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VCSEL applications in sensors and microsystems

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ABSTRACT

Vertical-cavity surface-emitting lasers (VCSELs) are uniquely suited to miniaturized free-space optical systems in which surface-mounting and hybrid assembly techniques can be used to combine different technologies together. Two examples are described of such microsystems that are being developed for sensing applications. The first example is a optical position sensing system for rotating parts. Progress on fabricating similar systems by flip-chip bonding techniques is then discussed. The second example is a chemical sensing/analysis system which uses a miniature fluorescence detection module that is based on surface-mounted VCSELs and diffractive optical elements. The detection module is integrated with a capillary electrochromatography separation system and uses substrate-mode light propagation to focus the VCSEL beam on the capillary channel.

Keywords: vertical-cavity surface-emitting lasers, diffractive optics, sensors, microsystems, position sensing, chemical analysis, capillary electrophoresis, capillary electrochromatography, fluorescence spectrometer, substrate-mode optical interconnects.

1. Introduction

Vertical-cavity surface-emitting lasers (VCSELs) are uniquely suited to many applications that require a miniaturized free-space optical system. The surface-emitting properties allow straightforward application of surface mounting techniques, like flip-chip bonding, to assemble miniature optical systems. One and two-dimensional arrays are available and the small areas of the devices allow tight packing of the arrays. In addition, the symmetric, relatively low divergence beams greatly simplify the design of optics to go with the VCSELs. They can be very efficient, which reduces thermal dissipation concerns for closely packed systems.¹ This paper briefly discusses the methods we are using at Sandia National Laboratories to build miniature systems that incorporate VCSELs, microoptics and other optoelectronic components to realize sensing systems for unique applications. Miniaturization is the primary driver for these designs. Some of these techniques are also applicable to communications applications for VCSELs as well.²

Sandia National Labs has had an active program in VCSEL development for several years and currently we are fabricating devices in the range of 650 nm to 1300 nm wavelength for a variety of applications. We are also designing and fabricating microoptical elements of different types. The work described here is exclusively using multi-phase level diffractive elements that are often referred to as "binary" optics. These are computer-generated fresnel-type structures that can be very efficient and that perform unconventional optical functions. They are patterned by microlithographic means and etched into planar substrates. One and two dimensional arrays of micro-optics of this type are easily fabricated and the planar substrates are ideal for miniature assemblies.

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2. Position Sensing

One of Sandia National Laboratories' primary missions is providing technology to ensure the reliability and safety of nuclear weapons. Some of the components developed for that mission are complex electromechanical assemblies that function as locks to prevent accidental detonation of a weapon. As the existing US stockpile of nuclear weapons ages, it will be necessary to refit them with improved systems using current technologies. If these functions can be performed with newer technologies, miniaturization is a natural benefit that can allow easy retrofit and allow for incorporation of additional safety and reliability functions. We are developing a simple position monitoring system for use in such systems. The monitors are necessary to provide feedback signals for piezoelectric motors that are being incorporated for their performance and small size and to provide monitoring of the physical state of the system. The primary system requirements are an extremely small package volume, 5V operation and a robust output signal.

The position monitoring consists of detecting a polished, highly reflecting spot on various rotating components of the system as shown schematically in figure 1. Figure 1 shows a toothed wheel with a smooth, reflecting spot on its edge being monitored by the position sensing system. The system consists of a hybrid assembly with a VCSEL array, a detector array and a microlens array. When the reflecting spot is properly aligned with the beam from a VCSEL, the beam is reflected back through the other lens and focused onto a detector array element. The system was originally designed to have a small optical spot size at the reflecting surface for high angular resolution, although is not necessary for the present application. The monitors have two channels working in parallel. The prototype systems are assembled on a ceramic header as used for hybrid microelectronic circuits. Figure 2 shows an assembled prototype sensor. The microlens array is spaced the proper distance above the VCSEL and detector arrays by the correct spacing with small spacers that are glued into place. The microlens array is actively aligned to the VCSELs and detectors and glued on top of the spacers with UV-curing optical cement. Currently the entire assembly is potted with the optical cement to provide some additional mechanical strength and protection. The microlens array is currently of fused silica with off-axis lenses as shown in figure 3. The lenses are fabricated by direct-write electron-beam lithography with eight phase levels per zone and etched directly into the fused silica. For mass-production, replicated copies of the master lens patterns would be effective and inexpensive.

