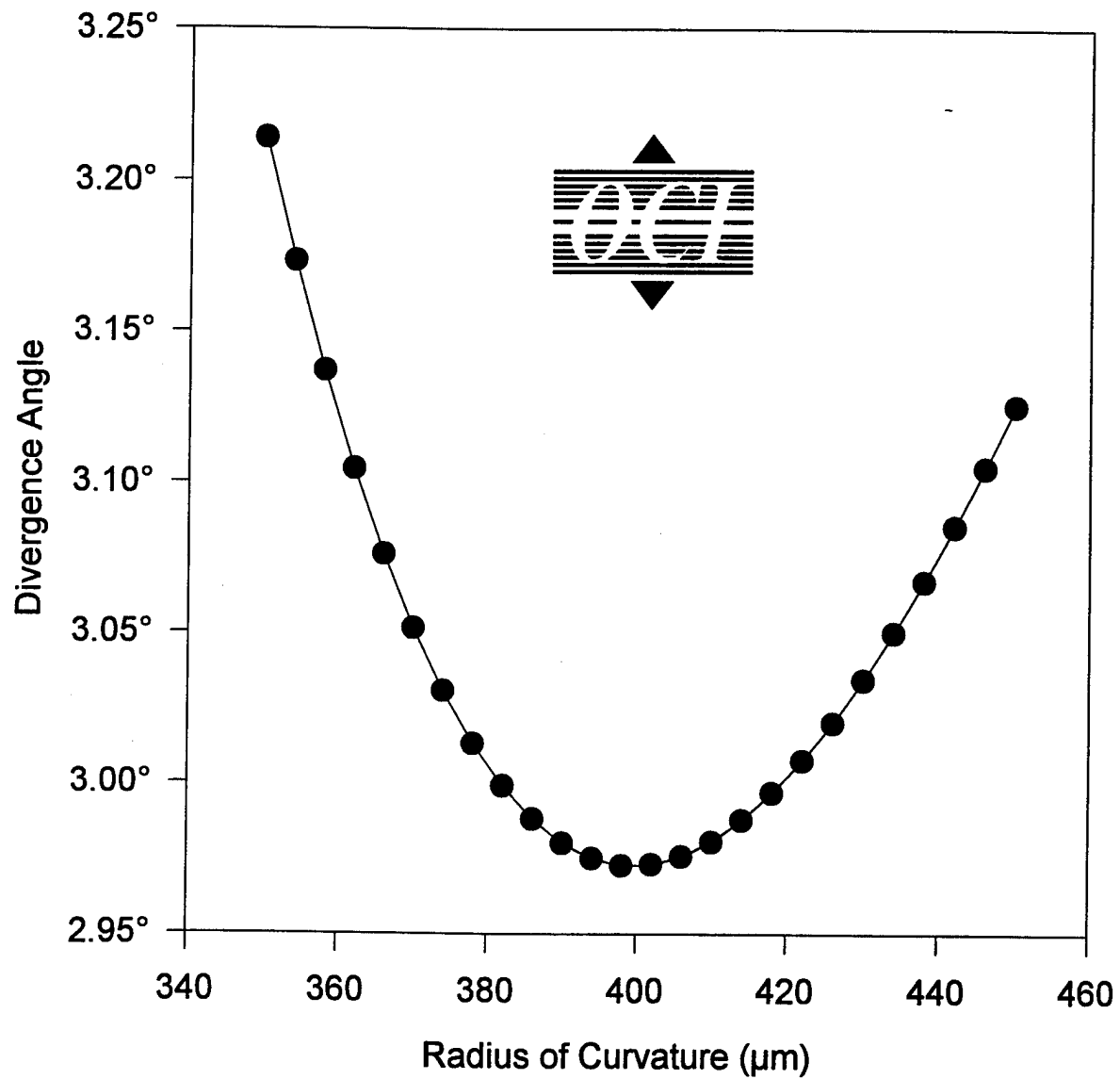
Figure 8

Optical Concepts, Inc.


```
103.220 ns          105.720 ns          108.220 ns

Ch. 4      =  250.0 mVolts/div        Offset  =  2.035  Volts
Timebase   =  500  ps/div             Delay   =  105.720 ns
```
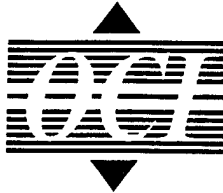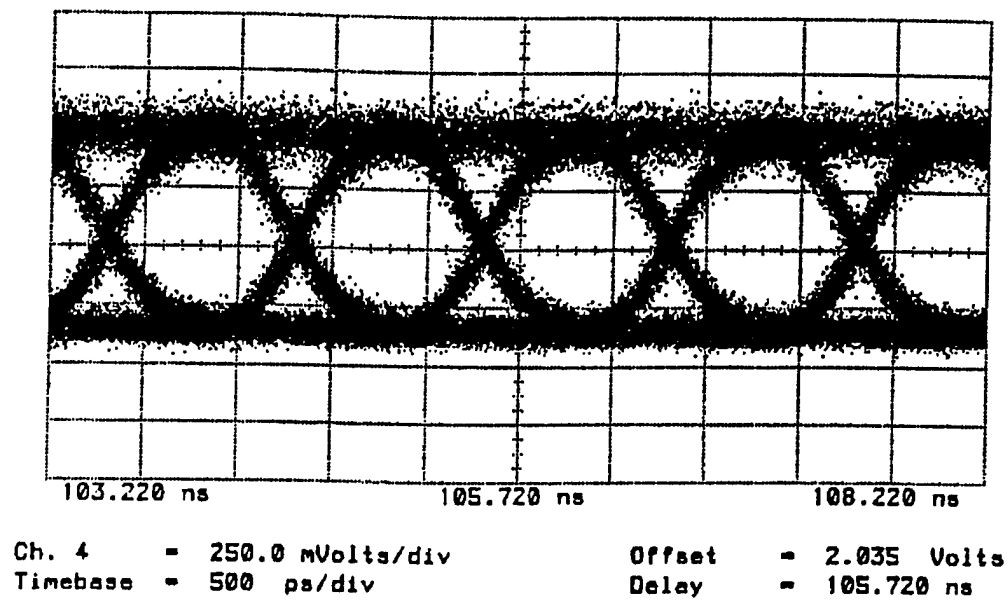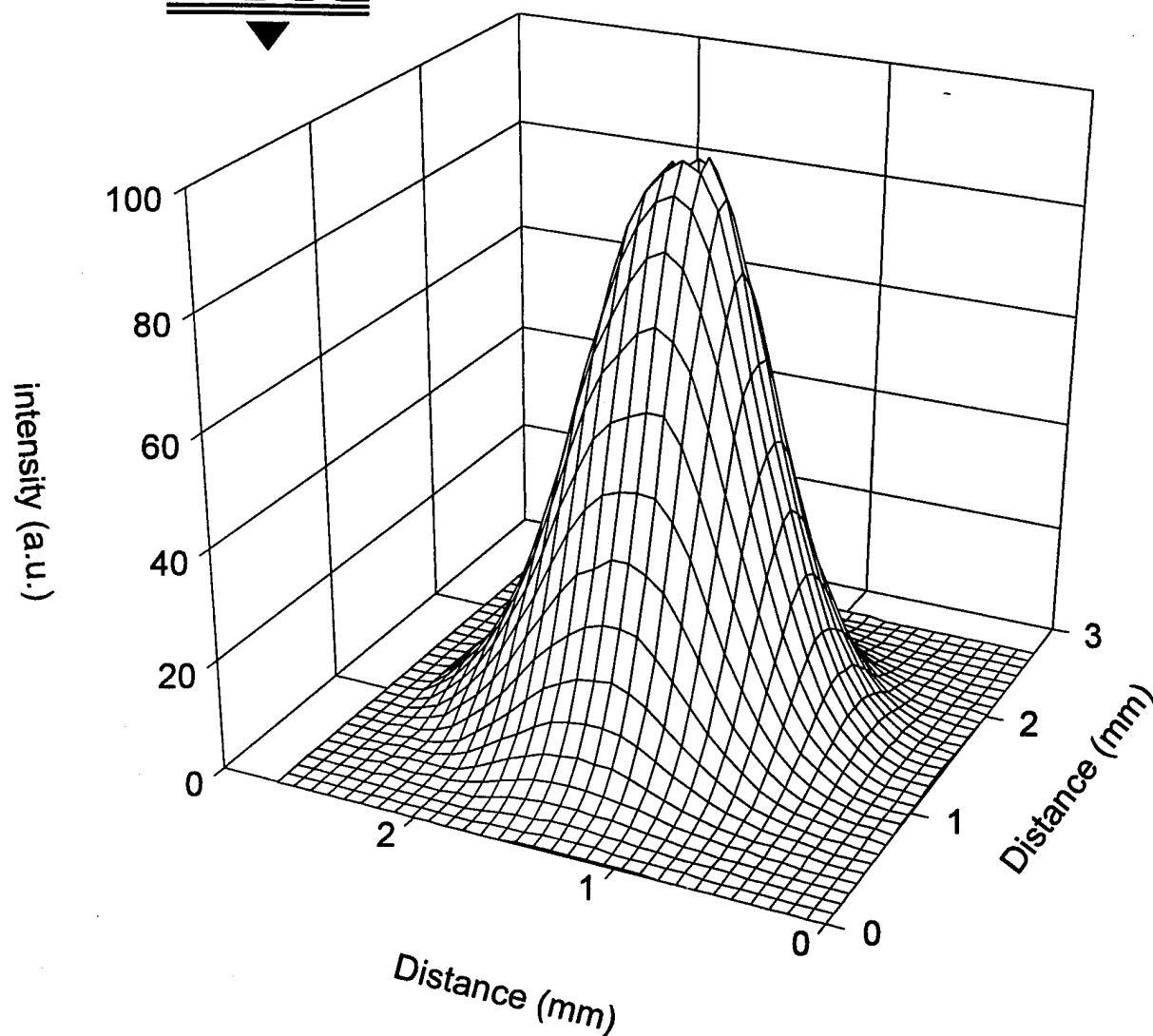
Eye diagram for 1 Gbps large signal data

Figure 9
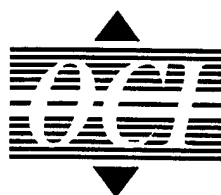
Figure 10

3.3 Mechanical and Electrical Connections

Continued development has been made on mechanical and electrical connections. For this project this has meant metallization and solder bump technology. We continue to see progress in this area. As a result our fabrication yields are excellent with our array yields becoming acceptable after bonding for larger devices. Devices are packaged with solder bumps on top of the devices as shown in Figure 11 and Figure 12. The close proximity of the solder bump with the VCSELs has resulted in bonding stresses causing failures for small area devices.

