POST WELD DISTURBANCE ANALYSIS IN LASER DIODE ASSEMBLIES

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ABSTRACT

Increasing demand for bandwidth and the development of DWDM (Dense Wave Division Multiplexing) optical communication technologies have resulted in opto-electronic packages becoming ultra compact and intricate requiring air tight assembly and reliable fixturing of micro-optical components to sub micron accuracies.

This paper discusses briefly the assembly and construction of laser diode packages, Operational characteristics of the semiconductor laser diode and why alignment of the fiber to laser diode is critical, and the process of aligning and attaching the ferruled fiber onto the substrate. Fundamentals of laser welding, laser parameters and factors affecting the quality of the are discussed in detail. Due to its amenability to automation, laser spot welding is the preferred method of attaching the ferruled fiber to the clip within the package. However post weld shift is a serious problem in the assembly of and packaging of the laser diode. Experimental methods of measuring the post weld shift are presented and compared with computational finite element analysis. It is observed that PWS is caused by residual thermal stresses experienced by the clip and ferruled fiber assembly. A method for measuring the magnitude and direction of the residual stress is proposed, followed by a procedure for automated stress relief.

If one can characterize the post weld shift and predict the displacement of the fiber under specific conditions, appropriate compensations can be applied to the assembly prior to welding such that the ferrule displaces into alignment under the weld disturbance and during weld pool solidification. Empirical methods and force reflecting servomechanisms must be used to obtain quantitative measurements. Using high stiffness stages, by design we can maintain optimal power coupling during and after the weld pulse. Unfortunately,

the weld clip and the lens attach structures have compliance and elastic deformation of the clip can well exceed 500nm under typical weld disturbances. As a result, if the ferrule gripper were to release the ferrule after the weld it could move off the optimal power coupling peak and beyond the specified limits for power loss. Furthermore, the weld process, by its nature introduces residual stresses that must be ‘relieved’ to ensure that temporal shifts in position do not occur.

There are several methods of overcoming post weld shift, of particular interest is a solution by which a high stiffness piezo-flexure drive stresses the clip along the principal axis of residual stress in a sequence of opposing motions pushing the clip material beyond its yield criterion. By causing the material to yield in both directions, the material loses its residual stress and can be placed back onto the peak of the power coupling curve.

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1.0 OVERVIEW

As we evolve into an “always-on” network computing society, Internet traffic continues to grow exponentially. Over 25 million personal computers will be shipped this year in the US alone and over 11million in smaller countries like Japan. The combined effect of digital broadcasting, increasing number of mobile phone subscribers, audio and video on demand, and demand for “anywhere, anytime” multimedia services has resulted in transmitted data volumes exceeding 1 Tbits/s, about 100 times the current levels. DWDM (Dense Wave Division Multiplexing) technologies have been developed to handle this dramatic increase in transmission volume. The development of DWDM along with all optical networking systems have resulted in the source and pump laser diode packages becoming more complex and compact requiring precision alignment, air tight assembly and reliable attachment of the fiber and associated optical components with sub-micron accuracies.

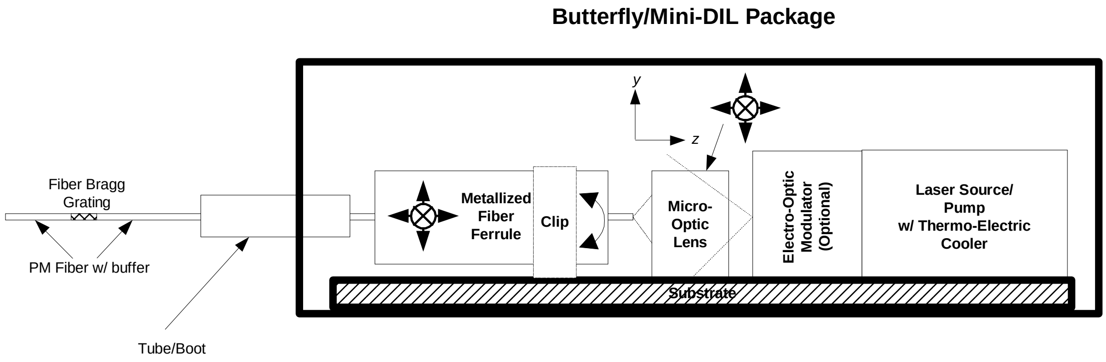

Fig 1: A typical Laser Diode package

1.1 Description of a Laser Diode Package

A typical Laser Diode package as shown in Figure 1, integrates a ferrule-fiber assembly, a clip attaching the fiber assembly to the substrate, micro-lens, and a semiconductor laser diode attached to a Kovar substrate mounted on a thermo-electric cooler. The semiconductor laser diode is very small and has dimensions of less than 1mm each side and emits a highly divergent beam of light. Since the operating characteristics and wavelength of the laser diode are highly temperature dependant, the assembly is mounted on a solid state thermo electric cooler. A Cu-W or Kovar substrate serves as a metallic support structure for attaching the laser diode and clip assembly. The ferruled-fiber assembly is around 1.5mm in diameter and several millimeters long and is attached to the substrate via a clip. Due to the extremely small dimensions and highly divergent laser beam, coupling the light into a fiber is difficult and requires precision alignment and attachment techniques.

