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Reliable Pigtailing of Photonic Devices Employing Laser Microwelding

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Abstract: Investigations and analysis of various parameters that contribute for increasing the efficiency of laser diode to single mode fiber coupling using lens coupling scheme are presented in this study. The low power laser weldability of Invar, Kovar and stainless steel 304 alloys make them suitable as the base materials and welding tools for different types of photonic devices packaging. The fiber attachment process and microwelds for fixing of various coupling components have been performed in what is so called active alignment process, where the system continues measuring the coupled power during the process of coupling and welding of (lens holder, fiber ferrule and welding clips). Nd: YAG Laser Welding system (LW4000S from Newport) has been used for the alignment and welding of the coupling components inside a butterfly module. The effect of laser weld beam parameters on the weld dimensions is optimized to get good and the desired weld width to penetration depth with small Heat Affected Zone (HAZ) for achieving good welds without damaging the sensitive optical components inside the module.

Key words: Pigtailing, welding, HAZ, phortonic devices, PWS, laser

INTRODUCTION

Understanding the optimal coupling method and determining the effective coupling scheme along with the packaging facilities is very important in the technology of photonic devices manufacturing because these processes account for (60-80%) of its overall cost. Photonic transmitters are usually required to operate for long time in field with potentially humid, corrosive and mechanically turbulent environments, that requires strong fixing of the aligned components and hermetic sealing inside metal hybrid housings. Laser welding proved to be the most effective tool for the automation of laser diode coupling and packaging process which yield a very reliable packaging and strong attachments of various components, it also enables producing more and hence reducing the devices cost effectively. Post Weld Shift (PWS) generally affect package yield, it represents an issue in the field of photonic devices packaging and manufacturing. In single mode fiber applications, if the PWS induced by the joining process is in the order of few microns, the loss in the coupled power may reach up to 50% resulting in module performance degradation. PWS in laser packaging can be minimized by properly controlling the laser beam-to- beam energy balance in dual beam laser welding system (Cheng *et al*., 1996; Hsu *et al*., 2005) and using laser pulses of power density ≈ (1.5×10^5) w cm^{-2}, since higher power densities of laser pulses could result in more PWS. It can also be greatly minimized by the selection of materials and design of welding tools (Tan *et al*., 2005). Laser Weld (LW4000S) which is configured with a laser hammering option to compensate for the PWS by making some additional weld spots in different positions is employed in this research. Another possible defect that can be detected after laser welding is the cracking, which arises from many different possibilities in the laser welding, large air gaps, solidifications, incompatible materials, impurities such as high levels of carbon, sulfur, phosphorus and a combination of two or more (Kuang *et al*., 1999; Soon, 2000; Lee *et al*., 2006). Post weld cracking is occurring mainly due to using alloys with different melting points as the welding materials and also the large air gap between the welded parts, which cause the centerline crack propagations (Kuang *et al*., 1999). The third serious defect encountered in laser welding process is the porosity which refers to the formation of holes or bubbles in the interior structure of the welded-joints. There are numerous sources which can produce porosity such as air intake, moisture into the weld pool and surface contamination with oil, grease, moisture and paint on or about the joint interface. All these can be eliminated by careful cleaning procedures. It has been reported that the major cause of hole formation in the laser welding process

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for laser packaging is due to the excess of laser energy and the gas bubbles trapped within the welded sections during solidification (Kuang *et al*., 1999). Laser welding is normally a liquid-phase (fusion) welding process i.e., it joins metals by melting their interfaces and causing the mixing of molten metal which solidifies on the removal of the heat source. The desired materials for this application are materials of low thermal conductivity or higher electrical resistivity (Dawes, 1992; Chryssolouris, 1991). Therefore the lower the thermal conductivity of a material, the more likely it is to absorb laser energy. Consequently, the normal weldable grades of steel and stainless steel are ideal for laser welding. The low carbon steels Austenitic stainless steel (300 series steel) which has carbon levels of less than (0.1%) produce good quality welds and reliable weld performance. Also Zinc-coated steels have been reported to be used for many applications (Kuang *et al*., 1999). Here we used kovar™ which contains (29% Ni, 17% Co, 0.2% Mn and 53% Fe), stainless steel 304 which is composed of (1.83%Mn, 18.1%Cr, 8.1%Ni, 0.39%Si, 0.04%C, 0.031% P, 0.002% S, 0.06% N and balance Fe) and Invar™ which contains (46% Fe, 36%Ni) for laser welding of photonic devices packaging.