When etched post devices are flip chip bonded, there are some device fatalities, few for larger area devices (~10 µm diameters) and many for smaller area devices. When the oxide apertured devices are flip chip bonded the mesas of the devices come off entirely for all but a few very large oxide apertured devices (>20 µm diameters). Clearly the oxide related stresses decrease the mechanical strength of the laser mesas to the point that the additional bonding stresses are too much.

These results force a number of development decisions. If solder bumps are to be placed on top of the VCSELs for thermal reasons (the solder bump provides a very good thermal path), then etched post devices are the only realistic VCSEL to be used in the near term. The oxide apertured devices cannot be packaged in this manner at present (possibly never). Implanted devices are more stable, but the optical properties are inappropriate for integration with microlenses. The thermal lens means that the beam waist is a variable that is dependent on the average bias on the device. A variable beam waist cannot be tolerated with integrated microlenses for reasons that are described in Section 3.4.4.

By removing the solder bump from the devices most of the packaging yield problems are eliminated. Now, both etched post and oxide apertured devices can be used provided the solder bumps are larger than the device mesas to prevent and stresses on the devices. This solution is easily done with high performance devices made on semi-insulating substrates. The parasitic capacitance will then be negligible, and the mechanical strength will be outstanding since the metallization and the solder bumps will be deposited directly onto the substrate. The only negative part of this process will be a reduction of the thermal conductivity between the devices
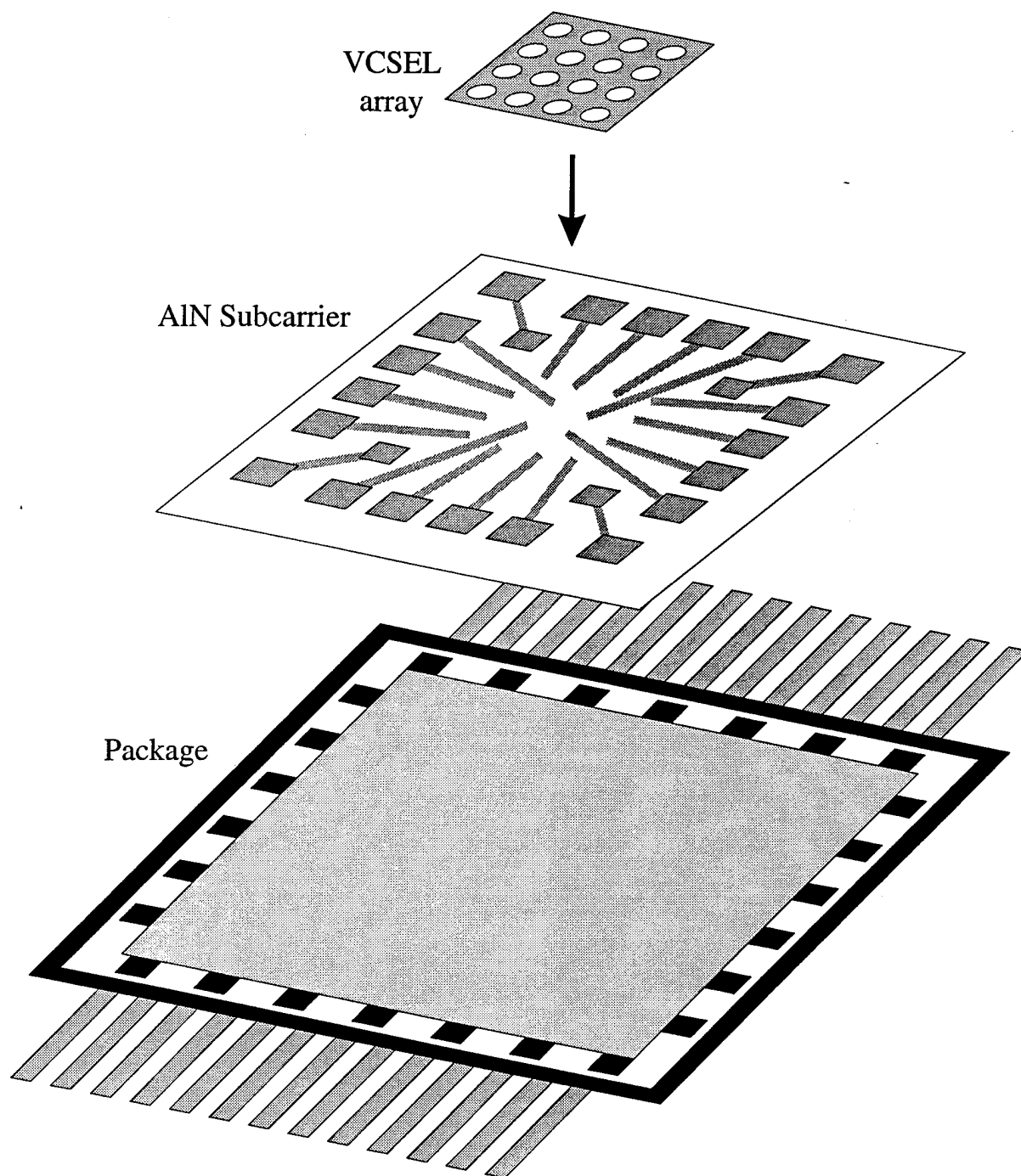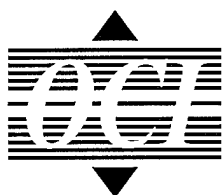
VCSEL Test Package

VCSEL
array

AlN Subcarrier
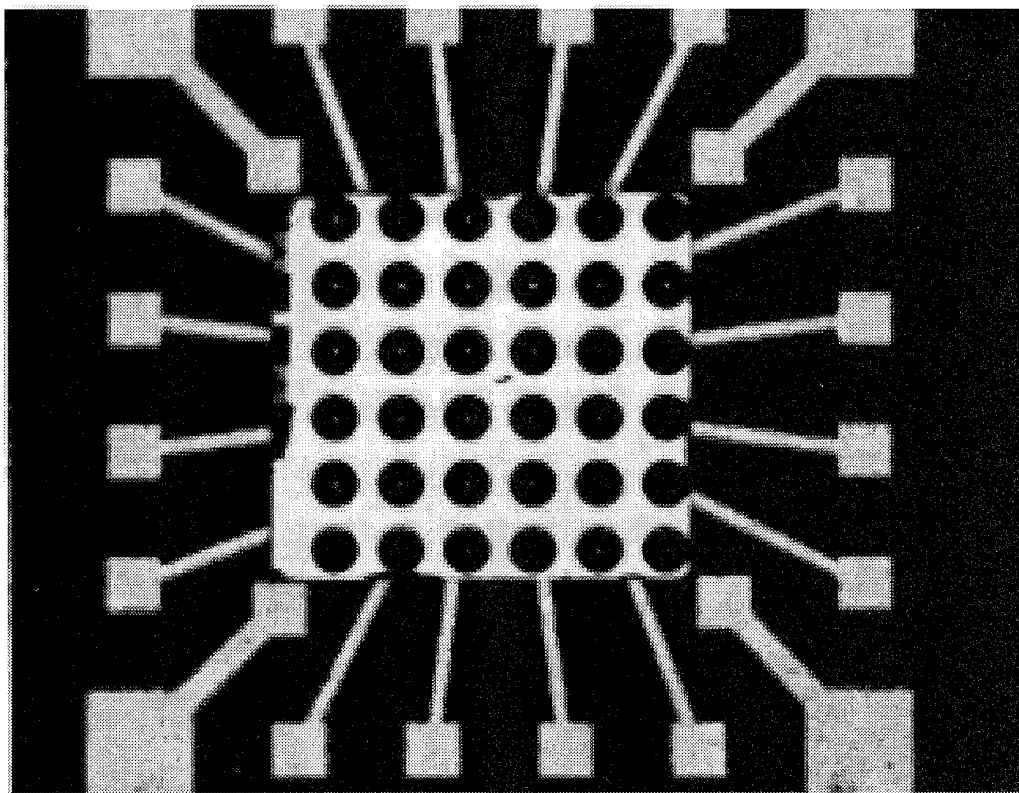
Package

Figure 11

OCI
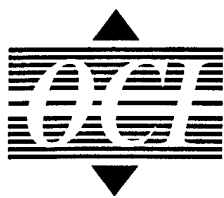
4x4 VCSEL Array

Figure 12

and the package. The devices will still have every bit as good a thermal path as do top emitting VCSELs, so this will not be problematic. This leads to the design choices that have resulted from our investigation.

3.4 Opto-Electronic Package Design

As mentioned in the previous subsection, there were two alternatives for the opto-electronic package design. To achieve high yield, reliable devices and packages in the most timely manner it will be necessary to remove the solder bumps from on top of the devices. As mentioned previously, this will result in a small performance loss, due to thermal reasons. Additionally, for high performance devices we intend to no longer use conducting substrates, rather only semi-insulating. This will allow us to use solder bumps for both the cathode and the anode, and the devices will then be entirely independent from an electrical and cross-talk standpoint.

During the Phase I investigation we have conversed with a number of larger manufacturing companies regarding free space optical interconnects. The only commercial application that appears to be a possibility is for high speed board to board interconnects. Many companies have even rejected this as a realistic application and quickly quote the potential of high performance electronic cables for these short distances. Even Northern Telecom, who admitted to be investigating free space interconnects was currently only looking at single channel serial optical free space interconnects due to the lack of any significant alignment problems when only an single serial channel is used.

In the military sector, more applications exist such as readouts from focal plane arrays, and for connectors in areas of high vibration where traditional electrical connections may fail due to shear stresses. For both of these applications either single serial channels or even massively parallel channels are possible. For focal plane array readouts the primary concern is the thermal management issue. When this type of application was first conceived, it was concluded that operating many VCSELs at low speed would take less power than to operate a single VCSEL at high speed with a multiplexer. At the time the conclusion was correct, however this is no longer the case.

For all military applications, the connection should be able to operate under great vibrations. This limits the usefulness of massively parallel free space links. Massively parallel links require precise tolerances for error free data transmission, and these tolerances will be difficult to achieve under vibration. In contrast, single high speed serial free space links are not susceptible to the same vibration problems. The optical beam can be collimated in a larger diameter, such that even if motion occurs as a result of vibration, the receiver will always receive the transmitted beam. This is possible due to the great deal of development that has taken place in the telecommunications field for high speed receivers. Very high speed receivers can be made that operate error free with very low input powers, a necessary property for long haul fiber optic communications. As a result, it is not necessary to achieve good coupling over a free space serial link, and by using a larger beam diameter the link will have a reduced sensitivity to movement.