1.2 MODULE ASSEMBLY

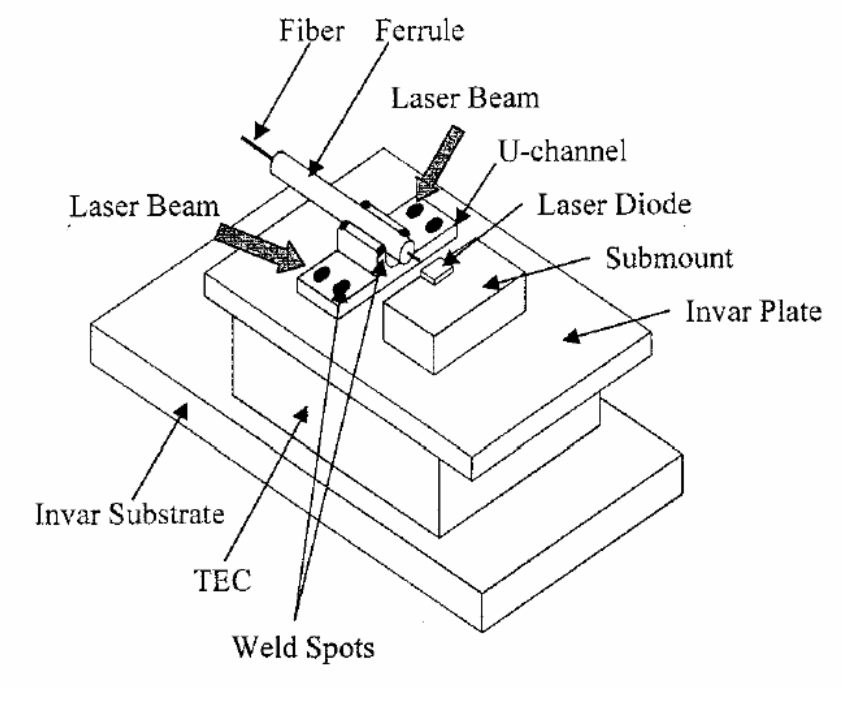

Fig 2: Laser diode assembly showing spot weld locations.

The laser diode assembly process involves first mounting the diode on a substrate, usually of Cu-W, Kovar or Invar using a die attach, then aligning a ferruled fiber to the beam emitted and while maintaining alignment, spot welding the ferrule to the clip at several locations simultaneously, as shown in Fig 2.

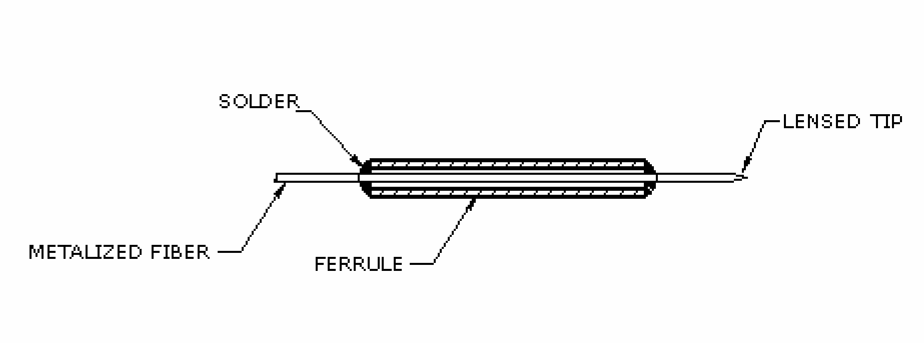

Fig 3: Ferruled fiber assembly

The ferrule-fiber assembly as shown in Fig 3 consists of a metalized fiber, which is soldered or glass sealed into a cylindrical Kovar ferrule, (referred to as ferruled-fiber). This ferrule serves as a rigid metallic structure for gripping, aligning and laser welding the fiber to an inverted U or **Ω** shaped mounting clip. The mounting clip(also made of Kovar) is first spot welded onto the substrate. The assembly of these devices involves precise alignment-often requiring coupling precision to the level of 50-100 nm—of optical fiber to the laser source. After alignment, the fiber is then spot welded to the clip. This micro-optical bench mounted on a substrate is then hermetically sealed in a butterfly style ceramic or Kovar® package. Efficiency and reliability of the laser assembly depends on how well the alignment accuracy is maintained over time as well package hermeticity.

2.0 CHARACTERISTICS OF A SEMICONDUCTOR LASER AND WHY ALIGNMENT IS CRITICAL.

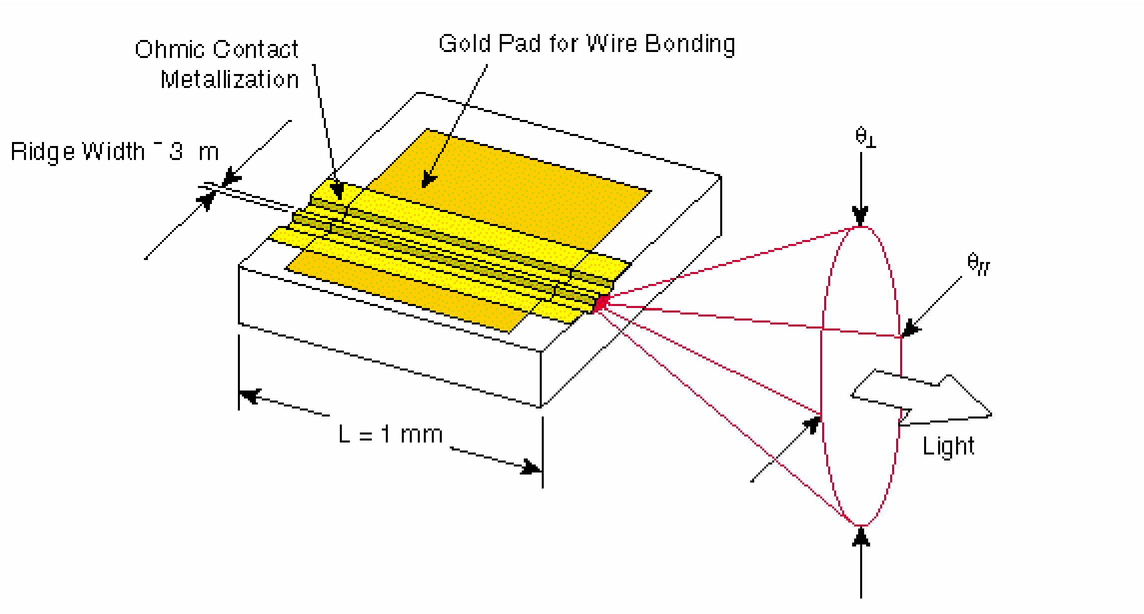

Fig 4: Semiconductor Laser diode showing its diverging Output Beam profile

The critical laser diode performance parameters include wavelength (λ), spectral linewidth (δλ), wavelength stability, polarization extinction ratio (PER), voltage threshold (V_T), peak optical power (L_{max}), and the sensitivity (δL(optical power)/δi(current)).