MATERIALS AND METHODS

Laser welding with two simultaneous beams of very small spot sizes can be employed for laser diode butterfly module packaging to weld the ferruled fiber tip via a special weld clip and to fix lenses inside their holders to the main substrate of the packaged module. All the coupling components, such as fiber ferrule and lenses are welded to the substrate with certain types of welding clips or holders from two opposite directions using dual Nd: YAG laser beams as shown in Fig. 1.

Precise alignment of the fiber to the laser diode is obtained using active alignment process in which the laser diode is powered by the system from its housing and emits light and in what is so-called a blind search alignment, Fig. 2, the system looks for the optimum position at which the coupling efficiency is maximum by continuously measuring the output power by a photodetector connected to an optical power meter. Laser spot welding has important advantages for these applications because it is a contactless tool, it can deliver a very precise amount of weld energy in a very short time to a very small location and can be accurately located on the weld joint through the use of delivery fibers and focusing optics.

Theoretical aspects and modeling: The general differential equation of heat diffusion is given as:

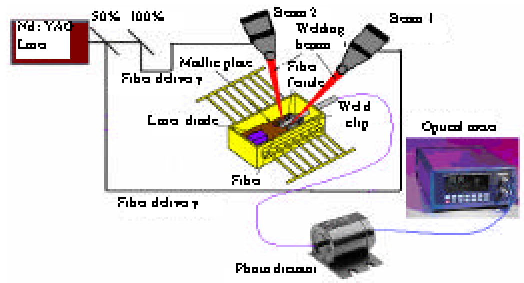

Fig. 1: Dual beam laser weld with active alignment

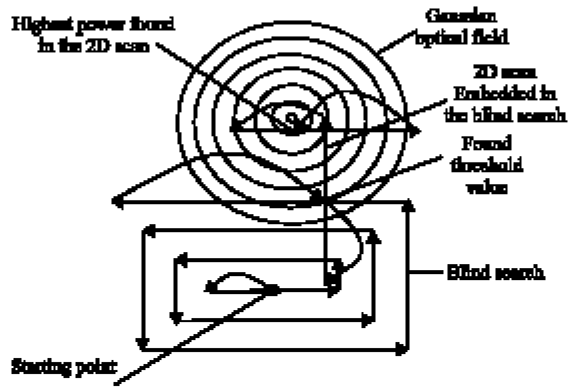

Fig. 2: Blind search in active alignment process

$$\frac{\partial T}{\partial t} = \alpha \nabla^2 T + \frac{g(r,t)}{\rho c} \quad (1)$$

Where, α is thermal diffusivity, $g(r,t)$ is the rate of internal heat generation/absorption at a point in the material expressed in units of (J m^{-3}s), α is given by

$$\alpha = \frac{k}{\rho c}$$

ρ is the material density, c is the specific heat and k is the thermal conductivity. Equation 1 can be solved to give the temperature distribution inside the workpiece as:

$$T - T_0 = \frac{2I_0}{k}\left(\frac{\alpha t}{\pi}\right)^{1/2} e^{-\frac{z^2}{4\alpha}} - \frac{I_0 z}{k}\left(1 - \mathrm{erf}\left(\frac{z}{2(\alpha t)^{1/2}}\right)\right) \quad (2)$$

Equation 2 is valid under the condition that $(\alpha t)^{1/2} \le r$ (radius of spot size on the workpiece).