It is our opinion that the most successful free space data link using VCSELs will be one using single serial links. These links will still have advantages over links using in-plane lasers even though the array geometries are not used. The primary advantages will be much lower cost for high speed devices, lower packaging costs and a much lower power budget required to drive the devices, all of which lead to broader commercial and military applications.

The following subsections will break down components of the Opto-Electronic Package Design.

3.4.1 VCSEL Development

For the Phase II portion of the investigation we intend to produce fully manufacturable high performance VCSELs. To ensure high performance, the devices will be fabricated on semi-insulating substrates to minimize the parasitic capacitance. This will also make it possible to use larger bonding pads without any penalties in performance. Figure 13 shows a schematic of the proposed VCSELs.

For optimum performance, we are recommending VCSELs that are bottom emitting operating at or near 980 nm. The device diameters will be defined by etching mesa as was done in Phase I. Depending on the size of the mesa the devices can be alternatively oxide-apertured or purely
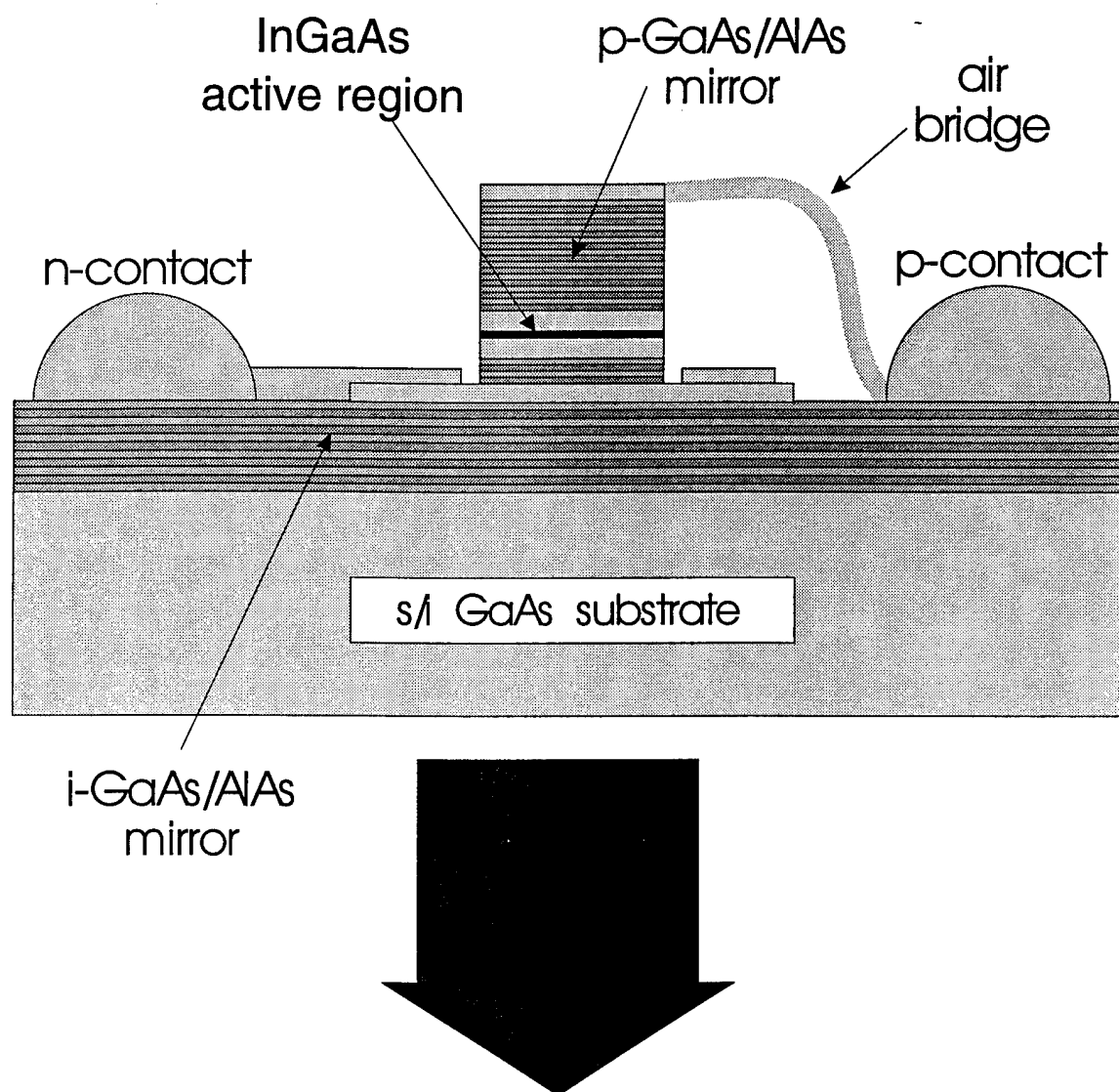
Figure 13

etched post devices. During Phase II we intend to continue the development of both of the device types.

The etched post devices have had the most internal development, and as a result we understand the design parameters well. Using the etched post design, VCSELs can be designed to operate in a pure single lateral mode. The mode selectivity is a function of the side wall scattering from the etched post, a relationship that has been successfully modeled. Practically, the amount of side wall scattering depends strongly on the method used to create the etched post. Given the Reactive Ion Etching (RIE) system now in use by Optical Concepts the single mode / multi mode VCSEL cutoff occurs with VCSELs with 8 μm diameter posts. So larger VCSELs will operate multi-lateral mode and smaller VCSELs will operate single mode.

Oxide apertured VCSELs are less well developed. Optical Concepts will have access to the best of this technology for Phase II through the transfer of personnel from Sandia National Labs, where the oxide technology was pioneered. Even given this inherited experience, there are some aspects of the oxide technology that are unclear. Presently oxide apertured VCSELs hold all the low power records (threshold, efficiency etc.), they have been shown to be reproducibly made and they have been operated continuously for many hours. Unfortunately these experiments were not performed with true manufacturability and reliability in mind. The reliability measurement was made while operating the device under low power, where a real reliability test would have operated the device at high input currents and at an elevated temperature. The other drawback to the oxide-apertured VCSELs that has not been reported is their mechanical fragility. These devices are known to shear off due to the application of a probe tip. The outstanding performance achieved by these structures would still make it unwise for us to abandon their development at this early stage. As a result the development will be continued, with the objective of modifying the device design, fabrication and packaging to eliminate or minimize the factors causing mechanical reliability problems.

For VCSELs coupled to microlenses, it would be ideal to have the smallest optical mode size possible, so that the beam would expand to fill the microlens and so that the devices will have the minimum threshold and operating currents. This implies either a very small etched post device

or a very small oxide aperture. In either case the mechanical strength will be a real problem. To reduce the difficulty this will have on the actual packaging of the devices it is our intention to remove any stresses from the mesas. This is done by using an air bridge from the mesa onto a bonding pad as shown in the figure. After the devices are flip chip bonded, the entire structure can be back filled with a low stress encapsulant and this will decrease the sensitivity of the devices to extensive vibration.

3.4.2 Microlens Development

After completing the Phase I portion of the research project we are confident that GaAs based refractive microlenses can be integrated with VCSELs, and used to collimate the light produced by the VCSELs. For Phase II we intend to continue to refine the microlens process in GaAs and to continue the development of InP based microlenses for receivers.

There are a number of issues that should be addressed in the microlens development which can be best introduced in a graphical manner. It was suggested the previous subsection that is would be helpful to make VCSELs with the smallest possible diameter, so that the beam diameter would be as large as possible for effective collimation. This relationship can be seen in Figure 14. For a given beam diameter (approximately the same as the VCSEL diameter) the divergence of the beam is shown in the right vertical axis, and the size of the beam at the microlens is shown in the left vertical axis. For example if one starts with a VCSEL with a 10 µm beam diameter, the divergence angle of the beam in air will be 7.15°. If an integrated microlens is used the beam will have expanded to a diameter of slightly more than 20 µm at the microlens. After collimating this beam with the microlens, the divergence angle will then be 3.6°. Although this is an improvement the divergence angle is still quite high for free space links across any significant distance, especially if multiple channels are to be used.

Clearly, it would be beneficial if the beam diameter could be made to be more in the order of 1 or 2 µm. In this case the beam would expand to approximately 100 µm at the microlens resulting in a new divergence angle of 0.715°. If this was the entire story, the development process would be straight forward. Unfortunately, things are not this simplistic. If very small beams diameters are to be used, then the accuracy of the microlens becomes more critical. Figure 15 shows the
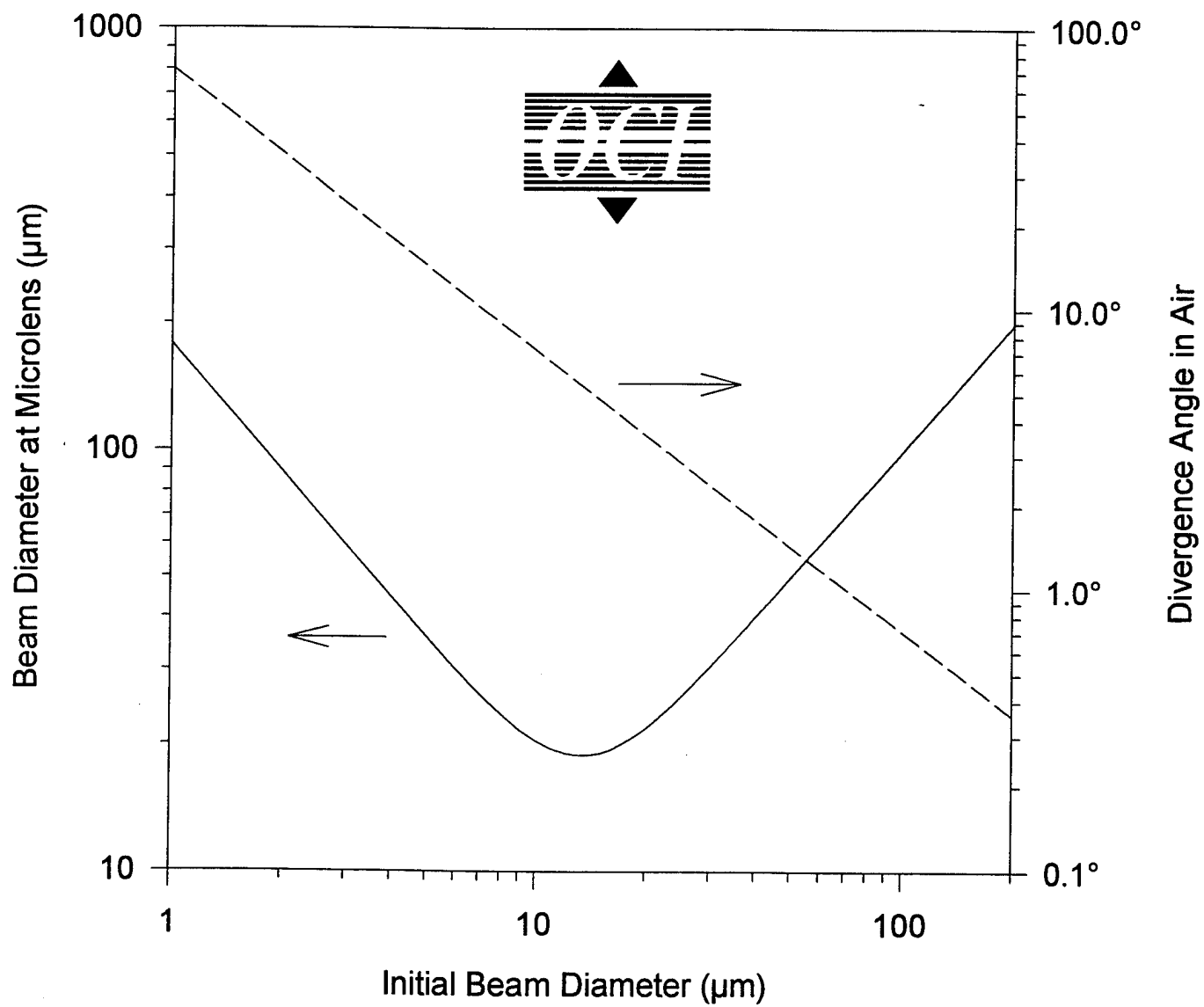
Optical Beam Properties

