Single Mode Laser Diode Packaging

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ABSTRACT

The development of optimized optoelectronics manufacturing processes may often require some understanding of the optics as well as of the mechanical and thermal design, materials, and process issues. This is certainly the case for the packaging of single mode laser diodes, where optical alignment and coupling plays a dominant role. Referring to a couple of current generic packages for illustration we discuss some of the manufacturing issues involved as well as potential improvements. Topics addressed include alternatives in terms of package design and contents, optical alignment and coupling schemes, and the use of laser welding, soldering, and adhesives.

Introduction

A very large fraction of the cost of any product containing a single mode laser diode is currently associated with that of packaging. This can largely be ascribed to a combination of a lack of manufacturing infrastructure (optimized equipment, process experience and materials data bases) and of design for manufacturing. In fact, one microelectronics packaging professional seemed on the mark in referring to some current photonics packaging practices as akin to 'building a ship in a bottle'. Of course, bringing optoelectronics packaging to the level of automation common in microelectronics will require a degree of concurrent engineering which can only really be justified if/when the overall volumes are there. Still, step-by-step improvements are clearly possibly and are, in fact, slowly occurring.

From a manufacturing perspective the packaging of photonic modules or components shares many issues with microelectronics packaging. Somewhat unique are, however, challenges posed by the need to reach and maintain optical alignment, concerns with regards to immediate or gradual contamination of the optical path, the handling of often extremely small and fragile parts, and the need to eventually link to an optical fiber. Until we succeed in developing the optical equivalent of the printed circuit board the latter, in particular, is not going to be very compatible with common microelectronics packaging approaches.

Single mode laser diodes certainly do pose challenges in terms of optical alignment. So far the coupling of these with single mode fibers has invariably been done through active alignment i.e. moving at least one component, usually a lens or the fiber, around in front of the active laser until the signal in the fiber is maximized. Any modification allowing for a switch to passive alignment, even if high accuracy is still required, might have tremendous consequences for automation and throughput, and thus for cost. However the proper distribution of placement/alignment tolerances across the individual components, including the choice of which component to align actively, may also allow for considerable progress and savings through balancing of equipment and process flow. Below we shall discuss current alignment options and potential developments, as well as associated materials, package design, and process alternatives. Emphasizing single mode laser diodes we shall focus on a couple of current generic designs.

Laser Diode Packages

Laser diodes come packaged in a wide variety of formats. In fact, a common complaint from anyone considering issues of automation is the complete lack of standardization. However, the amount of meaningful standardization is still limited, and should be so, among other by the absence of truly optimized designs. Because of space restrictions we shall limit ourselves to a couple of common formats in the following.

One format can really be referred to as an optical sub-package. Although fated to eventually go out of style as packaging technologies evolve TO-cans, or transistor outline header based assemblies, are probably still the most common laser diode sub-packages. The TO-can is really best suited for surface emitting (VCSEL) lasers. Figure 1a shows an SEM image of such a laser with the top surface electrode wire bonded to a pad on a ceramic submount. The laser aperture is at the center of the circle at the other end of the electrode. The metallized back side of the VCSEL is attached to another pad on the submount, and this again wire bonded to a third pad. Figure 1b shows a submount on a TO-header platform with three electrical feedthroughs, and Fig. 1c shows the complete header.

The overwhelming majority of VCSELs are still multi mode (in the transverse directions) 850nm lasers, but higher wavelength single mode VCSELs are starting to become available. TO-cans also see use with single mode edge emitting lasers. Figure 2 shows a sketch of an edge emitting laser mounted with a monitor diode on a ceramic substrate, the whole thing to be mounted on its edge on the TO-header near the two pins. Laser and diode are then wire bonded to a pin each and to a common ground (the header platform). Finally, a cover (or can) with a flat or lensed window is placed over the assembly and attached to the header along the rim

High performance laser diode products, such as pump lasers and Dense Wavelength Division Multiplexing (DWDM) signal lasers are often packaged individually in leaded packages such as the 14-pin butterfly package in Figure 3. These packages may also hold a large number of other components such as a monitor diode, a separate modulator, an isolator, a filter, a photodiode, thermoelectric coolers, waveguides, a fiber pigtail, and an assortment of lenses, as well as a variety of electronics. The packages are often hermetically sealed. The leads are configured to allow soldering to a printed circuit board without heating the package as the contents are often temperature sensitive and optical fiber jackets usually cannot survive much more than 80° C.