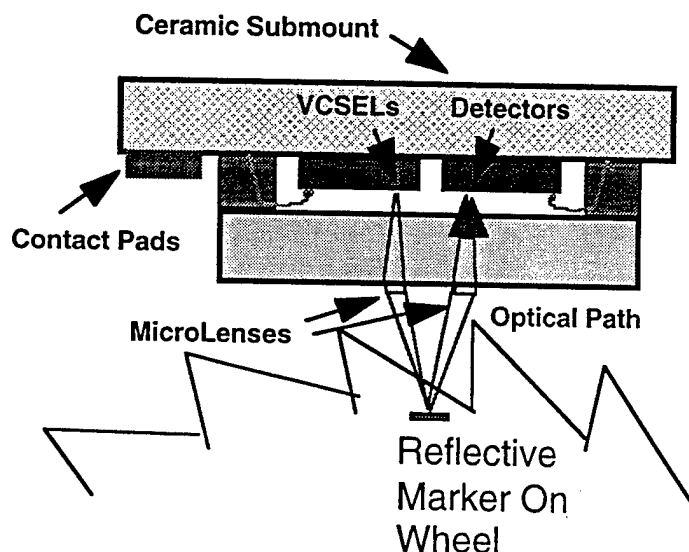


Figure 1. A drawing of the prototype position sensor in operation. A photocurrent is produced when the reflective marker passes the VCSEL beam. The off-axis lenses allow reflective operation with a simple polished surface.

The first prototypes of the system use implanted, 850 nm VCSEL arrays. The operating current is typically 10 mA and a photocurrent of 200 to 300 μA is produced by the silicon detector array elements when the optical beam is returned from a reflecting surface 1.2 mm away. The prototypes have functioned reliably and allow functional mechanical systems to be assembled and operated. We are currently redesigning the system for more robust packaging and ease of manufacture. We also plan to further reduce the volume of the system, allowing more flexibility for the mechanical designer.

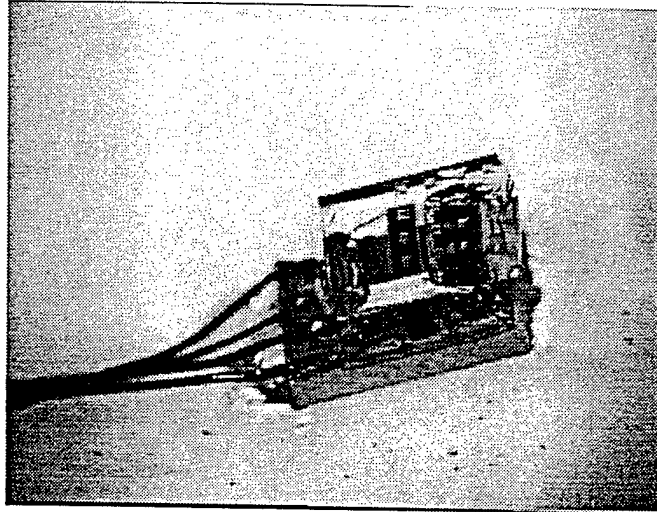


Figure 2. An assembled prototype position sensor. The current design is a hybrid assembly on a ceramic substrate. The prototype is 4 mm long X 2.5 mm wide X 2.1 mm tall.