Figure 14

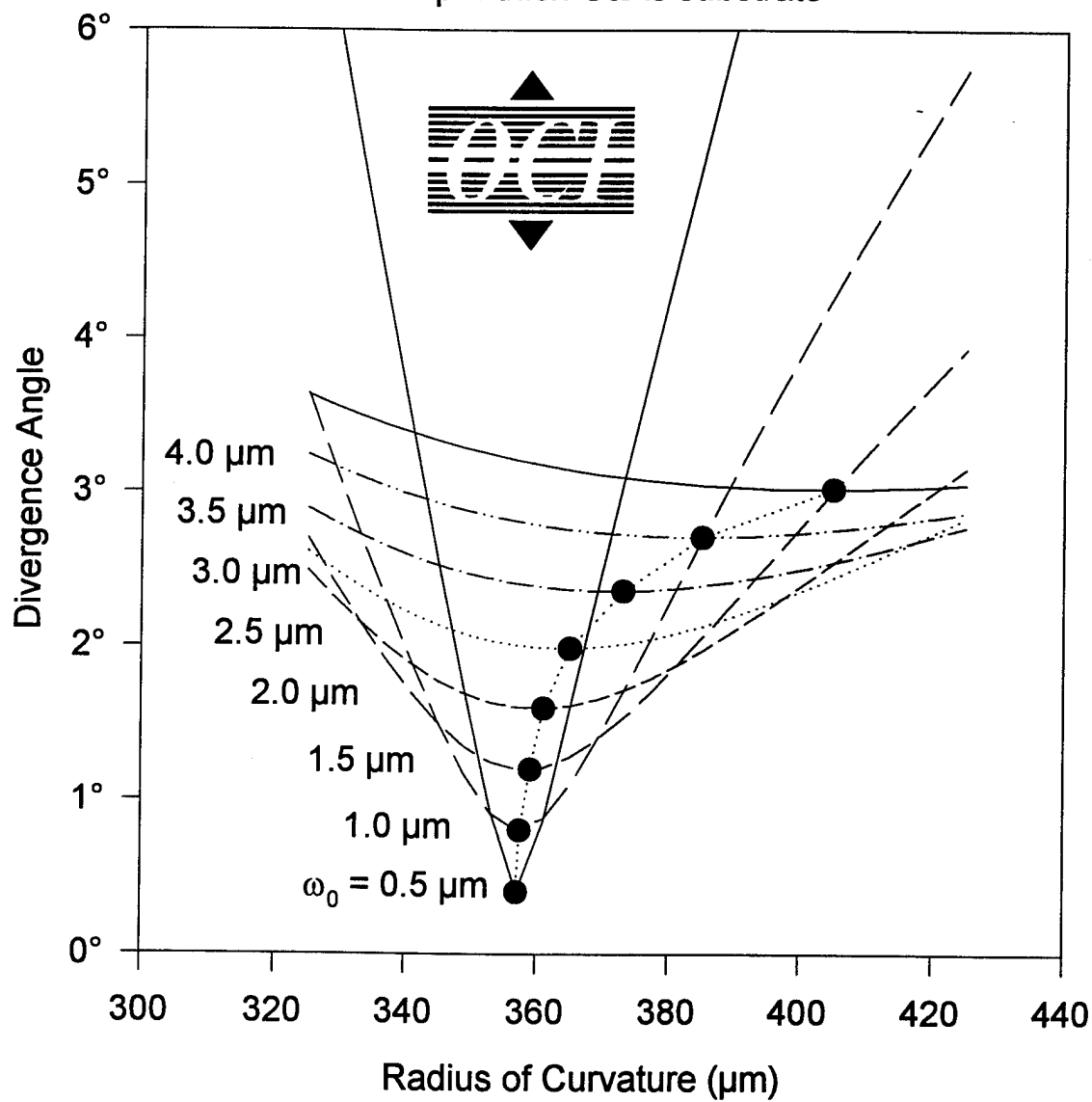# Radius of Curvature vs. Divergence Angle

500 µm thick GaAs substrate

Figure 15

relationship between the divergence angle of a VCSEL beam after going through an integrated microlens of varying radius of curvature. There are a number of important points to be gained from the figure. First, there is an inverse relationship between the theoretical smallest divergence angle and the sensitivity upon the radius of curvature. This makes the accuracy of the microlenses more and more critical as the size of the VCSELs is reduced. Second, there is no one correct radius of curvature for all VCSEL diameters. This is due to the relatively short distance between the VCSELs and the integrated microlenses. Ideally the microlens should be in the far field of the VCSEL. If this was the case then the radius of curvature would be well defined for all VCSEL sizes. For larger VCSELs the distance is not great enough for the far field approximation to be accurate.

For this reason VCSELs operating in a single lateral mode are necessary. In the near field the radius of curvature for the different lateral modes is not the same. This can be best described using Gaussian optical modes. The lateral VCSEL mode is best approximated by an equivalent Gaussian mode to estimate the optical properties. For higher order Gaussian modes the beam width is much wider than the fundamental mode although the optical properties of the mode is based on the spot size of the fundamental mode. The higher order VCSEL modes on the other hand are the same physical dimension as the fundamental VCSEL modes. This means that they are best described by a Gaussian mode with a smaller spot size than used to describe the fundamental VCSEL mode. Looking at the figure one can see that the higher order modes will not be collimated if the fundamental mode has been collimated.

There are a number of directions that could be pursued given these limitations. First, using integrated microlenses and standard substrate thicknesses it should be assumed that the divergence angle will be at least 2.5° given the accuracy of the microlens fabrication. For parallel free space communications this limits the total distance to approximately 2 mm. This assumes 250 μm center to center spacing between different elements. The free space distance could be increased by using larger device spacings, but this increases the cost of the transmitter links due to increased die size. The cost estimates will be covered more in a later section. If serial free space links are used then the maximum distance is only dependent on receiver

sensitivity. Here a new topic appears for which a certain amount of discussion is required. The next section will discuss the relative merits of serial versus parallel free space links.

3.4.3 Serial versus Parallel Free Space Links

At the beginning of the program, it was anticipated that we would utilize 2-D arrays of VCSELs for massively parallel free space communications. After examining this in more detail during the Phase I investigation, our conclusion is that this approach is not economically sound, even for focal plane array applications where the power budget is more important than the total cost. The following two subsections compare the power budgets and cost estimate of highly parallel links compared with higher speed serial links:

3.4.3.1 Power Budget Comparison

If, for example there is a 100 MHz data stream of 64 channels, this could be broadcast over an 8x8 VCSEL array at 100 MHz. With a 5 V power supply and 2 mA drive current per device, this would be a total power budget of 640 mW. Alternatively, the data could be transferred over two VCSELs each at 3.2 GHz. The power budget for the higher speed VCSELs would be about 50 mW plus about 500 mW for the high speed laser drivers and multiplexer circuitry using current GaAs technology. Thus, the total power budget would be almost 100 mW less for the high speed serial channels then for the parallel link. At the receiver end the equivalent argument can be made.

3.4.3.2 Cost Comparison

Building upon the previous example, but now adding in the cost estimates the comparison is in favor of the higher speed links with fewer VCSELs. The cost of VCSELs to the first order is proportional to the size of the die. Assuming that 250 µm VCSEL spacing were sufficiently large (this is unlikely, and 500 µm spacings would result in a die four times larger), the 8x8 VCSEL array would require a die size of at least 4 mm^2. The two channel high speed link would use two individual VCSELs with a total die area of 0.125 mm^2, or 32 times smaller than the 8x8 array.