A variety of packages, such as the surface mountable mini-FLAT and the mini-DIL packages from Kyocera, share most of the packaging and design issues with the butterfly. Others, on the other hand, are quite different. For example, so-called Coarse WDM (CWDM) transceiver modules used in local and metropolitan area networks usually include several single mode lasers and detectors as well as WDM optics, but the looser tolerances eliminate the need for cooling and allow for simpler optics [1]. Anyway, in the following we shall concentrate our discussion on TO-can and, in particular, butterfly package based products.

Discussion

A few products are currently under development in which stud bumped VCSEL arrays are flipped over and mounted face down on a substrate. Taking advantage of the existing understanding and infrastructure relating to electronic flip chip assembly the various approaches to this would seem to offer considerable promise for manufacturing. So far, however, almost all lasers are mounted on their substrates either through soldering or through adhesive attachment to the electrode covering one side of them. Adhesives here offer some clear advantages, in terms of automation, but also some challenges in terms of deposition, contamination, and long term behavior.

'Inexpensive' laser diode modules are quite commonly based on TO-can sub-packages. Figure 1 shows a TO-header with a VCSEL laser diode submount soldered to it, but this might just as well have been attached using a conductive adhesive. In fact, because of the distance from the back electrode to the aperture on the top surface the VCSELs themselves are often attached to the submount with a conductive adhesive too. This obviously requires an adhesive that does not outgas too much in cure, but the nature of the outgassing species may be even more important. Also, a photophoretic effect may lead to a gradual build up on the laser aperture of species outgassing from the cured adhesive inside the closed TO-can during service.

The vast majority of actual VCSEL products are, as said, still multi mode but the contamination concerns do not necessarily change when going to single mode. Alignment and optical coupling issues, on the other hand, clearly do. The circular beam profiles obtained with VCSELs are particularly easy to couple into optical fibers. A multi mode product offered a coupling efficiency of over 90% and a lateral misalignment tolerance of 15μm (1dB loss) with just a flat window in the TO-can opening and a single aspheric lens further downstream [2]. With a reasonable control of adhesive dispensing (location and volume) and laser placement this should, in principle, allow for passive alignment, except that the tolerances on the TO-header dimensions (5.3-5.6 mm) are much too large. Together with a price on the order of $1.00 each this makes the metal TO-can decidedly unattractive for high volume, low cost, automated assembly of multi mode products.

A longer wavelength single mode VCSEL may be coupled just as efficiently into a single mode fiber, with relatively simple optics and/or direct mode matching, but obviously with less misalignment tolerance. Still, a perfectly matched VCSEL could be misaligned by over 2mm relatively to a typical single mode fiber without a loss of more than 1dB, perhaps even making it a candidate for the development of an automated assembly process based on passive alignment, as discussed below. This would, however, obviously require a much more accurate platform than the metal TO-can. For those 'inexpensive' products, such as coaxial modules, where the form factor may still be attractive injection molded TO-cans may help and should easily be price competitive.

For reasons of performance almost all single mode laser products are still based on edge emitting diodes. Because of the proximity of the electrode to the laser facets conductive adhesives are usually not considered an option. In fact, soldering is normally required to be flux less to prevent contamination and degradation of the facets. The perceived advantages of using eutectic AuSn solder for this include good thermal conductivity and very little creep, as well as a lower melting point than other hard solders. The creep resistance is of concern because thermal expansion mismatches, for example between the laser submount and the structure underneath, almost invariably lead to some degree of warpage which cannot be allowed to vary with time in service. Thermal conduction is important for pump lasers, which generate a lot of heat, and for DWDM lasers because edge emitting laser diodes tend to be quite temperature sensitive. In order to prevent 'hot spots' because of the poor lateral heat conduction within the laser the soldering has to be essentially void free. For the same reason a high performance laser cannot be allowed to hang out over the edge of the submount. On the other hand, with a (vertical) divergence angle of 50-60° the beam will scatter off of the submount if the laser is recessed by more than a few mm behind the edge. The laser solder attach process thus involves relatively accurate placement and holding of the diode until after the solder solidifies. To make matters worse the most common process involves 'scrubbing', to break up surface oxides, above 280°C as well as an active ambient such as N2(10%H2). Neither this nor current alternative approaches seem to lend themselves well to a high volume in-line process. The use of a pre-deposited AuSn layer or a properly designed Au/Sn multilayer structure, as opposed to the use of a typical 1 mil thick preform, together with process optimizations may help. Nevertheless, optimized production planning may still require a separation of this soldering step from the rest of the packaging process.