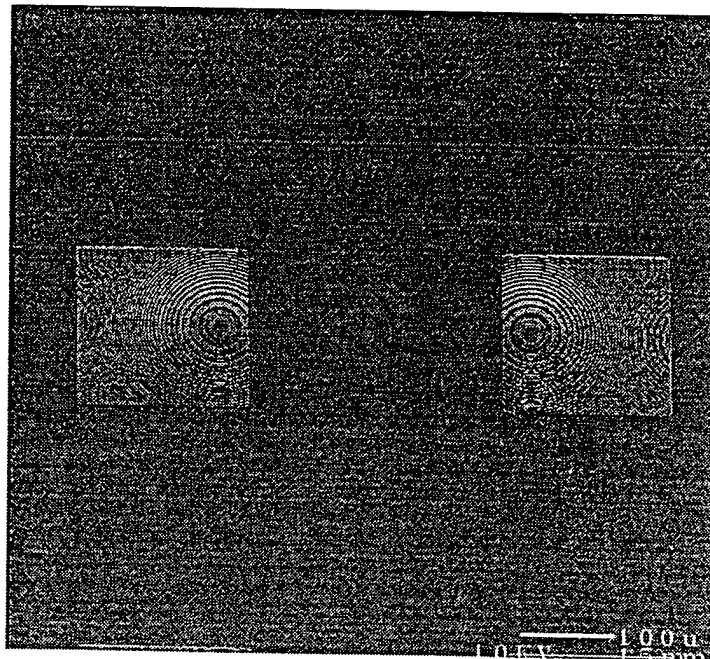


Figure 3. A scanning electron micrograph of the fused silica off-axis diffractive lenses used in the position sensor. The lenses are 500 micrometers apart, center to center. The moire fringes in the figure are an artifact of the micrograph.

3. Flip-chip Bonding of VCSEL Arrays

More compact versions of systems that incorporate VCSELs and microoptics can be fabricated using surface-mounting technologies such as flip-chip bonding. Flip-chip bonding, which has numerous variations, is a packaging technology developed for electronics manufacturing.³ The basic concept is to mount one semiconductor die onto the active surface of another. The die are positioned with the active, patterned surfaces toward each other, hence one die is "flipped" over onto the other. The mounting process bonds electrical pads on each of the surfaces together, providing both electrical interconnection between the die and mechanical attachment. Flip-chip bonding can be done with great precision using specialized equipment. This mounting precision is important for assembling optical microsystems. At Sandia, we have been developing flip-chip bonding processes for assembly of microsystems similar to the position monitoring system described previously. The approach we have been using to realize microsystems is to flip-chip bond the VCSELs to fused silica substrates which incorporate diffractive micro lenses. In this way, top-emitting VCSELs are readily combined with the microoptics to form very compact systems.

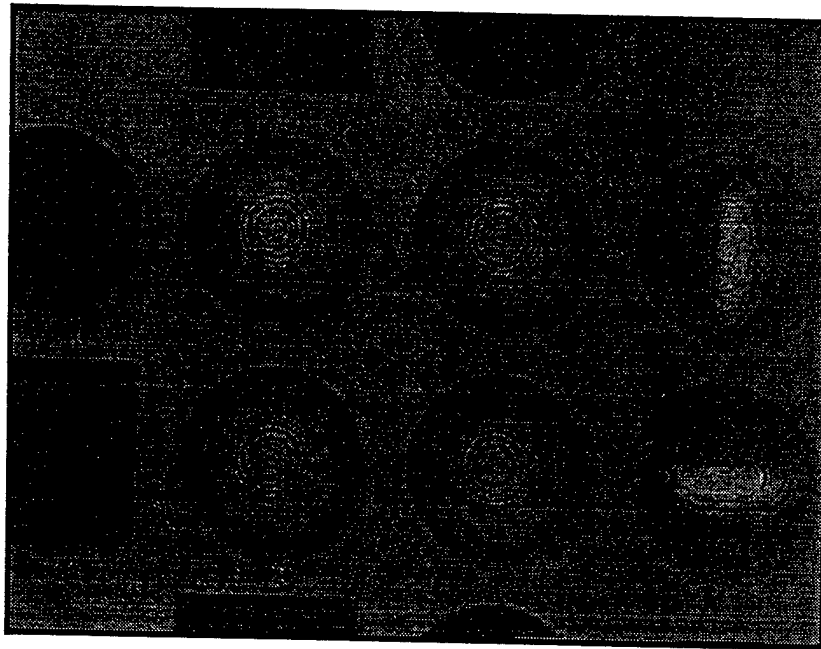


Figure 4. An optical micrograph of an array of on-axis and off-axis lenses fabricated in fused silica. The picture is taken in white light and shows partial focusing of the transmitted light. The lens array also includes anamorphic on-axis and off-axis designs that produce elliptical and line focii. Some positions in the array do not have lenses for comparison.