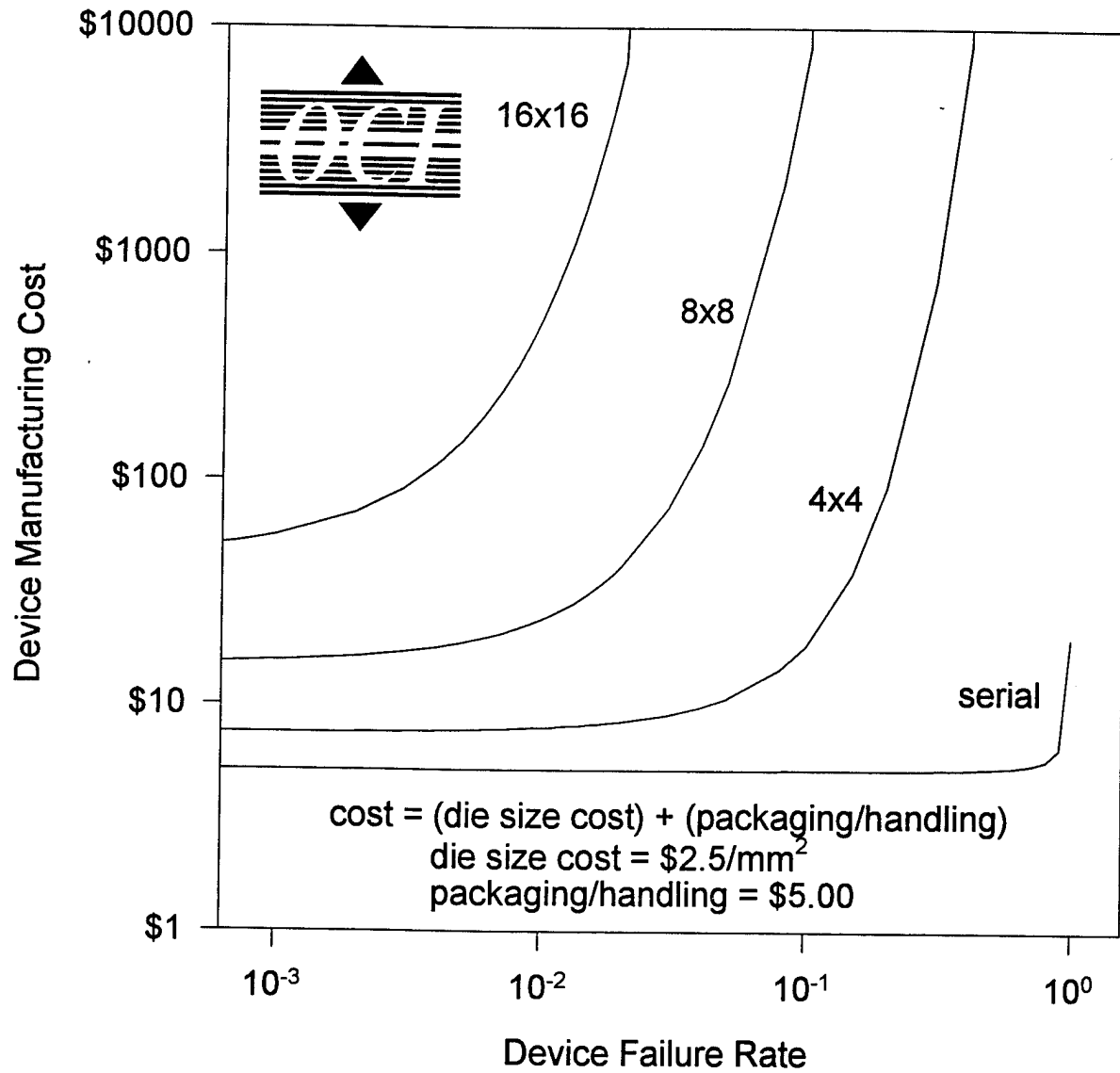# Device Cost/Yield Comparison

Figure 16

The cost of the devices is then affected by the individual yield of the VCSEL. Figure 16 shows a estimate of device cost assuming there is a die cost of $2.50/mm^2, and a packaging or handling cost of $5.00. In real manufacturing of VCSELs it is unreasonable to assume 100% device yield. If there is a 99% individual device yield, then the cost of the individual devices will be virtually unchanged, while the cost of 8x8 array will almost double. The yield may well be worse than 99% since VCSELs made for free space links need to operate in a pure fundamental lateral mode. These single mode VCSELs tend to be less mechanically stable due to their small size, and as a result their yield often suffers. The yield problem could be solved by only using individual devices and by forming VCSELs arrays during the packaging stage. This method is not cost effective since it would require 64 elements as opposed to 3 elements (2 VCSELs, 1 mux/driver) for the high speed interconnect approach. The cost estimates for a matching receiver are equivalent to the transmitter. Here there is another factor of at least two in favor of the high speed serial link.

If all the different cost estimates are put together the total transmitter cost might be as shown in Figure 17. Here the multiplex circuitry is assumed to cost $10.00 and there is a small cost for laser drivers for all the link options. The point of this graph is that for parallel links of up to 16 elements the costs may be the lowest. Realistically, this graph may be deceiving since the assumption is that there is no multiplex circuitry for the parallel links. For real applications, it is unlikely that the native data path will be 16 elements wide. The addition of any multiplex circuitry would then need to be added to the cost estimate of the parallel link.

So, for both power budget and cost it makes the most economic sense to concentrate on high speed individual VCSEL links.

3.4.4 Optical Design Considerations

In section 3.4.2 the limitations of VCSELs with integrated microlenses for free space optical links were introduced. Beginning with this basic case, alternative optical geometries will be discussed. To begin with it has been shown that it is possible to manufacture a VCSEL link with a beam divergence of 2.5°. Assuming that the receiver is able to collect all light that passes through a 200 μm aperture (the size of a collection microlens), then the optical power at the
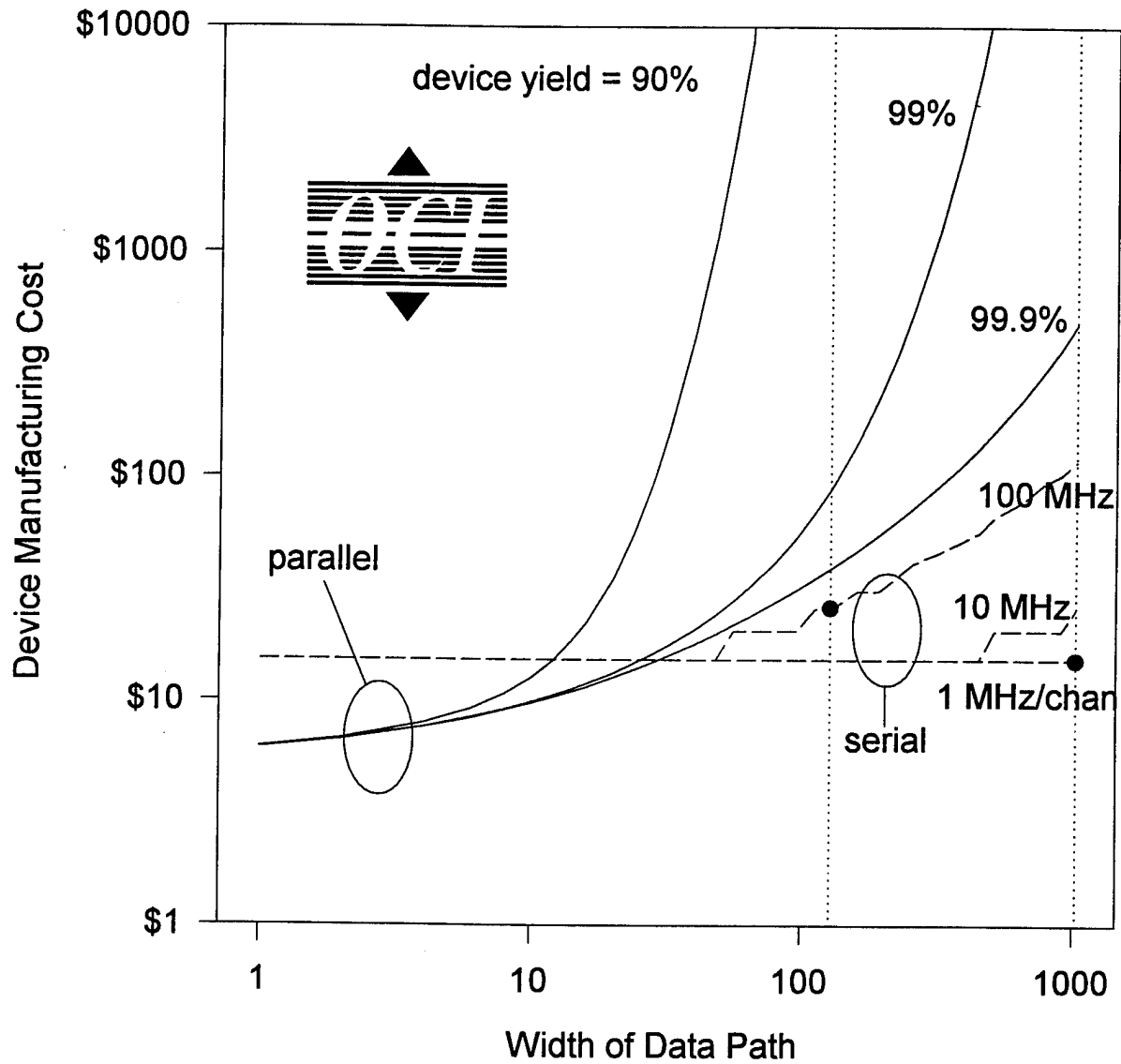
Transmitter Cost Estimates

Figure 17

receiver is as shown in Figure 18. The point of this figure is that even a VCSEL without a microlens (divergence angle of 8°) can be used for free space optical links provided the VCSEL is single mode and the receiver is reasonably sensitive. The justification for the microlens then becomes somewhat questionable for short free space links. Here the microlens allows for the use of a less sensitive receiver, a potential cost saving factor. For longer distance free space links the addition of the microlens becomes critical for effective communications.

For a standard wafer thickness, the lowest realistic divergence angle is about 2.5°. If the application requires a smaller divergence angle there are a number of options: using thicker substrates or using external microlenses. GaAs wafers can be purchased with substrates as thick as 1000 μm (1 mm). Using the increased thickness, the graph shown in Figure 15 will be altered to that seen in Figure 19. A comparison of these two figures shows that the additional thickness makes the optical path much closer to the far field of the VCSELs. Also, much smaller divergence angles can realistically be achieved.

If external microlenses are used, then optical beam is given the chance to expand more, making possible better collimation of the beam. This can be seen in Figure 20. With this increased distance between the VCSEL and the lens, the optical path is closer to reaching the far field condition as can be seen from Figure 21.