To determine the penetration depth of the laser spot welds as a function of pulse duration and incident average power per pulse power density, assuming that the energy balance at the laser spot can be expressed as

$$(1-R)I_0 = \rho L_m \frac{\partial l}{\partial t} - k\left(\frac{\partial T}{\partial z}\right)_{z=0} \quad (3)$$

R is the reflectivity, L_m is latent heat of the material and I_0 is the pulse energy density ($I_o = p/\pi r^2$). Where ρ the pulse power and r is the laser spot radius. The temperature distribution inside the solid is given by:

$$\frac{T - T_0}{T_m - T_0} = \exp\left[-\frac{1}{\alpha}\left(\frac{dl}{dt}\right)z\right] \quad (4)$$

T_m and T_0 are the melting and the ambient temperatures. The temperature gradient at the welding front can be determined as:

$$\left(\frac{dl}{dz}\right)_{z=0} = -\frac{1}{\alpha}\left(\frac{dl}{dt}\right)(T_m - T_0) \quad (5)$$

Subs. into (3) and solving for and by integration we can get the penetration depth

$$l = \frac{4(1-R)pt}{\pi r^2 \rho\left(L_m + c(T_m - T_0)\right)} \quad (6)$$

The penetration depth is proportional to laser pulse power and duration.

RESULTS AND DISCUSSION

The 1550 nm laser diode is coupled to a single mode fiber via double ball lenses of 1 mm diameter and packaged in a butterfly module as shown in Fig. 3. This coupling system has wide misalignment tolerances.

The process of loading the ferruled fiber tip is shown in Fig. 4 where a pneumatic gripper is used to hold the ferruled fiber during the alignment and welding process. The effect of displacement of the ferruled fiber tip in x and y direction from the optimum coupling position on the coupled power is shown in Fig. 5. The experimental variation of the coupling efficienc with the working distance (coupling system to fiber seperation) is shown in Fig. 6.

Laser pulse duration, energy, average power and focusing position have been optimized to get the desired weld yields. The aspect ratio (weld width to penetration depth) required to be less than unity for best weld results meaning that a good penetration is achieved for strong weld and at the same time the width is as small as that the Heat Affected Zone (HAZ) is minimized and hence prevent the damage to sensitive optical component inside the module during the welding process.

The experimental measurements of laser weld width with the incident pulse energy are shown in Fig. 7 for stainless steel 304L, Kovar and Invar alloys.

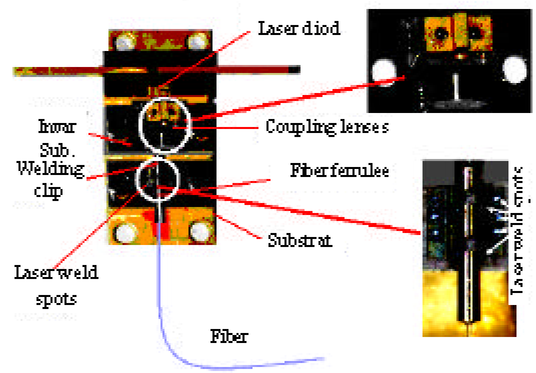

Fig. 3: A pigtailed laser diode coupled via double ball lenses using laser welding

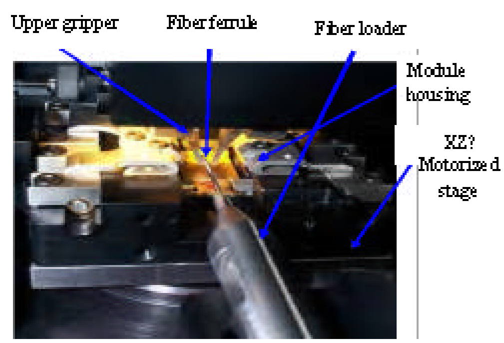

Fig. 4: The process of loading the ferruled fiber tip in active alignment method

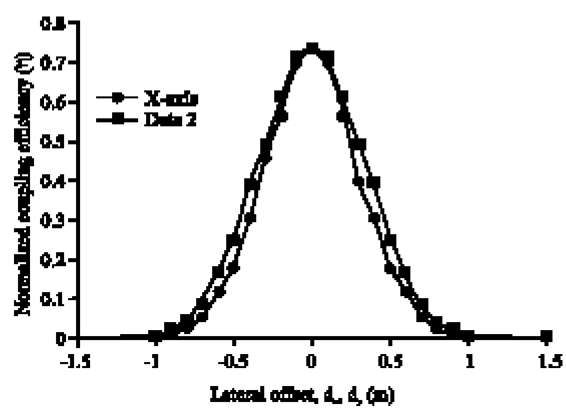

Fig. 5: Coupled power versus displacement in x and y directions during the alignment process