We have thus far relied on a relatively simple version of flip-chip bonding that is based on thermocompression bonding of the parts with gold.⁴ In our work, both the fused silica substrate and the GaAs VCSEL array have gold-pad metallizations in a matching pad layout. A wire bonder is used to form a gold "bump" on each pad of one die. The special palladium/gold alloy wire is more brittle than conventional bonding wire and can be broken off after each bumping step. Heat and pressure are applied after alignment in a flip-chip bonder to form the bond. This technique has been used to bond a 4 X 4 array of visible wavelength VCSELs to an array of microlenses.

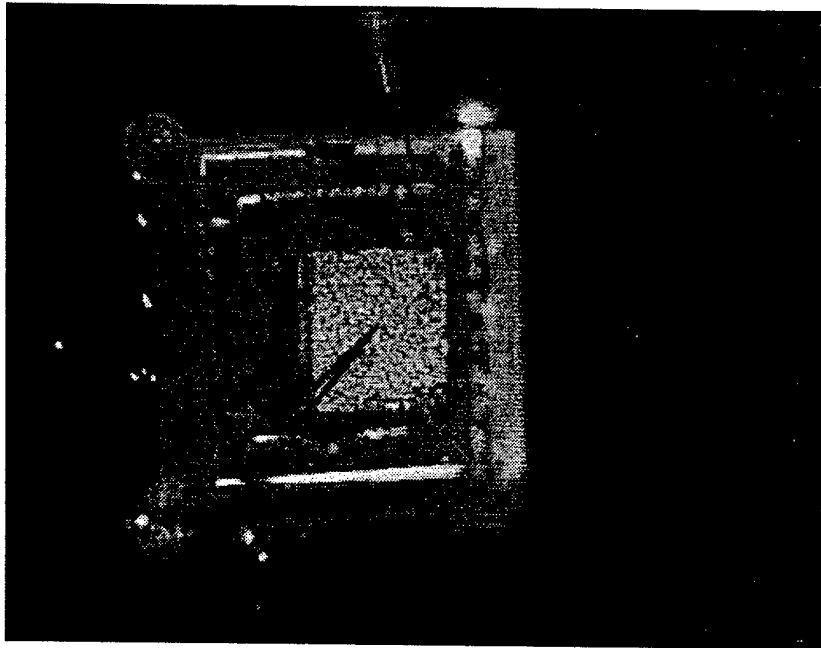


Figure 5. A photograph of a red VCSEL array, flip-chip bonded to a fused silica substrate with microlenses. The device is being electrically probed.

An array of on-axis and off-axis diffractive microlenses fabricated in fused silica is shown in Figure 4. The lenses were designed for operation at 670 nm. The array contains a variety of elements, with the central four elements being on-axis collimating lenses with a focal length of 1.4 mm and a 400-micrometer diameter. The top of figure 4 shows two anamorphic designs that are orthogonally oriented. The dark patterns in the photograph are off-axis designs that appear dark because the light is being directed away from the center of the figure by 10 degrees, an angle that is larger than the acceptance angle of the microscope objective used to take the photograph. In this work, the fused silica substrate had contact pads and interconnect traces that allowed power to be routed to the VCSELs in the array by probing the pads on the outer surface of the fused silica as shown in figure 5. Each VCSEL in the array was probed and the optical characteristics of the laser beam formed by the VCSEL-microlens combination were measured. The collimating lenses performed exceptionally well, as shown in figure 6. The measured divergence of the collimated beam was less than 0.5 degrees, which was the lower limit of resolution for our setup. Figure 7 shows an example of an astigmatic beam from an anamorphic lens, which can be used to tailor beam shapes for specific applications.