3.4.4.1 Parallel Limitations

The previous discussion on optical design considerations has much to say about the limitation of parallel free space links. Figure 18 can be replotted using a logarithmic scale over a limited range as in Figure 22. Here, the condition at which the pseudo-collimated beam no longer enters entirely into a 200 μm diameter aperture can be seen as a drop in the optical signal at the receiver. For parallel free space communications systems, this point in the graph is also the point after which one will be concerned about cross-talk between adjacent channels. Thus, if no microlenses are used, the largest span of the parallel free space link would be about 0.6 mm. Using microlenses on a standard substrate thickness this can be increased to about 2 mm, and finally to about 4 mm using the other microlens options described above.
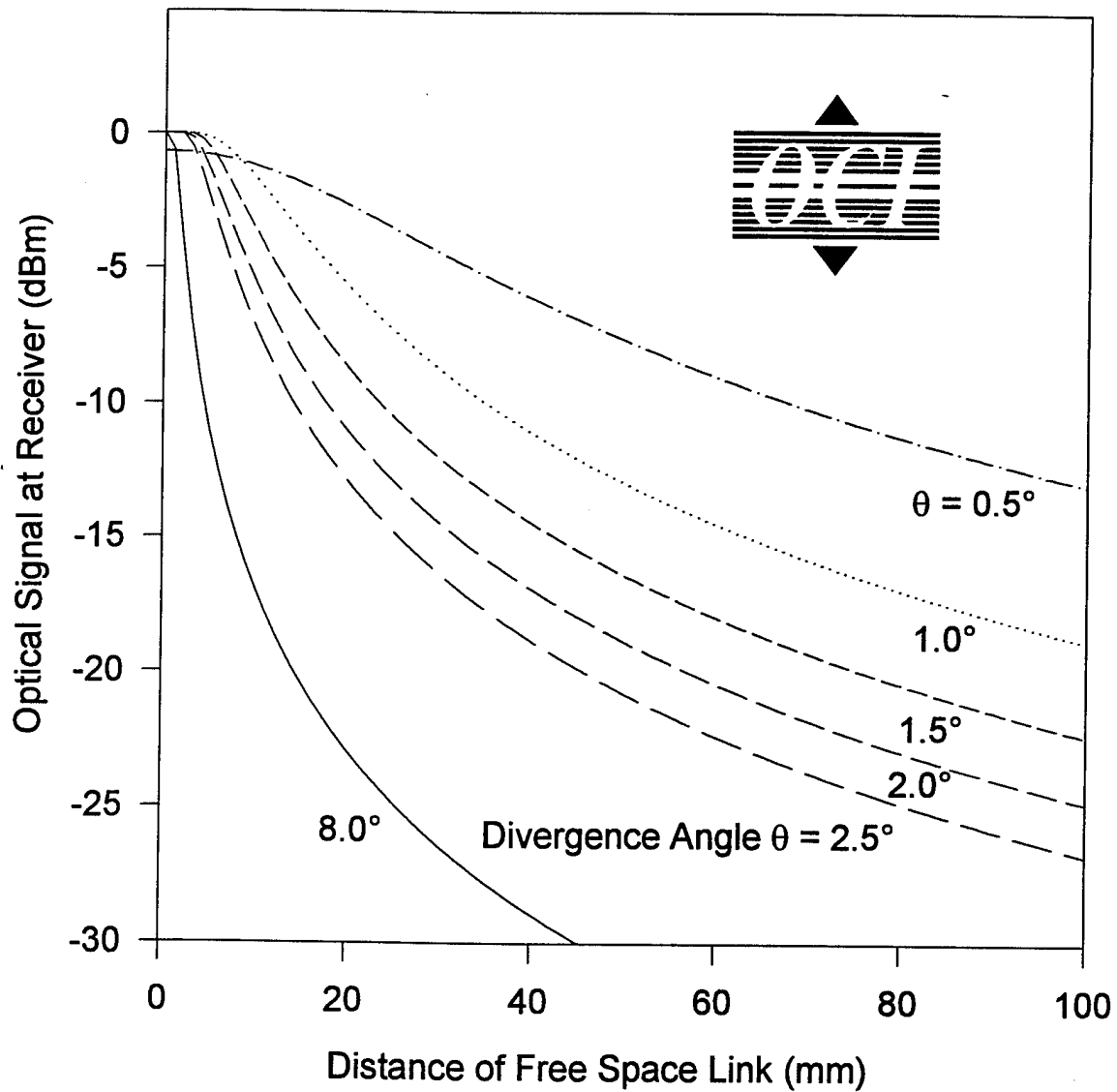
Free Space Link Design

Figure 18
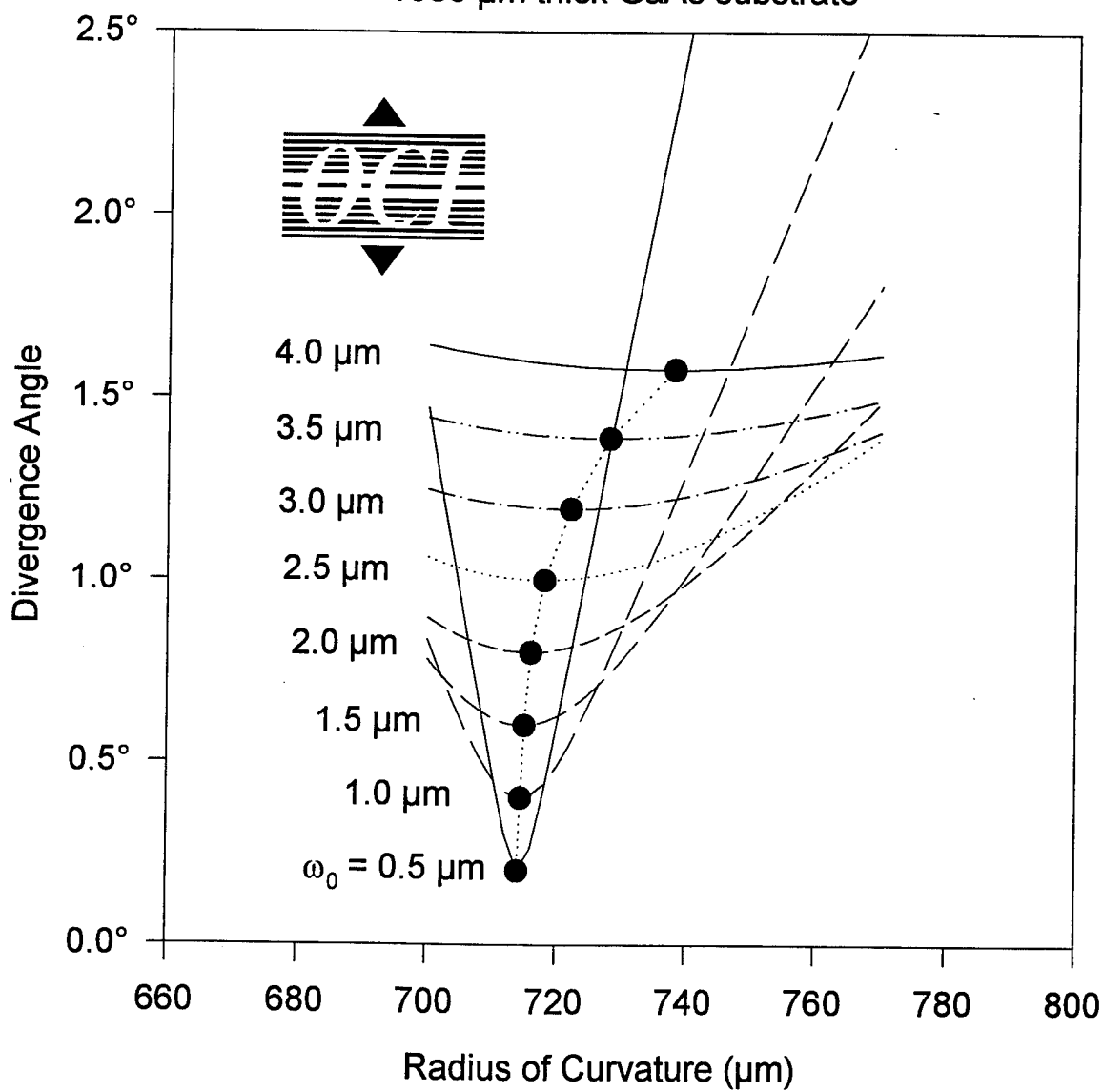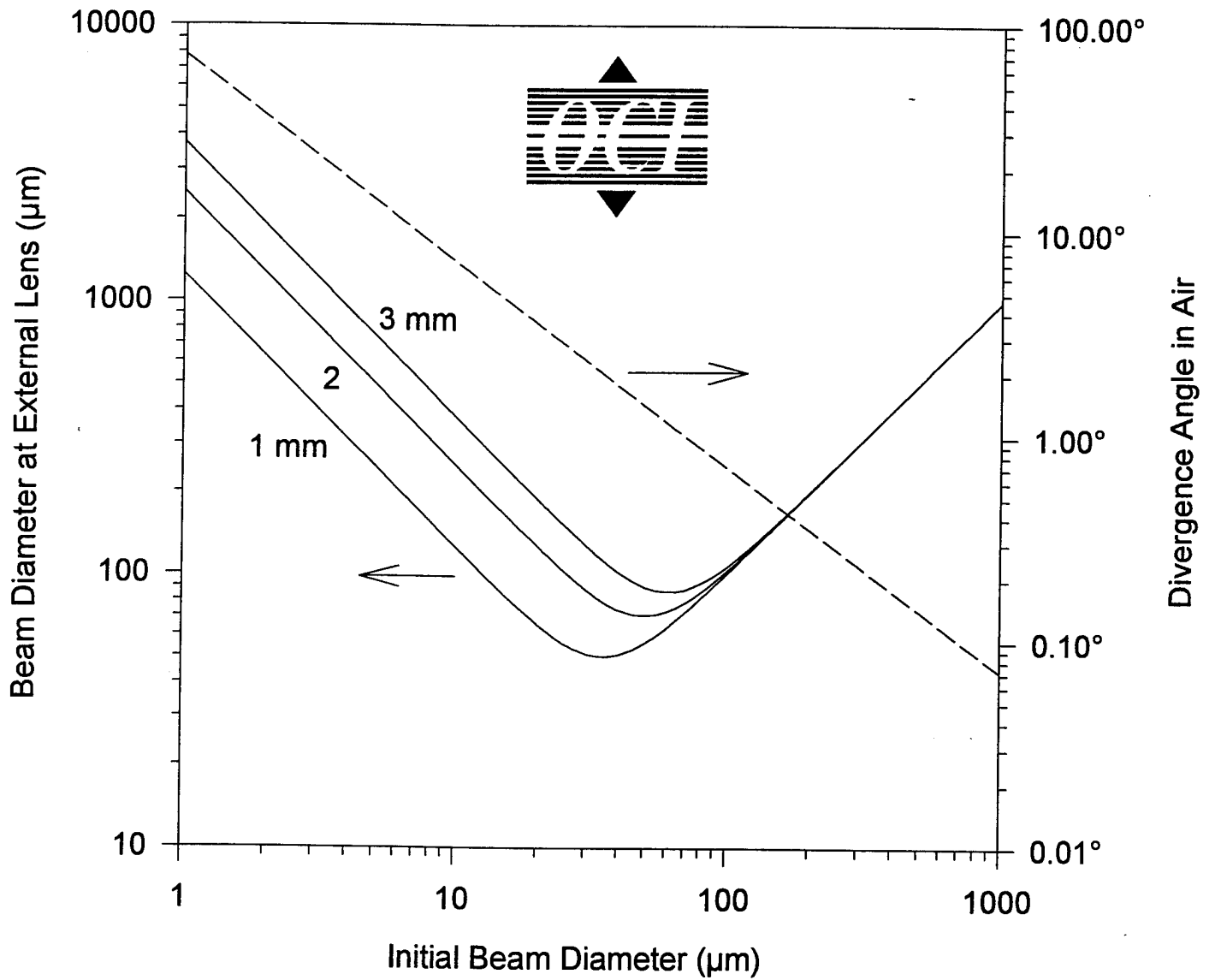
Figure 19