The main task of in assembly of the laser diode package is to align the critical optical components to couple maximum optical power from the laser into the fiber for a given drive voltage/current and to bond the fiber to the substrate without degrading the optical power coupling. Achieving optimal power coupling quickly is not easy due to

1) the nature of the far-field radiation pattern of an in-plane laser, Guassian, highly divergent elliptical and astigmatic beam- refer Fig 4.
2) cavity oscillations or the etalon effect, related to light reflections within the laser diode itself, and

3) the stringent optical power budgets imposed by the device manufacturers.

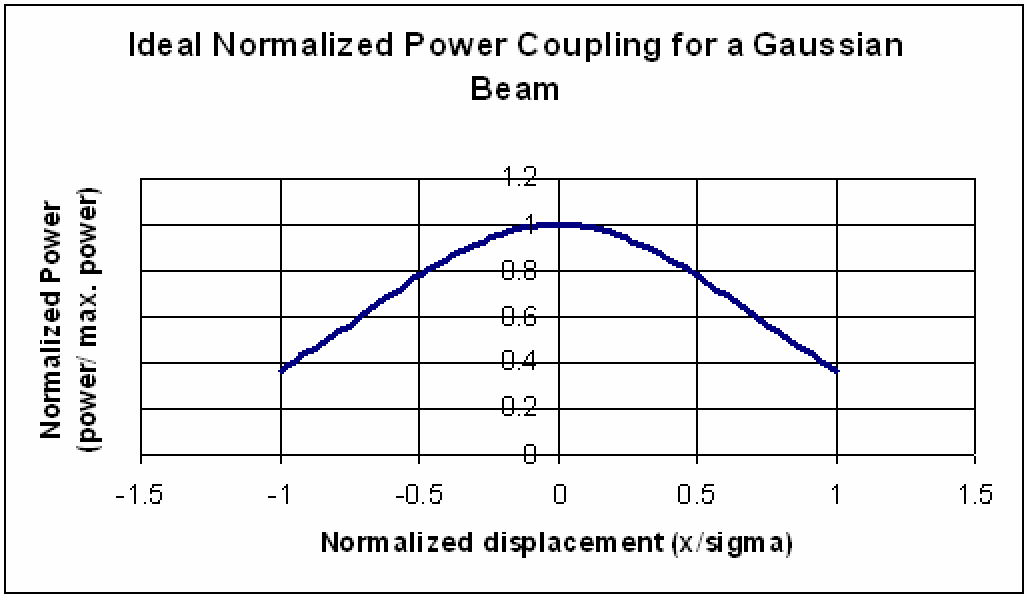

Fig 5: Normalized power coupling curves that relate optical power to translation of fiber position in either of the lateral directions—x and y.

Due to the asymmetry in the cavity-cross-section of an in-plane laser—basically that the width (x-dimension) is much larger than its thickness (y-direction)—the value of sigma (the spatial decay constant) exhibits the same asymmetry. For a typical pump laser implementation, sigma_x might typically range from 2-3μ, while sigma_y might typically range from 0.6-0.9μ. The power budgets imposed by the device manufacturers are specified in dB, where the power loss in dB is $-10\log_{10}$(actual power/peak power). The typical maximum dB loss is specified at 0.05 dB.