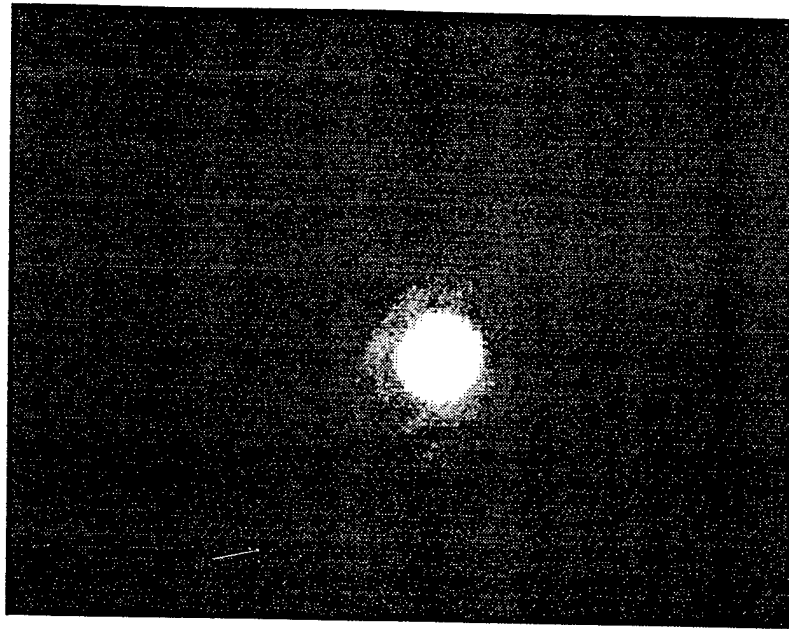


Figure 6. A photograph of the beam spot formed by collimation of one of the VCSELs in the 670 nm array by a diffractive microlens in fused silica. The photograph is taken 50 millimeters from the device and beam divergence is less than 0.5 degrees.

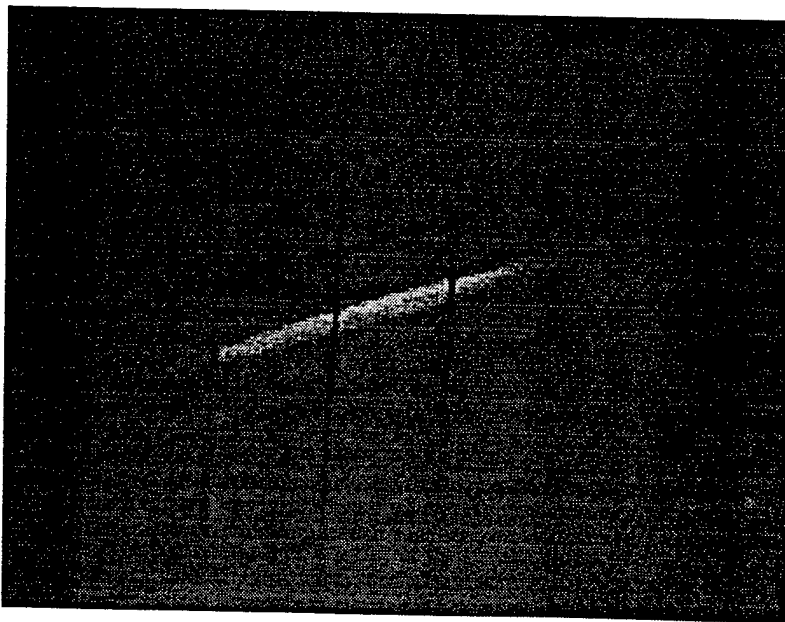


Figure 7. A photograph of the beam spot formed by an off-axis anamorphic lens. The beam spot is a line focus propagating at an angle of 10 degrees off from the lens axis. This is an example of controlling both the beam shape and direction.

4. A Highly Integrated Chemical Sensing System

At Sandia National Labs we are currently exploring the use of VCSELs for miniaturized chemical analysis systems. These systems use capillary separation techniques in conjunction with optical fluorescence detection. Since the wavelengths of currently available VCSELs are not short enough to do direct fluorescence in most materials of interest, these systems use dyes as either tags or in the form of indirect fluorescence.