Optical Beam Properties

Figure 20

Radius of Curvature vs. Divergence Angle

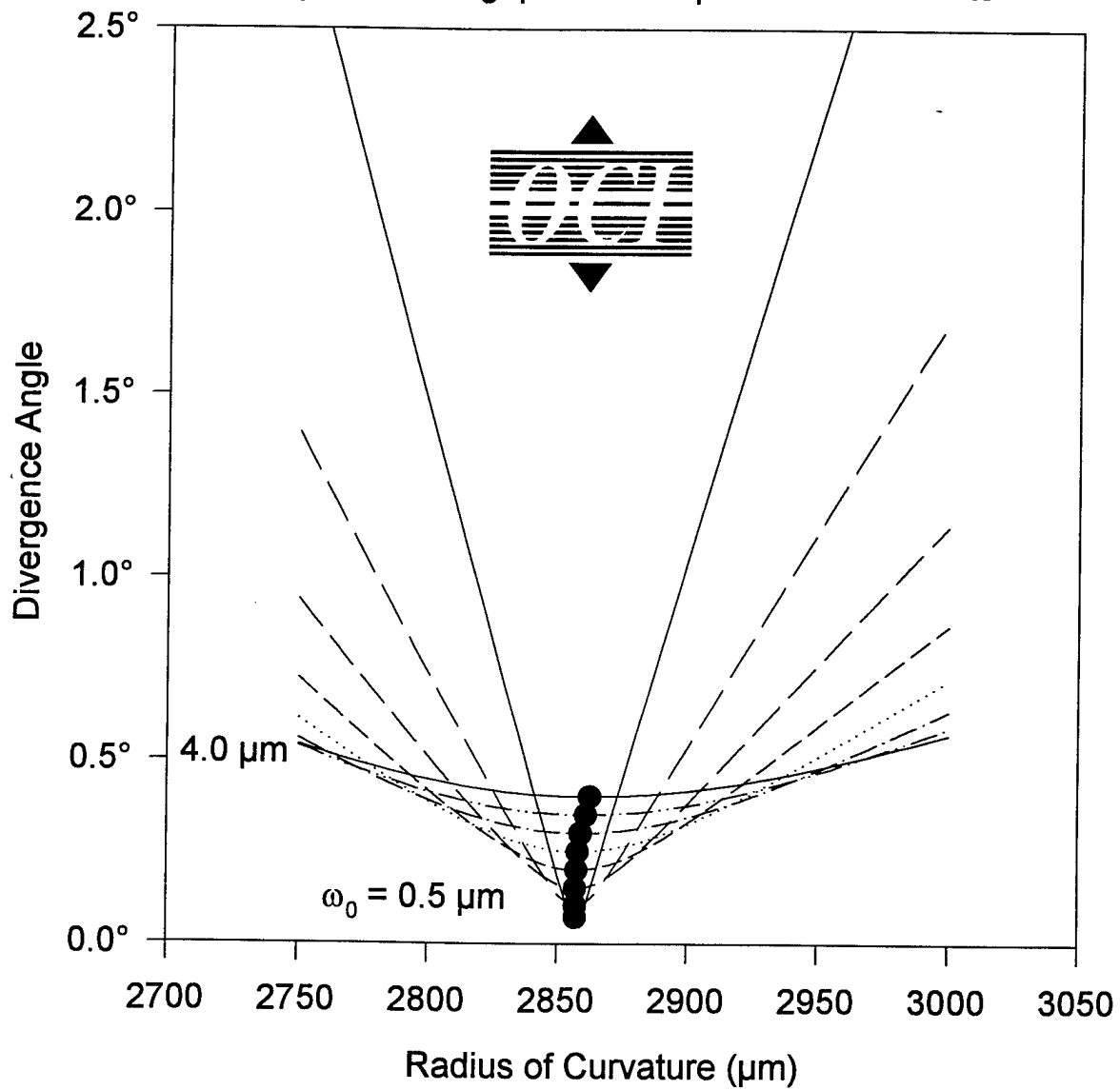## 1000 µm thick airgap after 500 µm GaAs substrate

Figure 21

Free Space Link Design

parallel limitations

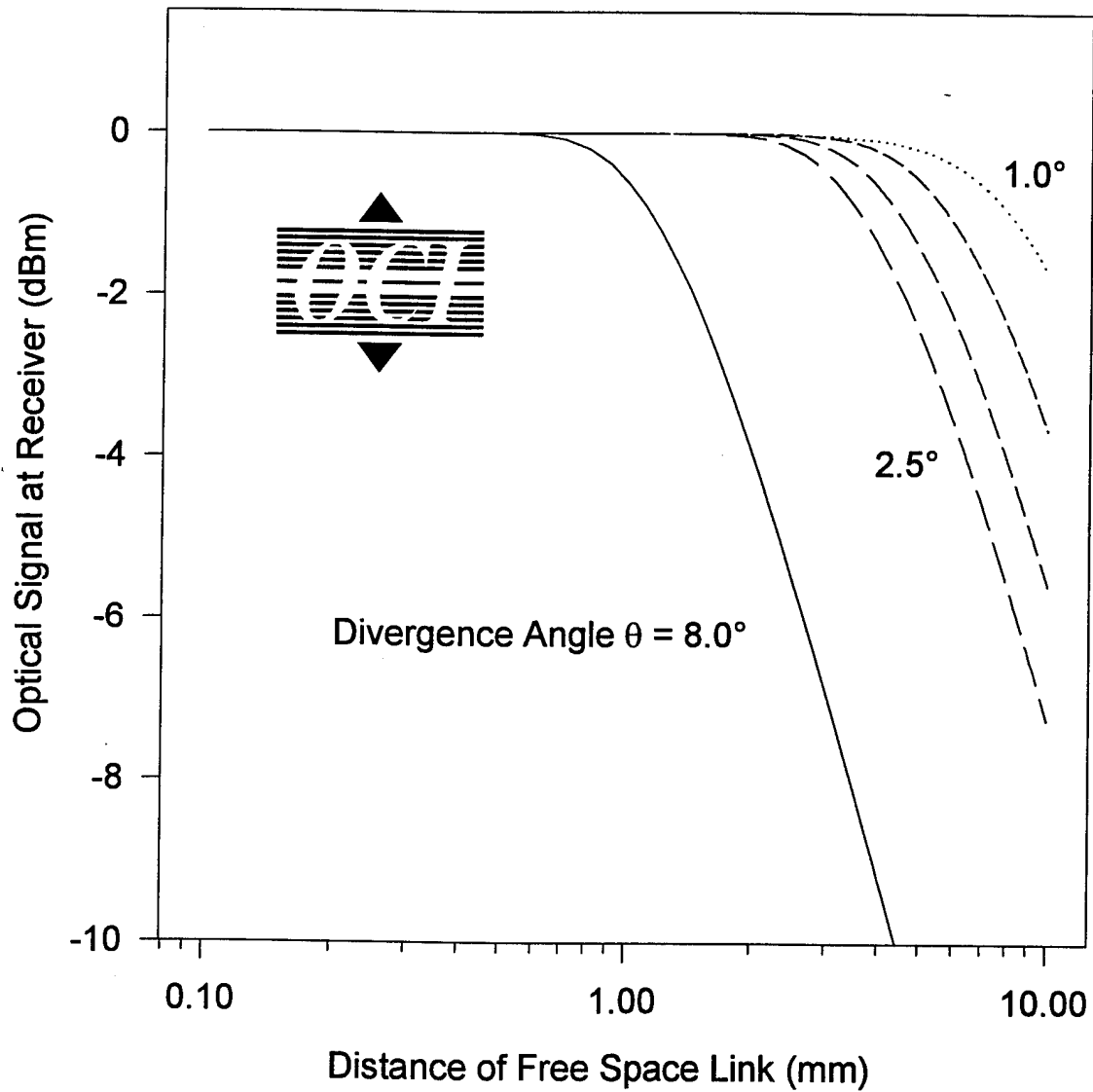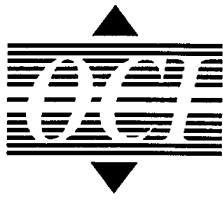**Figure 22**

In the figure, the minimum divergence angle that is considered is 1°. This is because for the optical system to have a smaller divergence angle, the waist of the optical beam at the microlens would need to very close to or larger than 200 μm. Thus, even a small amount of divergence would result in cross talk between adjacent channels. This problem has been recognized by the research group at Bell Northern Research (BNR), where private communications has indicated that BNR is considering the possibility of using short fiber bundles to transmit parallel optical signals. In so doing, any distance limitations are removed, even for very dense optical communications. For the purposes of this research project, this alternative will not be investigated since it implies a very directed end application as opposed to a general free space communications chip set.
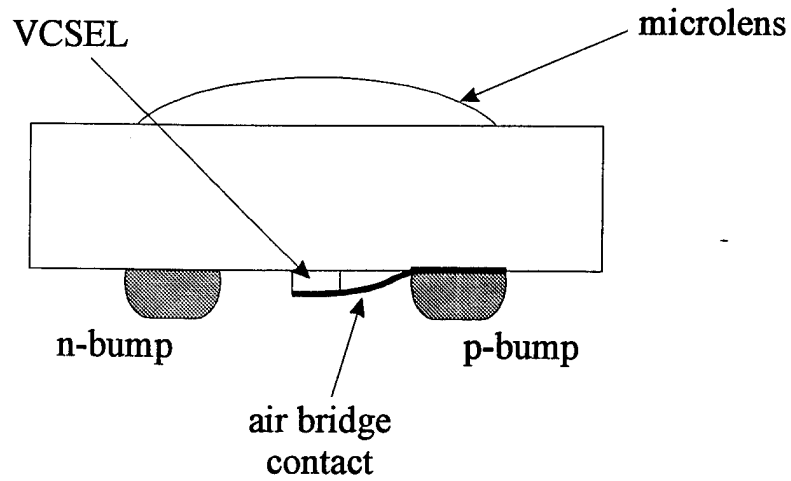
3.4.5 Package Design

As a results of the cost estimates and the optical design considerations, we propose to develop multi-pin packages that contain a single high speed VCSEL with integrated microlens and all the appropriate interface circuitry (laser drivers and multiplexer). Figure 23 shows a schematic of the proposed transmitter package. The receiver package will be identical with the VCSEL replaced with an InP based bottom illuminated detector, and with the laser driver/mux circuitry replace with transimpedance amplifier / demux circuitry.