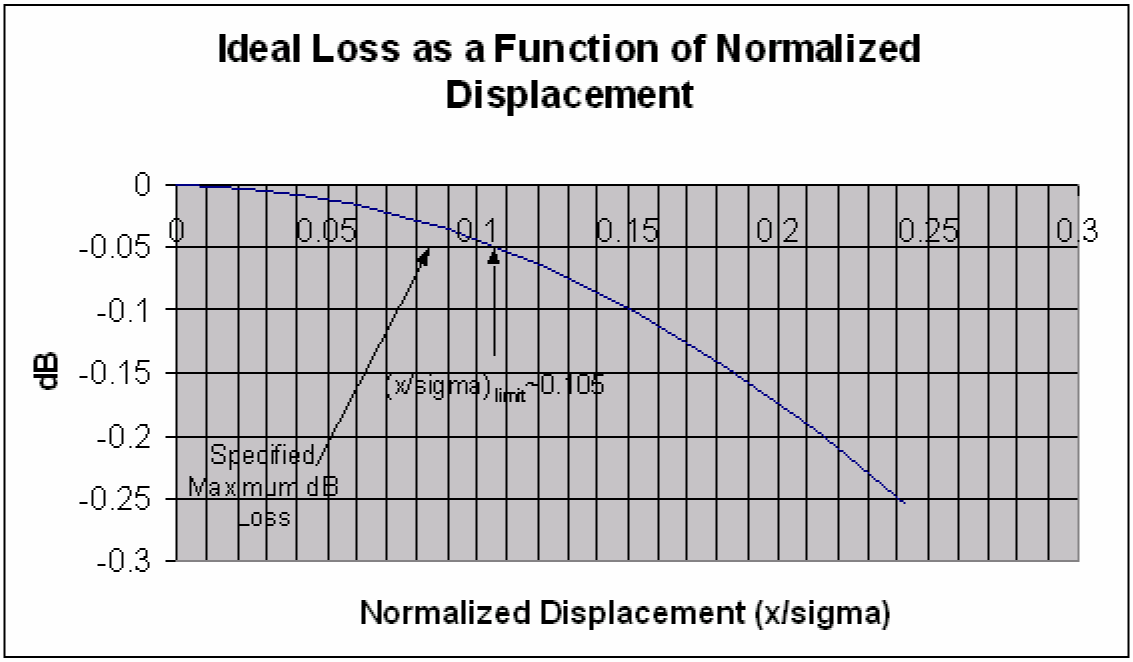

Fig 6: Normalized Power coupling characteristics as measured in dB

As shown if Figure 6, which plots the normalized power coupling as measured in dB, the normalized deviation at the specified limit is about 0.105. So the typical allowable end-to-end deviation in fiber position ranges from 400-600 nm in x and 120-180 nm in y! As can be seen, the tight tolerances in the y direction impose serious difficulties in finding the peak—finding first light—and in maintaining position in the presence of disturbance forces. It is for this reason that a high stiffness and high precision alignment mechanism is required. With piezo driven flexure based stages fiber position can be maintained to a precision of better than 10 nm. It must be stated that the y-axis “alignment problem” is mitigated by the use of a cylindrical or anamorphic lens assembly to focus the light, albeit with the complexity of additional alignment degrees of freedom.

3.0 METHODS OF ATTACHING THE FIBER

3.1 SOLDERING

In earlier designs of the laser diode package, the fiber was attached to a metallized alumina substrate using solder. However this method is very messy and produced large shifts upon solidification. Once the solder cooled it was not possible to correct for any shift. Besides large amount of thermal damage was also observed on the fiber. This resulted in poor reliability of alignment within the laser diode package.

3.2. EPOXIES

Epoxies have also been used for bonding the fiber to the substrate after alignment. However, Stiffness and outgassing are serious issues in optoelectronic packages. Epoxy bonding within a small confined package is difficult and requires elaborate dispensers, besides they are messy, require curing time and post bond shift is difficult to control and correct.

3.3 LASER WELDING

Spot welding using a pulsed Nd-YAG laser is the quickest and cleanest method to bond the fiber to the substrate while maintaining alignment with the laser diode. In a typical application, one alignment is complete, the clip and ferruled fiber are attached to the substrate with a series of laser welds-upto 4 on each side of the clip and four on each side of the ferrule.

3.4 ADVENTAGES OF USING LASER WELDING

Using a laser for fiber attach has numerous advantages as follows, laser welding

1. is highly repeatable
2. a non contact process
3. no parts to wear or contaminate the weld

4. can be carried out in any atmosphere: inert atmosphere produces better welds
5. minimal HAZ and bulk temp rise is small
6. refractory metals can also be welded, no limit to the weld pool temp
7. dissimilar metals can be welded
8. welding can be done in tight geometries
9. laser beam is unaffected by electric or magenetic fields

4.0 UNDERSTANDING THE LASER WELDING PROCESS

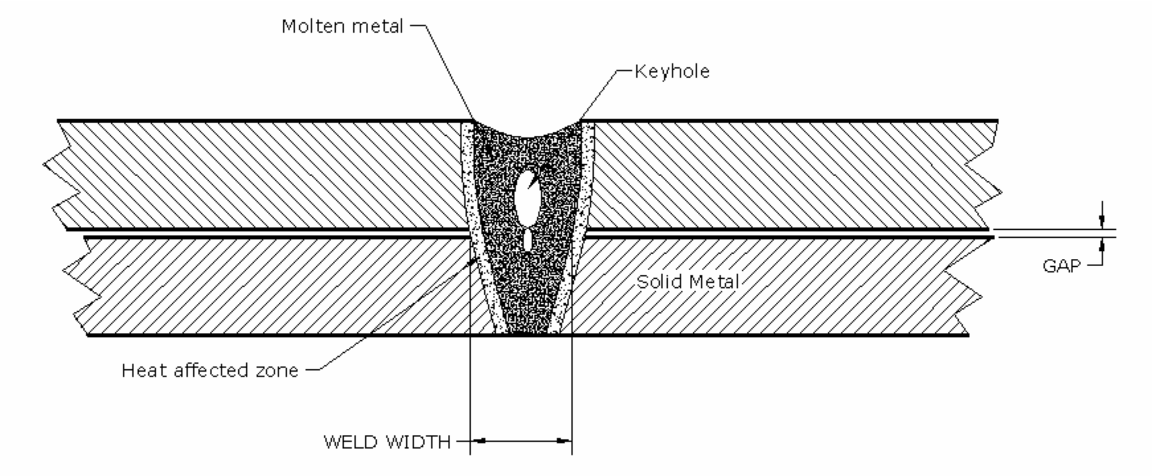

Fig 8: Elements of a Weld Joint

For laser welding to work, the metal must absorb the laser light. While selecting the material and a suitable laser it is important to study the absobtion spectrum of the metal and select the optimum wavelength of the laser. For packaging materials such as kovar, Invar and stainless steels the Nd-YAG laser at 1064nm is ideally suited.When a focused laser beam is incident on the metal surface, it quickly heats up and absorbtion increases as the density of conduction electrons increase. Since the laser in pulsed at a high frequency the surface heats up faster than it can conduct the heat away and begins to melt. As melting begins the reflectivity drops from 90% to about 50%. For welding metals like kovar, invar or stainless steel a laser power density of about 10e5 to 10e6

w/cm^2 are required. As surface absorption accelerates, heat is conducted into the metal, melting the deeper layers. Continued application of laser pulses will generate significant vapor pressure of the metallic atoms. The vaporized metal opens a cylinder (keyhole) down through the underlying layers of the metal, holding back the surrounding liquid with vapor pressure. The vapor ionizes and absorbs more of the laser radiation, becoming incandescent and radiates energy to the molten metal along the side of the keyhole. Thus most welds have an elongated shape as shown in fig 8, with a HAZ that tapers downwards. The aspect ratio of this zone depends upon the spot size, pulsewidth, and thermal conductivity of the metal. For deeper penetration sufficiently long pulsewidths are required to effectively transfer energy into the keyhole.