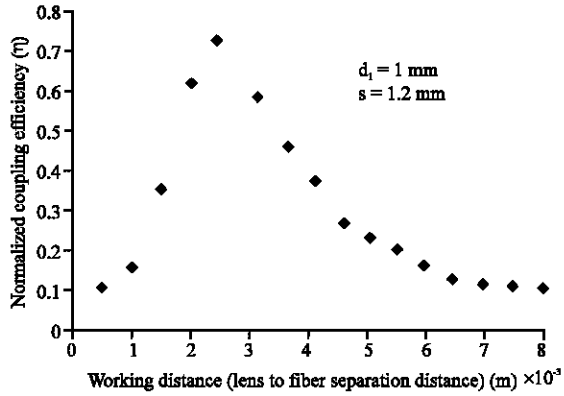

Fig. 6: Effect of variation of coupling efficiency with the working distance (Exp.)

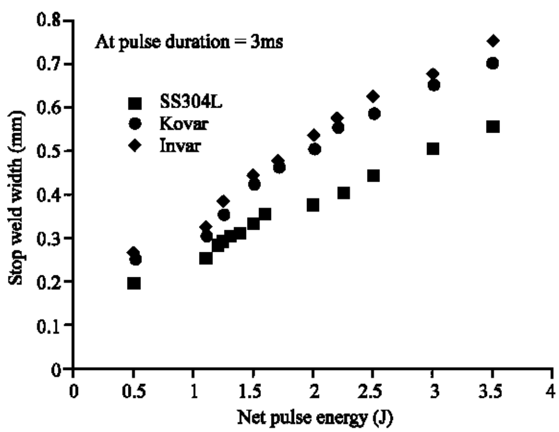

Fig. 7: Laser weld width with the incident pulse energy for three different alloys

It has been found experimentally that the focusing point of the laser beam on the target has a significant effect on both laser weld width, Fig. 8 and depth; therefore it has to be optimized to make the target in the depth of focus (the distance at which the spot radius is increased by 5% form the minimum spot radius at the focus point).

The result of modeling the penetration depth as a function of laser pulse average power and duration found to be in a very good agreement with the experimentally measured results. For pulse of 1 ms duration, three samples have been subjected to the same average incident power and all show a good interaction as suitable base materials for photonic devices packaging application, Fig. 9. In Invar alloy the effect is more because of its higher thermal conductivity comparing with other two samples.

The effect of changing pulse duration on the penetration depth is shown in Fig. 10 for SS304L for