The attachment of a monitor photodiode to the submount behind the laser is potentially less demanding and may allow for the use of an adhesive. Certainly, the bottom or back edge of the submount is far enough away that we may attach this to the next level in the package with a properly selected adhesive without contaminating the laser facets. Most practitioners do not allow any organics inside a hermetic package, but indications are that this may be overkill in many cases. Nakaya et al. did not reveal how their DFB laser submount was attached to the TO-header used in their coaxial module, but their use of laser welding in further assembly would suggest an aversion to adhesives [3]. Still, thermal management was clearly not a major concern, so it should have been possible to relax the demands on a soldering process.

So far, single mode laser diode packaging invariably involves active alignment but it may eventually become possibly to avoid it, at least for some applications. More than any other single factor this would have great consequences for the development of equipment and fully automated processes. While not suitable for high frequency application TO-cans may be hermetically sealed if required, so the choice between adhesives, solder, and laser welding for further assembly is clearly not an issue of protecting the laser. Nakaya et al. chose to laser weld their coaxial module after simultaneous active alignment, along a total of 6 axes, of a holder with an aspheric lens and an optical isolator to the laser and of an optical fiber to the holder [3]. Unavoidable shifts on the order of 1.5mm still allowed for a coupling efficiency of about 50% which was considered acceptable for their 'high power module'. Mobarhan et al. describe the passive alignment of a GRIN lens and the active alignment of the fiber along 3 axes in a laser welder that also allows a reduction of the post-weld shifts to less than 0.5mm by subsequent 'laser hammering' [4]. This does, however, require substantial product specific process development and highly sophisticated equipment. Economically more attractive in the long run would seem to be the natural extension of the approach described by Hogan et al. [2] to a single mode laser product, i.e. active alignment to molded optics and the liberal use of adhesives.

Of much greater consequence might actually be the suggestion that available edge emitting laser powers may be sufficient for us to live with 1.5-2μm misalignment in some 'high power' telecommunication products. This would be so because the 'ultimate limit' for passive alignment today, as defined by the combined uncertainties in laser beam spot location, optical fiber core concentricity, etc., is about 1mm. To the extent that 50% coupling efficiency would be acceptable for an edge emitting laser, we might thus start considering the development of sufficiently accurate but reasonably fast automated equipment. Of course, as mentioned above this would require a much more accurate platform than the metal TO-can.

Considering finally the assembly of a high performance product in a butterfly package the issues, and options, become much more complex. Depending on the product we may, for example, need to bring some of the electronics as close as possible to the photonics in order to maximize the overall speed. However, the operating temperature of a laser in a DWDM module, for example, must be kept constant to within 1-2oC or better, making thermal design and the effects of the placement and attachment of the electronics a major concern. Still, some issues remain rather generic.

For a start a primary purpose of the laser diode package is of course to couple light from the laser into an optical fiber. Except in the case of a pump laser the light will be in the form of pulses the bandwidth of which may need to be minimized by the incorporation of an external modulator, rather than modulating the laser directly. Although electroabsorption (EA) modulators do not offer quite the ultimate in performance they may, unlike LiNbO3 modulators, be integrated monolithically in the semiconductor. This reduces loss and, more importantly, has significant consequences in terms of the details of our coupling and alignment options. In general, these options include the use of a lensed fiber, silica wave guides, a so-called beam expander or spot size converter (SSC), and a variety of lenses.

Because of the mode field mismatch between the edge emitting laser and the single mode fiber even optimized (butt) coupling and perfect alignment would typically lead to less than 10% coupling efficiency. A lateral misalignment of about 1.7mm (depending on the laser) would, however, only reduce this by 20% (1dB loss).

The coupling efficiency may be enhanced considerably by the insertion of one or more lenses to match the mode fields to each other. In fact, a combination of aspheric and GRIN or self-focusing lenses may ensure better than 90% coupling. This typically reduces the tolerance towards misalignment between the laser and the first lens to 0.5mm or less, but the lens-fiber misalignment tolerance may increase to the point where passive alignment becomes an option. Inserting a properly designed lens in the hole in the package wall (Figure 3) as part of the hermetic seal could, for example, allow for more than 2mm misalignment of a single mode fiber mounted on the outside. The final, sensitive (active) alignment step then emphasizes the first lens inside the package, which should be placed as close to the laser as possible. This should expand the beam substantially so as to minimize the sensitivity of the further free space coupling to variations in the unavoidable thermal mismatch induced warpages.