The localized nature of the HAZ when a laser pulse impinges on a metal allows joining of metals to take place with minimal thermally induced distortions. The metals are simply made to melt and quickly re-solidify. Cleanliness and absence of foreign matter at the weld spot improves the strength of the weld. In practice several issues must be addressed in order to obtain a good weld.

4.1 HEAT DISTRIBUTION MODEL FOR LASER WELDING WITH PULSED LASER

Heat from a small focused laser spot, when it is incident on a metal surface, will be conducted away from the heated area into te body of the metal. Thermal distribution is determined by the thermal diffusivity of the metal

$k=K/\rho*C$

where

k=materials diffusivity

K= thermal conductivity watts/cm/°C

ρ= density

C=heat capacity J/cm/°C

For constant heat source applied for time τ, the thermal diffusion distance is given by

$D= (k*\tau)^{1/2}$

The thermal diffusion distance provides a measure of the heat distribution of the metal and is used to estimate the penetration depth of the weld. If a certain depth of penetration is desired, the parameter D can be used to determine the pulsewidth of the beam. From the expression we note that smaller the value of k for a metal, the smaller heat zone it has and hence more efficient use of the laser energy for heating.

The Parameter k also influences spot size selection. To form a good weld, the diameter of the weld pool should be smaller than the penetration depth of the laser pulse. In most lasers with fiber optic beam delivery the spot size is fixed by the core of the fiber and hence pulse width will directly control the depth of penetration.

Laser welding is best performed on metals with lower k and lower reflectivity. If the reflectivity of the metal is high, the laser energy must be sufficiently higher in order to have sufficient energy absorbed bto melt the metal. Once the metal is molten, thers is a rapid chage in absorbtion which leads to vaporization of the base metal leading to a violent reaction creating air pockets and poor welds. This limits the amount of energy which can be deposited and the quality of the weld. Pure metals such as Cu and Au have high reflectivities and are therefore poor candidates for laser welding, while alloys such as Kovar(Fe-Ni-Co), stainless steels and Nitinol(Ni-Ti) shape memory alloy are good absorbers of the 1064 nm laser radiation and therefore good candidates for laser welding.

Absorbtion of materials is also a function of wavelength of the laser. Broadly, the Nd-YAG laser is more suited for processing metals and ceramics and the CO2 laser is more suited for organic materials(polymer, wood ,paper etc).

4.2 LASER WELDING PARAMETERS

With laser spot welding three parameters must be selected for any application:Spot size ,Peak power and Pulsewidth. The first two parameters determine the peak power density of the laser pulse impinging on the metal surface-for metals this value has to be around 105 to 106 Watts/cm2 to cause melting of the metal, for some metals with higher reflectivity, such as Cu and Al an even higher peak power is required. The third parameter determines the penetration depth of the laser pulse and is related to the thermal diffusion distance of the metal. Spot size is usually determined by the fiber core diameter and magnification ratio. For e.g using a 400um core fiber with a 1:1 magnification ration produces a spot size of 400um, while a 200um core fiber with a demagnification ratio of 2:1 will produce a spot size of 100um. For Guassian beams the theoretical spot size is given by the equation

Spot Size = $2*Q*\lambda/\pi*NA$

Where λ= laser wavelength

NA= Numerical aperture and

Q= “Q” factor of the laser beam is a measure of the quality of the beamand is given by

Q= $D*V_m/13.5$

Where D= waist diameter and V_m= far field divergence of the beam.

In most lasers Peak power is adjusted by changing the applied Voltage. The laser pulsewidth and the applied voltage determine the total laser energy and can be measured with a power meter. Peak Power can be derived using the following expression

Peak Power(Watts) = Energy(Joules)/ Pulsewidth (seconds)

Power Density (Watts/cm^2) = Peak Power/ Spot Area (cm^2)

The product of the peak power and pulsewidth is equal to the laser energy delivered. This energy is much larger than required to melt most metals.

5.0 THE “PROBLEM”- POST WELD SHIFT IN FIBER ATTACH

Having studied the fundamentals of laser welding and the parameters affecting the quality of welds, we can now address the problem that is critical to the laser diode assembly-post weld shift (PWS). As described in section 2.0, the fiber attach process consists of aligning the ferruled fiber to the laser diode beam and then attaching it to the clip with a series of laser pulses. Fig 12 shows a laser setup for fiber attach using a dual beam Nd-YAG laser mounted on a motion platform and the laser diode package being mounted on a high stiffness precision stage.

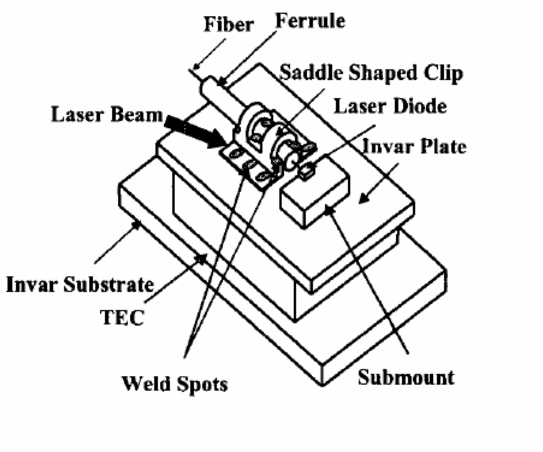

Fig 12: Laser welding setup

A gripper holds the ferruled-fiber and aligns it to the emitted laser beam. The gripper is a stiff structure mounted on a multi axis piezo driven flexure stage. A typical weld schedule for fiber attach would consist of rapidly firing a series of 4x2 weld spots with a laser energy of around 1.5x105 W/cm2 with a pulse width of about 3ms-depending upon the depth of penetration pulse width varies from 0.1ms to 20ms.