Chemical analysis techniques based on high-performance separations in capillaries using optical detection methods provide powerful tools that are widely used to analyze complex chemical mixtures. A separation step in liquid samples is usually required since the broad spectral features in liquids often precludes analysis of its components on the basis of spectral properties alone. Currently, Sandia is working in two areas of high performance chemical separation and analysis--capillary gel electrophoresis and capillary electrochromatography (CEC) at the Combustion Research Facility. In both cases, high voltages are used to drive samples through free-standing capillaries (about 100 micrometer diameter) that are coupled with sensitive laser-based detectors. The key to the separation of the chemical components of a complex mixture in a capillary is a combination of electrophoresis (the motion of charged species in a liquid under the influence of an external electric field) for ions and electrokinetic flow (the bulk flow of an ionic solution in a capillary due to an applied electric field) for the neutral (uncharged) species in the solution.^{5,6} Both ionic and neutral molecules undergo separation as the solution flows through the capillary, often assisted by various packing materials that enhance the separation effects. As the separated components pass by a point near the end of the column, identification by fluorescence under optical excitation provides an extremely sensitive detection method. The direct fluorescence of the chemical species can be identified in some cases. In other cases, the components can be "tagged" by specific reactions with dye molecules that can be easily excited and identified in the separation column.

These chemical analysis systems can benefit greatly from miniaturization. In the case of CEC for neutral species, the required driving voltages and the analysis time are significantly reduced. In general, miniaturization leads to devices that are field portable, versatile in that they may contain many different kind of columns and detectors, and mass producible. Electrophoresis and electrokinetic flow occur in micromachined channels as well as they do in free-standing capillaries--so separation channels can be constructed in flat substrates. Manipulation of fluids in these channels does not require pumps, valves, etc.--just applied voltages to the solutions in them.^{7,8} Once the separation system is built into a flat substrate, then the key that enables the miniaturization of an entire chemical analysis system is the combination of vertical-cavity surface-emitting lasers (VCSELs) and diffractive optical elements with surface-mount packaging technology to assemble the elements together to form compact optical systems. With this technology we can combine the separation technology with the optical excitation and detection functions as integrated and miniaturized systems.

The basic building block of the instrument is a transparent substrate of fused silica with etched channels in a serpentine pattern, as shown in figure 8. The channels can be fabricated by conventional photolithography and wet etching processes with cross sections of 50-100 micrometers. Initially, simple electrophoretic separation techniques in open channels have been employed, but more advanced versions can incorporate beads or gels in the capillaries. The channels can be sealed by a bonding of a fused silica plate to the etched side by a number of different processes. The assembly then has two optically-flat surfaces on which the optical functions of the system can be implemented. VCSELs can be used as excitation sources, with either direct illumination of the channels by surface-mounting them over the channel or the VCSEL beam can be directed to the desired location by diffractive optical elements that can provide focusing and direction. Figure 9 shows an example of such a beam path using substrate-mode propagation of the beam by launching the beam at an angle that allows multiple internal reflections in the substrate. Detection of the fluorescence signal is by commercial detectors bonded to the substrate. Diffractive lenses can be etched directly into the substrate and coated to act as reflecting elements. By using lithographically fabricated optics, the alignment and assembly steps are eliminated for the optical system. In this design the VCSEL array is bonded to a separate substrate that can be actively aligned, if necessary.

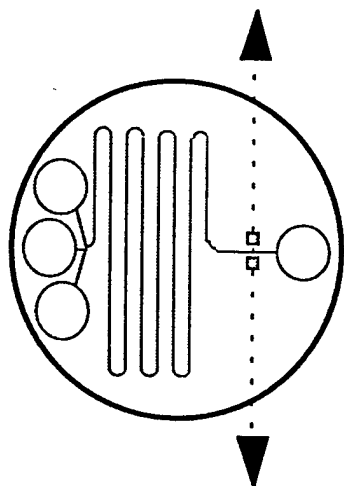


Figure 8. Drawing of capillary channel in a silica substrate. Voltage applied between the reservoirs will induce electrokinetic flow along the capillary. The dotted line indicates the location for the fluorescence detection system