Alternative designs involve threading the fiber in through the hole in the package wall or redesigning the package to a ‘clam-shell’ format, in which the fiber is lowered into a groove in the wall instead, to facility automation. One way or the other the fiber feedthrough then needs to be sealed if the package is to be hermetic. This is usually achieved by metallizing part of the fiber and AuSn soldering it.

One of the alternatives involves aligning a lensed fiber right in front of the laser. Of course, this is only an option with either direct laser modulation or a monolithically integrated EA modulator. Lensed fibers are quite expensive but they may be directly free space coupled to the laser with an efficiency of more than 90%. This typically requires a lateral alignment accuracy on the order of 0.2-0.4mm, something which it takes careful process optimization to maintain while fixing the fiber by laser welding. However, misalignments of a few mm along the optical path are much less critical, so thermal mismatch induced creep in that direction is not a major concern. Fixing of the fiber in front of the laser is, therefore, quite readily achievable by judicious application of a UV curable adhesive to a Ruby ring support.

Other approaches involve bringing a regular cleaved fiber, usually terminated in a ferrule or sleeve, into the package and attaching it to the substrate or 'optical bench' on which laser and lenses are mounted. Again, depending on the optics fiber alignment may here not be the most critical step. Taking advantage of the accuracy with which V-grooves and other features may be etched into silicon, the 'silicon optical bench' may provide the platform for passive alignment of, for example, a single mode fiber to lenses and other optical components. If necessary, a silica waveguide may be incorporated which gradually expands the laser beam to match the fiber, again relaxing alignment accuracies. Usually, however, the laser still needs to be actively aligned.

One way or the other coupling of a typical edge emitting laser to a perfectly matched external component with less than 1dB of loss still requires lateral alignment to within about 0.3mm. The vertical location of the active laser region relative to the top surface is of course very accurately known. Designing the laser for 'flip chip' mounting (active side down) on a silicon optical bench may therefore in fact allow for passive alignment in the vertical direction. However, passive horizontal alignment schemes still tend to offer less accuracy.

So far, the only approaches offering the potential for completely passive laser alignment would seem to be those involving an expansion of the beam before emission. At least one company already incorporates an SSC at the exit edge of some of their lasers, and others are developing product. This clearly reduces accuracy requirements and/or enhances coupling and there is hope that it may soon help facilitate passive laser alignment. Of course, it does not come without a cost, notably in terms of wafer real estate.

Ideally, the choice of alignment schemes for a given product should of course provide a careful balance of available equipment, materials, and process capabilities to optimize throughput and total product cost. Currently, this is far from always achieved in practice.

Summary

For a variety of reasons metal TO-can based products are likely to be going away before too long, and the butterfly package format will probably never become relevant for volume manufacturing. Current trends suggest telecom moving towards planar optics and datacom towards molded optics. However, TO-cans, coaxial modules, and butterfly packages were used to illustrate some general issues and alternatives involved in designing both low and high end products for manufacturability. These include the balancing of alignment alternatives, as well as materials selection and process development.

References

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4: Kamran S. Mobarhan, Soon Jang, and Randy Heyler, "Laser Diode Packaging Technology: Coaxial Module Assembly", Newport Application Note 7

Figure 1: VCSEL assembly onto TO-header. (a) SEM of wirebonded VCSEL. (b) TO-header platform with laser submount. (c) TO-header with laser submount.

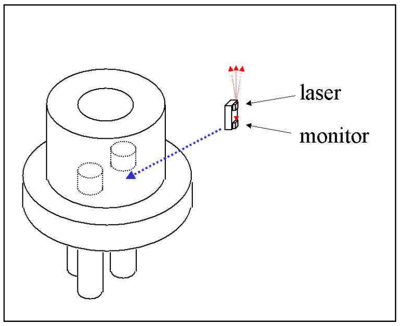

Figure 2: Edge emitting laser subassembly mounted in TO-can.

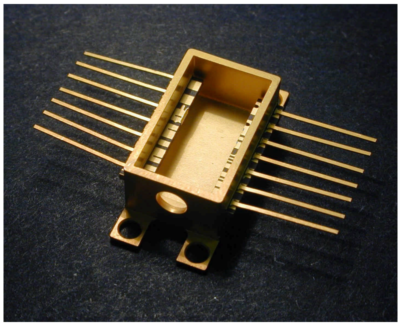

Figure 3: 14-pin butterfly package