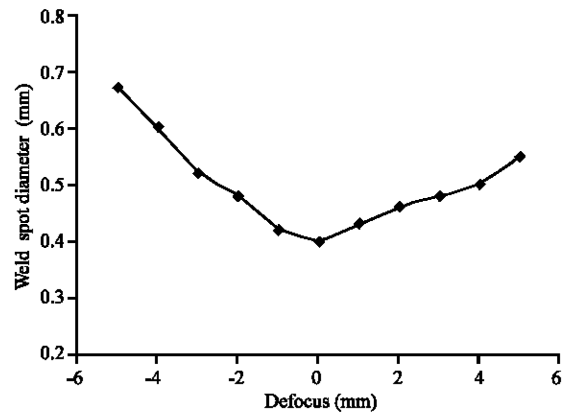

Fig. 8: Effect of focusing position on the laser spot weld diameter

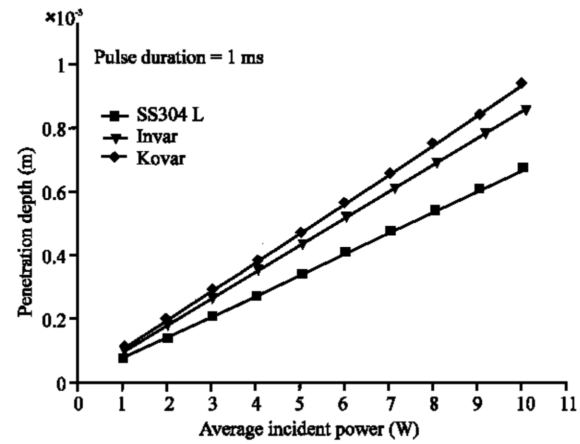

Fig. 9: The change of penetration depth with the incident average power

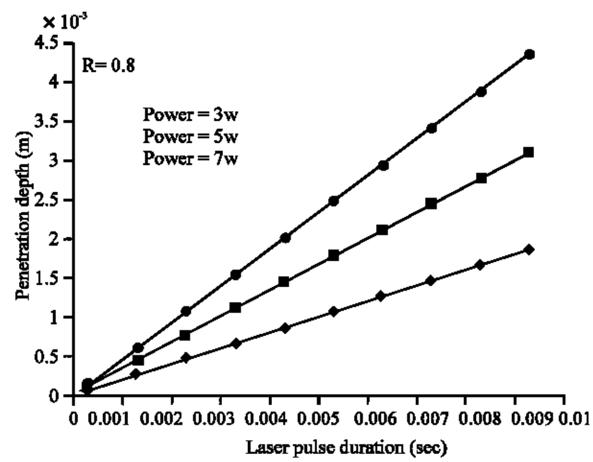

Fig. 10: Effect of laser pulse duration on the penetration depth for different incident powers

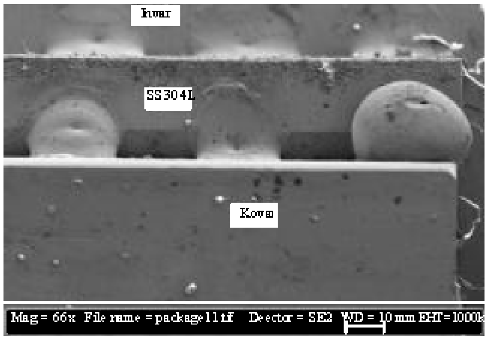

Fig. 11: SEM of a part of the prepared sample

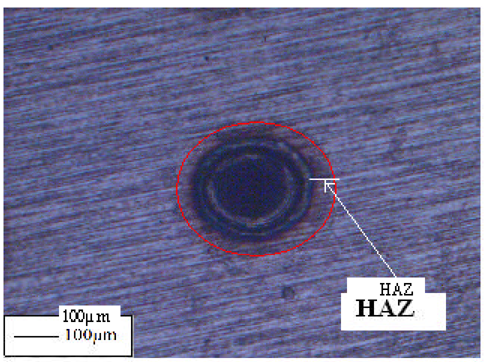

Fig. 12: The metallographic measurement on SS304L sample

different incident power. Same effect is found also with the other two alloys but of course with different range of penetration depths.

In welding the coupling lenses in their holders to the substrate via welding clips, three different alloys have been used, i., e. Kovar, Invar and SS304 as shown in Fig. 3 and illustrated by using SEM Fig. 11, which shows the position and the size of three spot welds on the interfaces of each two materials and since the height level of Kovar material is higher than that of SS304L, the interaction is clear on the top surface of SS304L alloy.

In Fig. 12 the metallographic measurement shows that the Heat Affected Zone (HAZ) of the laser pulse on SS304L sample is significantly small.

CONCLUSION

The 1550 nm laser diode module is coupled via double ball lenses into a single mode fiber with ferruled tip. All the coupling components have been fixed by using dual laser beam microwelding technique. The active alignment possibility and the firmed fixing of all coupling components leads to a coupling efficiency of about 75% with relaxed misalignment tolerances. Laser pulse parameters found to have a very significant effect on the spot weld dimensions and the heat affected zone; therefore, an optimization of all those parameters is necessary to achieve good weld yields with less than unity ratio of spot weld width to depth. The modeling results have been found to be in a very good agreement with those obtained by experiments previously. SEM measurements shows that spot weld with small dimensions are joining the three different alloys firmly. The HAZ accompanied with laser spot welds is significantly small which is an advantageous in welding very sensitive optical components.

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