During this 3ms weld pulse, the acoustic pulse and the ejection of molten metal introduce relatively small but high frequency disturbances. This is followed by a nearly exponential force disturbance related to the solidification of the weld pool as can be seen in Fig 13. These forces cause relative movement of the ferruled fiber and the clip causing misalignment and loss in coupling power.

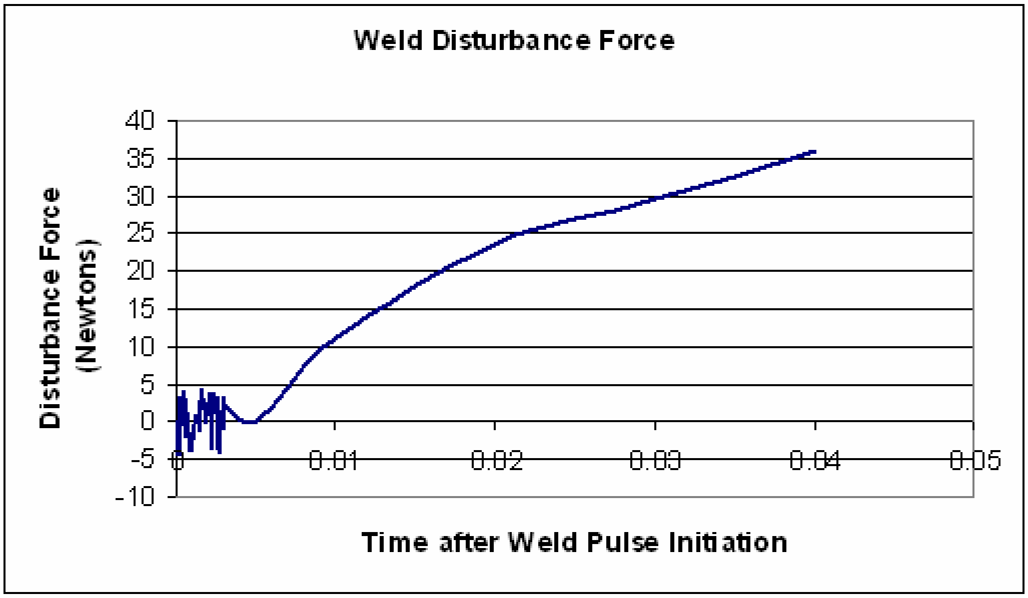

Fig 13:Lateral Weld force Disturbances

If the stiffness of the gripper and alignment stages is high and operate in a tight servo control loop, the position of the ferrule and clip can be maintained during the welding process. However, there are practical limitations to size and geometry of the gripper and clip and ferrule and hence the achievable stiffness of the assembly. The disturbance forces that the ferrule clip assembly experiences during and after the welding sequence are enough to cause a PWS in excess of 500nm-this displacement is enough to cause the assembly to loose almost all of the coupled power. Even if the gripper is rigid enough to withstand the weld disturbances, the clip and ferrule being compliant will experience residual thermal stresses and “spring out of alignment as soon as the gripper is released.

5.2 WELDING SIMULATIONS AND PREDICTING RESIDUAL STRESS

In practice post weld shift can be easily observed using high magnification vision systems by detecting reference edges before and after the welds are fired. In the fiber attach process the displacements due to laser welding are generally small (<500nm) and occur in all three axes. At least two cameras would be required to measure the resultant PWS. Due to the small size of the package and also due to space constrains created by the gripper and tooling, it is often possible to view the assembly only in one direction, I,e from the top. White light Interferometry as well as X-ray metrology tools can also be used to measure the PWS during the weld process. Experimental measurement indicate post weld shifts as large as 3-4um in the X-axis. It is also observed that the weld sequence plays an important part in the resultant loss in coupling power. For example it is observed that when the first two welds are fired towards the front, that is towards the tip of the fiber, the residual stress tends to pull the ferrule downwards the substrate and the results in displacement of the fiber tip by about 70nm to 110nm. If the first welds are fired towards the rear end of the fiber, it is observed that the displacement of the tip is much larger, around 2500nm. This would result in almost complete loss in coupling and is an unacceptable situation in an automated assembly process, often resulting in rejection or requiring reworking or manual tweaking.

5.3 PREDICTING RESIDUAL STRESS AND MODELLING THE WELD SEQUENCE USING FINITE ELEMENT ANALYSIS

Not enough research has been done on the use of finite element modeling to predict the PWS. If we can characterize the PWS and predict the residual stresses and displacement of the fiber under specific conditions, appropriate compensations can be applied to the assembly prior to the welding sequence, such that the ferrule displaces into alignment under the weld disturbance force and after weld pool solidification. Welding simulations to predict residual stresses require three dimensional analysis in the vicinity of the weld and are computationally intensive and difficult to substantiate. Several assumptions are made relating to material properties, boundary conditions and constraints in the geometry and assembly as well as heat transfer models. With the availability of fast computers with large memory and sophisticated finite element analysis software, a three dimensional model, as shown in Fig 14 can be created and the effects of welding and PWS modeled. The resulting analysis has been used to predict the PWS under different weld conditions a well as to generate an optimum weld sequence.