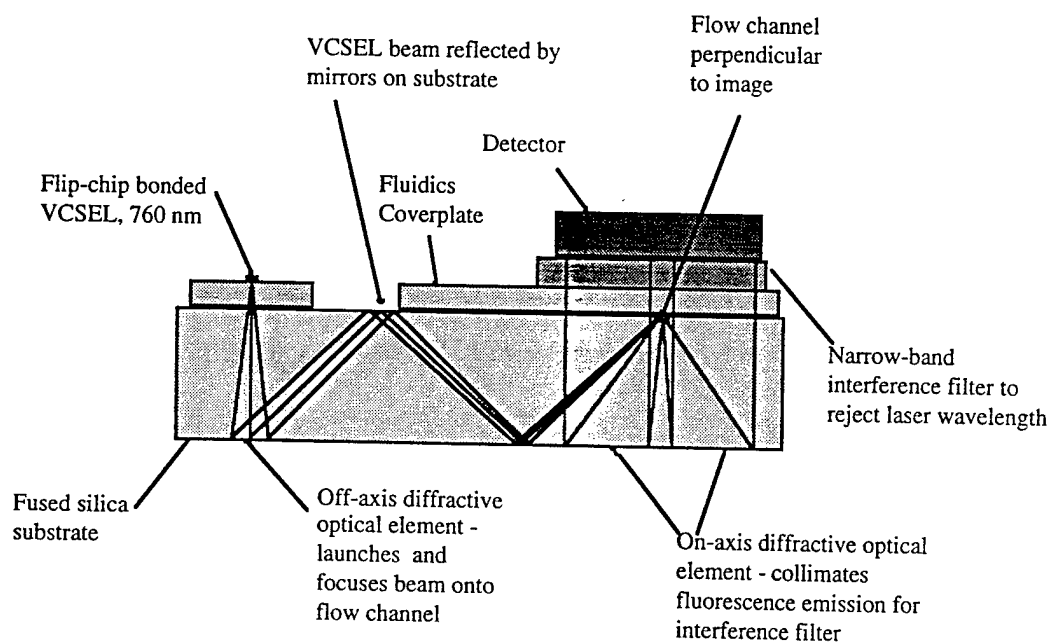


Figure 9. Cross section of a portion of the capillary channel showing one approach to providing excitation from a VCSEL and detection by a solid state detector.

Figure 10 shows a another VCSEL array, developed for the chemical sensing project, flip-chip bonded to a fused silica substrate by the process described earlier. The 2 X 2 array was designed for applications where a large number of sources are not needed but with a sufficient number of bond pads for

successful flip-chip assembly. The fused silica substrate can be aligned and bonded to the chemical separation system in a separate assembly step.

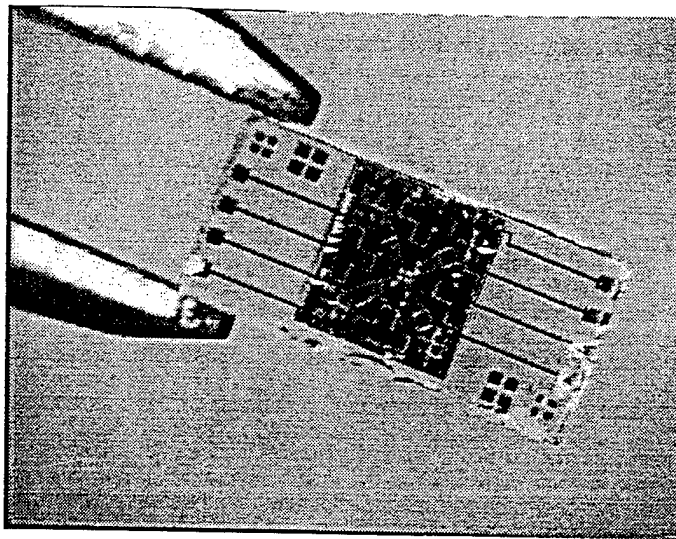


Figure 10. A 760 nm VCSEL array flip-chip bonded to a fused silica substrate as a component of a miniaturized chemical analysis system. The VCSEL array is a symmetric layout of 4 lasers designed for a small flip-chip compatible die. The fused silica substrate is 2 mm X 4 mm.

5. Conclusions

The combination of VCSELs with microoptics and surface-mounting techniques, developed for the electronics packaging industry, allows one to design miniaturized optical systems that can actually be fabricated and tested with current technologies. Sandia National Laboratories has a number of unique sensing applications that are suitable testbeds for applying this approach to making optical microsystems. We have described here some of the preliminary work we have done in this area. Much remains to be done to prove this concept and develop the design and fabrication tools for further applications.

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