As a alternative to the integrated microlens for longer distance free space links we propose working with the optical group at Army Research Labs to develop diffractive microlenses that would be used as part of a transparent package covering. This approach would not use microlenses integrated with the VCSELs, allowing the beam to expand inside the package. The package window containing the diffractive microlens would then serve to collimate the optical beam. With the larger beam diameter it is then possible to achieve an optical beam that stays collimated over a much larger distance as shown in previous subsections. Using this approach for both the transmitter and receiver also serves to further relax the alignment tolerances. The two approaches are compared in Figure 24.
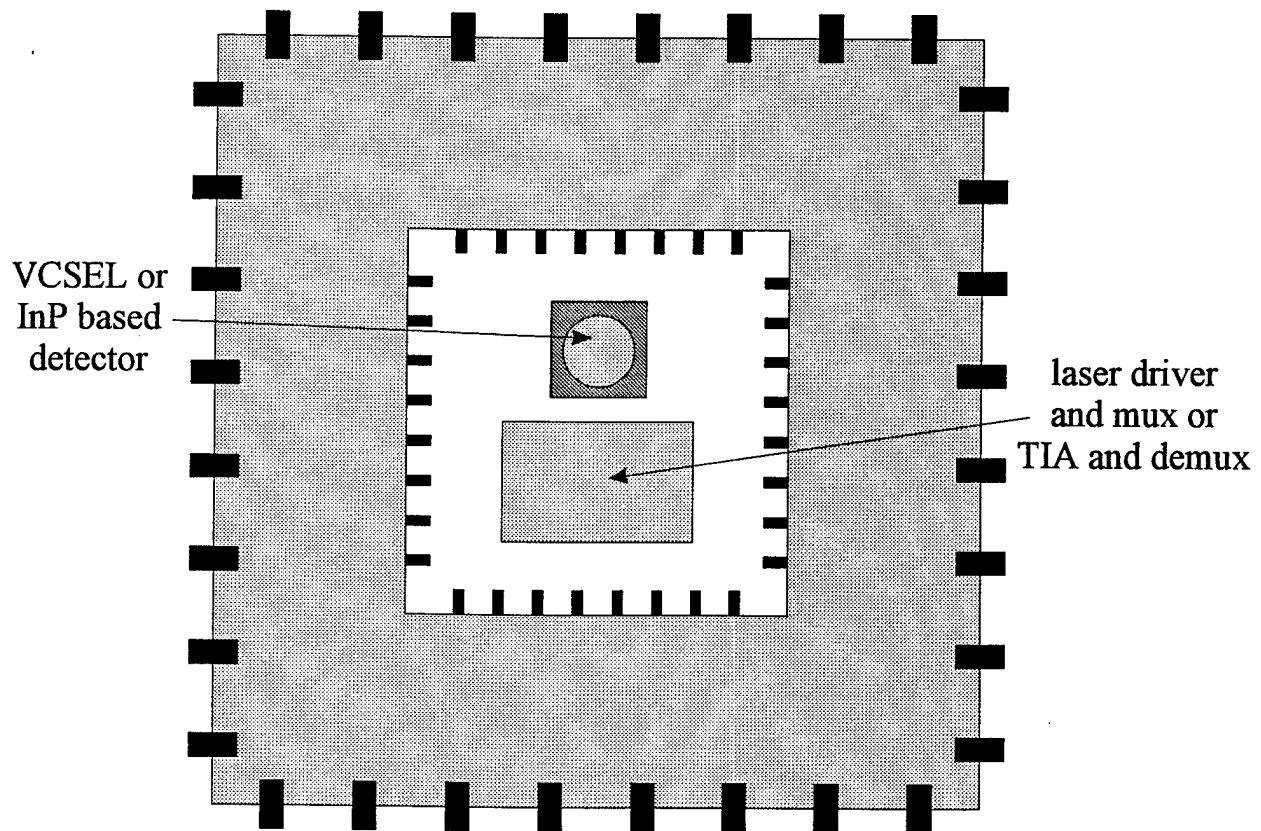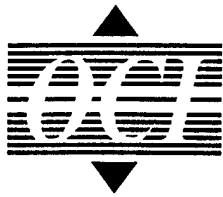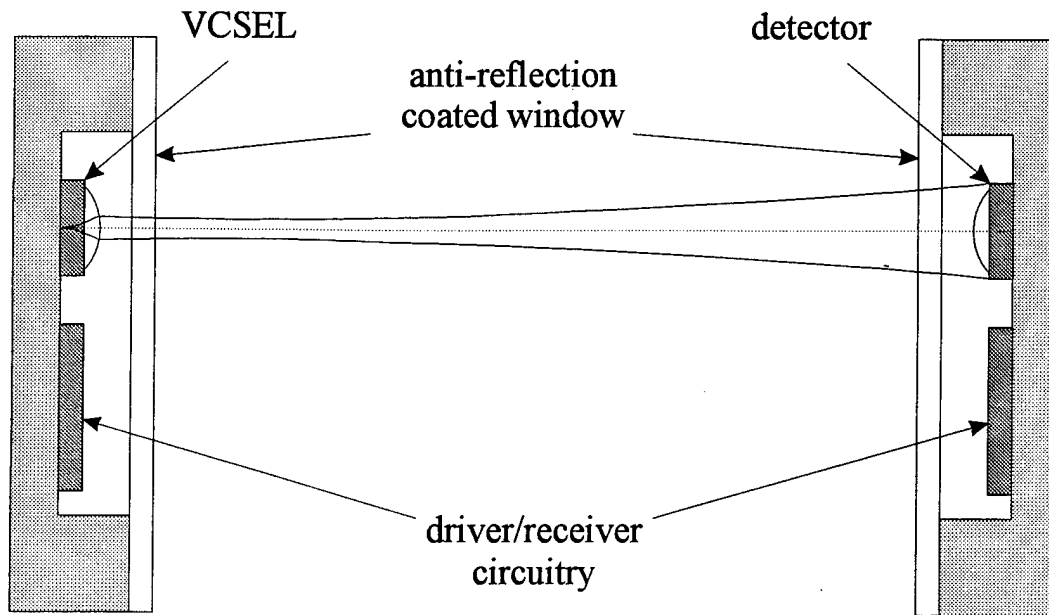
VCSEL   microlens

n-bump   p-bump

air bridge
contact

Figure 23a VCSEL Design

VCSEL or
InP based
detector

laser driver
and mux or
TIA and demux
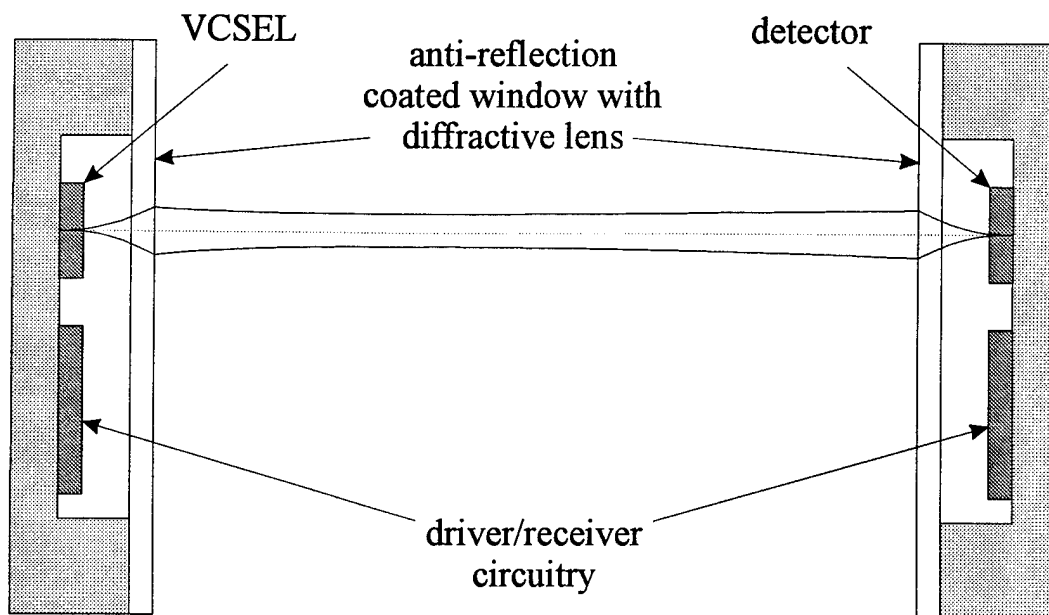
Figure 23b Package Design

a) integrated microlenses on VCSEL and detector

a) diffractive lens on package window

Figure 24

4. Summary

During Phase I an effort has been made to seriously consider and overcome the technological and economic steps that need to be addressed in order to develop high performance free space optical links using Vertical Cavity Surface Emitting Lasers (VCSELs). Central to the effort has been the development of a microlens technology invented by Optical Concepts. It has been demonstrated that GaAs microlenses can be made in a repeatable manner and can be integrated with VCSELs. The continued development of the VCSELs themselves has also be outlined although this was not a major focus of the program.

It has been shown that the most cost effective VCSEL based free space optical link will be a high performance serial link as opposed to a massively parallel link. For many reasons that are discussed in this report, the serial option can be used even for very high data throughput at a moderate cost. The primary limitations of the parallel approach are due to the inherent limitations of light itself. Collimation of light over any significant distance requires microlenses with diameters much larger than are practical for use with parallel VCSEL arrays. In contrast serial links can afford to have a slightly expanding beam since cross talk is not an issue and there is plenty of signal to achieve a reliable link. This also greatly reduces the alignment tolerance between the transmitter and receiver.

It is recommended that the Phase II portion of this program should concentrate on a complete free space optical link including receivers and transmitters. It is estimated that the completed serial link can be made to operate up to 5 Gbps, that is with a small signal bandwidth of greater than 15 GHz.