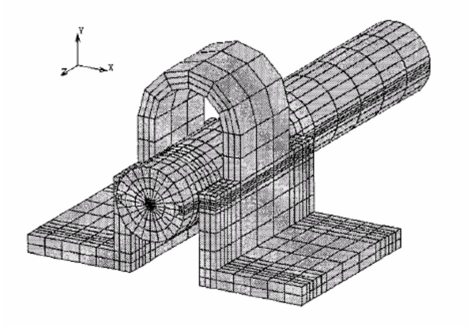

Fig 14: A meshed model of ferrule-clip assembly ready for FEA

Fig 15 shows the distribution of residual stresses after cooling and fig 16 shows the displacements in the y-direction.

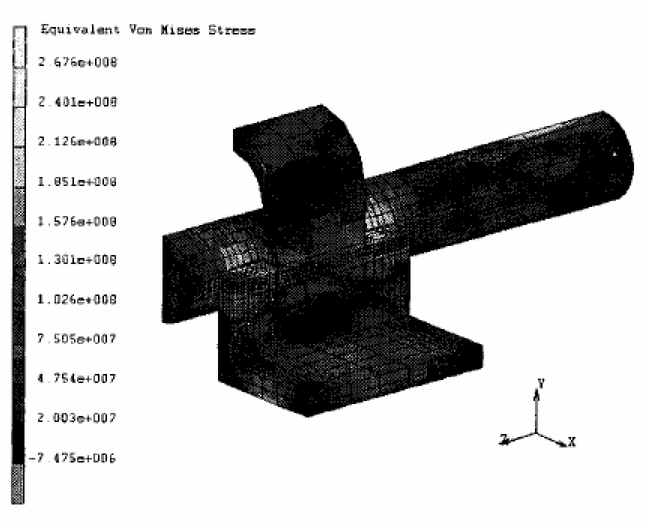

Fig 15: Von Mises stress plot showing residual stress at weld locations.

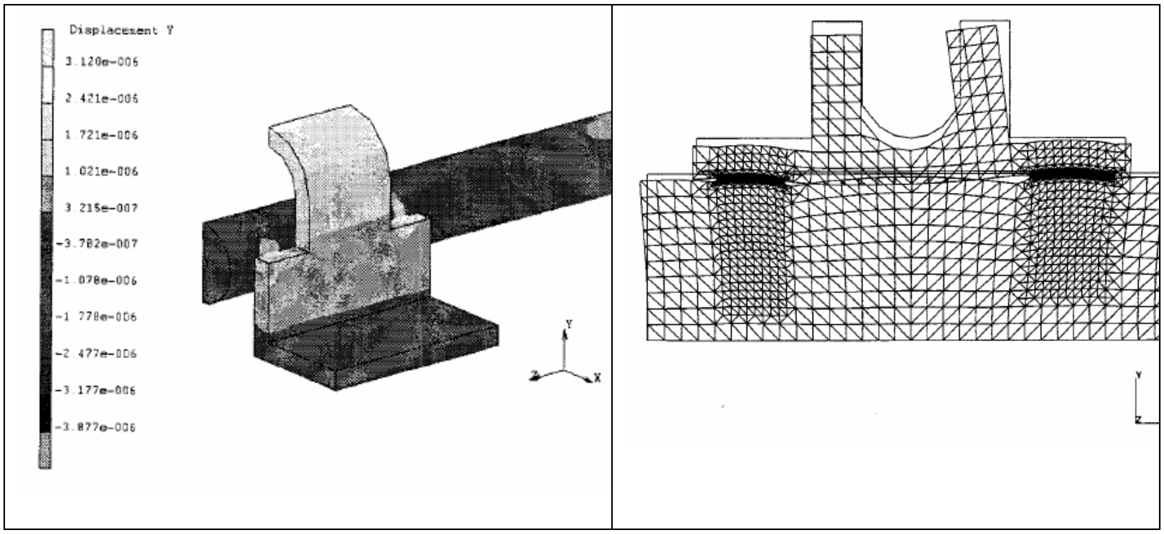

Fig 16: FEA plots showing y-displacements

The above FEA models demonstrate that the weld spots tend to pull the fiber downwards and that the previously formed spots act as a pivot .If the beam is incident towards the back of the ferrule, it is evident that the front will move upwards. Thus to minimize the PWS the optimum weld sequence would be to weld the spots nearest to the laser diode first and then weld the spots towards the rear of the ferrule, this way the displacement caused by the first welds would be compensated. This process of impinging weld spots on the ferrule to bring the fiber back into alignment is known as laser hammering.

However, in practice several other factors, including beam delivery angles, energy balance between the two parallel laser beams, clip shape and material, gripper stiffness etc play a more significant role on the PWS. An important point to note is that the displacement in x-direction is ignored, although it is clearly evident that the incident beam angle will have a significant component in this direction. Also due to the nature of the beam, displacement in the x-direction is more critical and needs to be controlled more precisely.

6.0 REALIGNMENT AND PLASTIC DEFORMATION OF CLIP

Although FEA modeling of the post weld shift process has been the subject of investigation in several research papers, it has had little practical significance. The laser weld disturbance forces are random and not predictable. In practice methods used by manufacturers range from manually “tweaking” the ferrule into alignment after welding to fully automated “bend-align” and “laser-hammering methods. Tweaking is the process in which a skilled technician works under a microscope with the laser diode and carefully adjusts the position of the tip of the fiber with a tweezer or similar tool while measuring the output power. This process is time consuming and dependent on the skill of the technician. In places where labor is cheap this method is widely practiced.

Automated solutions include elaborate tooling and and alignment algorithms for finding first light and then performing a circular, spiral or raster scan to optimize coupling. Since a robotic tool performs this operation of “automated tweaking”, the process is accelerated, but lacks the intelligence required limiting the range of motion in finding first light.

LASER HAMMERING: is the process of compensating for post weld shift by using the welding laser to adjust the position of the components with additional, calculated spot welds. Once the ferrule has been welded, a series of low energy weld spots can be impinged upon the ferrule at specific locations to rock the fiber back into alignment. This method is limited in that the applied force is relatively small and not sufficient to plastically yield the clip material in order to overcome the residual stress.

AUTOMATED STRESS RELIEVING: It has already been established that in order to realign the fiber, the clip-ferrule assembly must undergo plastic deformation to relieve the residual stress due to welding. If the direction and magnitude of the residual stress is known using a 6 axis force sensor, the clip-ferrule assembly can be stressed along the principal axis of residual stress in a sequence of opposing motions, as shown in Fig 17, pushing the clip material beyond it's yield criterion.

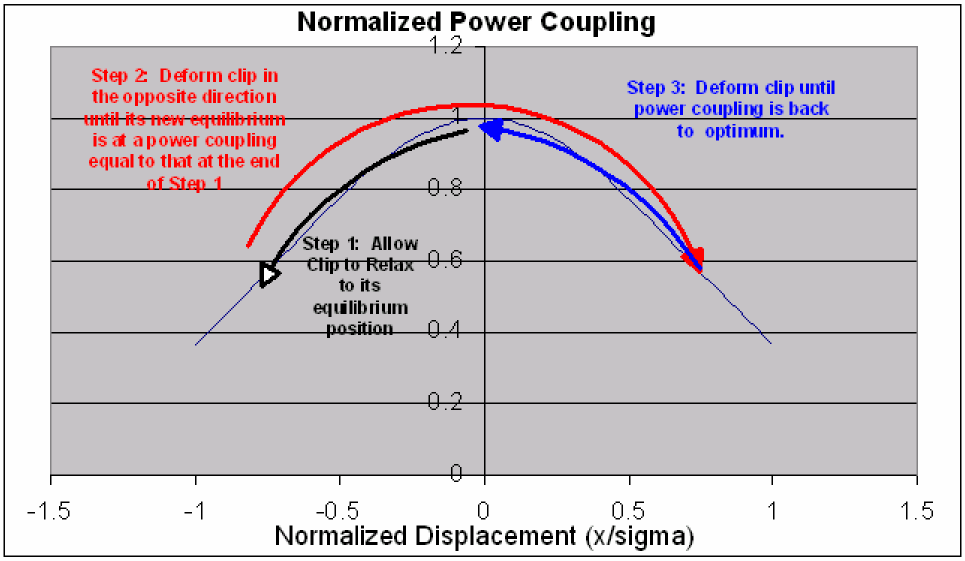

Fig 17:Automated Stress Relieving

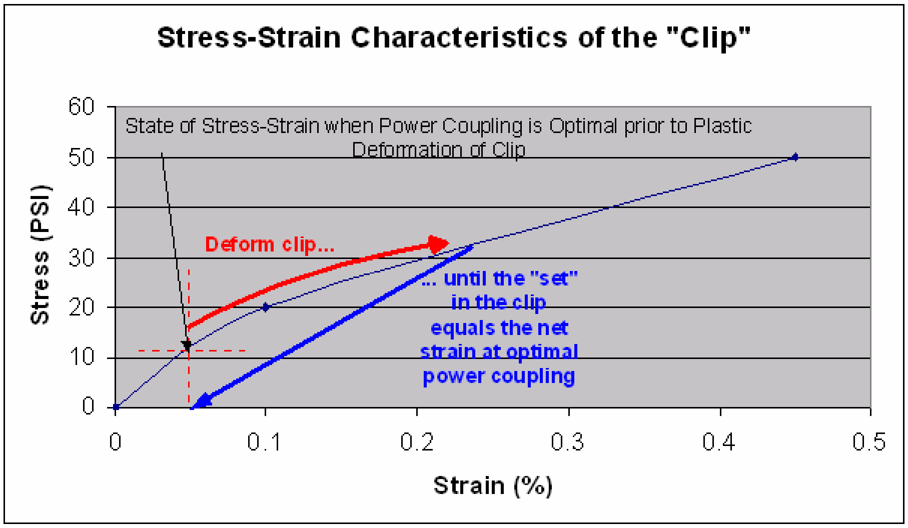

Fig 18: Plastic Deformation of the clip to achieve final state of zero Residual stress

By causing the material to yield in both directions as shown in Fig 18 the clip loses its residual stress and can be put back onto the peak of the power coupling curve.

7.CONCLUSION

Having studied the construction of a typical laser diode assembly and understanding its critical parameters, it is evident that maintaining good alignment is absolutely essential for the device to perform reliably and efficiently. Laser welding is the preferred tool for attaching and permanently fixturing the ferruled fiber to the substrate within the package. Due to its non contact nature and highly repeatable characteristics laser welding ideally suited for this application. Post weld shift is a serious problem in the fiber attach process and it is desired to understand its nature and be able to predict it, if possible, as well correct it quickly and reliably. Finite element models have been developed to understand the phenomenon and come up with algorithms to calculate the best weld sequences as well as offsets to compensate for the post weld shift. These models are computationally intensive and, due to the numerous assumptions that have to be made, are practically unusable. Laser hammering is also a useful mechanism to compensate for very small shifts, however it does not provide the required force when the clip has to be plastically deformed to relieve the residual stress and retain alignment. Empirical and experimental methods have been developed by various vendors to eliminate the residual stress caused by PWS, however most of these methods are proprietary and there is little literature describing any one process that is proven and yields consistent results. The proposed method of measuring the magnitude of the residual stress using a 6-axis force sensor, and then stressing the clip, using opposing motions, along the principal axis of the residual stress is cheap reliable and is expected to yield consistent results.

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