LASER DIODE PIGTAILING AND PACKAGING USING Nd: YAG LASER WELDING TECHNIQUE

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Abstract
In this paper we present some investigations and analysis of various parameters that contribute for increasing the coupling efficiency of laser diode to single mode fiber coupling using lens coupling and butt coupling schemes. The fiber attachment process and the 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. Results of optimizing laser beam parameters to get good welds with small heat affected zones (**HAZ**) such as (variation of weld dimensions with changing of laser beam parameters are also presented. We also studied the weldability of different materials to determine the suitability of using those materials as the base material and welding tools for different types of photonic devices packaging.

Keywords: Single Mode Fiber, Coupling Efficiency, Laser Welding System

INTRODUCTION

Photonic devices used for telecommunications or military applications are usually required to operate for long time in field with potentially humid, corrosive, and mechanically turbulent environments. Long-term reliability in such hostile operating conditions requires strong fixing of the aligned components and hermetic sealing of the photonic devices inside metal hybrid housing. Most of the production cost of the laser diode module is due to the coupling and packaging process, therefore understanding the optimal coupling methods and determining the effective coupling schemes along with the packaging facilities is very important for reducing the devices cost. 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, automated laser welding also enables producing more and hence reducing the devices cost effectively. The mismatch between the elliptical mode-field of the laser diode emission and the circular mode-field of the single mode fiber is the major cause of coupling loss. Different coupling schemes have been proposed, either **discrete microlenses** [6] or **fiber tapers** are used. Butt coupling is the common and old direct coupling but this coupling scheme results in a very low coupling efficiency (5-15%). A coupling method using a cylindrical lens has been developed [4, 15] for coupling laser diodes to single-mode fiber. It has been also reported that a combination of a cylindrical lens and Graded index (GRIN) rod lens [14] can be employed to give a relaxed tolerances with high coupling efficiency. Another efficient coupling scheme with a hemispherical lens fabricated on the fiber endface [13]. The use of tapered hemispherical end single-mode fiber also reported to give efficient and reflection insensitive coupling [12]. Fiber microlenses with different shapes and configurations (circular, cylindrical, hemispherical, and hyperbolic) reported to achieve good coupling efficiencies, however, the lens aberration can not be avoided which affect the coupling efficiency. Apart form the problem of lens aberrations that affect the coupling efficiency, single lens or a combination of confocal two lenses are promising methods for efficient couplings with wide lateral and angular misalignments, but these configurations have the problem of the attachments and fixing the components in an active alignment process. These requirements become available due to the advancement in laser applications. Laser welding with two or three simultaneous beams with very small spot sizes can be employed for fixing lenses at their holders to the substrate during an active alignment process, and then the ferruled fiber tip is welded to the substrate using various types of welding clips. Coupling of laser diode to single mode fiber using optical elements and lenses is associated with lot of difficulties regarding alignment, positioning, and fixing. Moreover, the key issue in packaging a fiber-pigtailed module is the alignment of the optical fiber with the active or passive device within the package and maintaining the alignment under all operation conditions. The benefits of active alignment's lower insertion loss and relaxed manufacturing tolerance of the individual components outweigh its costs. Active alignment is more important when aligning laser diode to single-mode fibers. In the simplest form of a transmitter module, a single mode fiber is first aligned to the laser diode so that the maximum light coupling is optimized, and then the fiber is fixed at that position.

MATERIALS

The reported weldable materials are materials of low thermal conductivity, 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. Recently, some other alloys became popular for laser welding of optoelectronic devices packaging, such as:

- Kovar™ which contains (29% Ni, 17% Co, 0.2% Mn, and 53% Fe).
- Invar™ which contains (46% Fe, 36%Ni).

THEORETICAL CONSIDERATIONS

Assuming Gaussian field distributions for both the laser diode source and the single-mode fiber, and since the actual field distribution of the laser diode emission is elliptical, we can express its mode field distribution as elliptical Gaussian distribution with beam waist radii ω_{lx} and ω_{ly} along two mutually perpendicular directions.

The laser field U_L on laser diode plane 1 at a distance d from the coupling optics or the tip of the lensed fiber (Sarker et al.,1984).

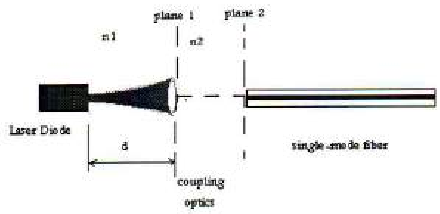

Fig.(1) laser diode to single mode fiber coupling

$$\psi_{1L} = \left(\frac{2}{\pi w_{1x} w_{1y}}\right)^{\frac{1}{2}} \exp\left[-\left(\frac{x^2}{w_{1x}^2} + \frac{y^2}{w_{1y}^2}\right)\right] \exp\left[-jK_1\left(\frac{x^2}{2R_{1x}} + \frac{y^2}{2R_{1y}}\right)\right] \quad \text{..........(1)}$$

k_1 is the wave number in the incident medium, R_1 is the radius of wavefront curvature.

The fundamental mode for the circular single mode fiber is expressed as:

$$\psi_f = \left(\frac{2}{\pi}\right)^{\frac{1}{2}} \frac{1}{w_f} \exp\left(-\frac{x^2 + y^2}{w_f^2}\right) \quad \text{...(2)}$$

ω_f is waist radius of field at the single-mode fiber. After the coupling optics arrangement the laser field at plane 2 is get transformed to become:

$$\psi_{2L} = \left(\frac{2}{\pi w_{2x} w_{2y}}\right)^{\frac{1}{2}} \exp\left[-\left(\frac{x^2}{\omega_{2x}^2} + \frac{y^2}{\omega_{2y}^2}\right)\right] \exp\left[-j\frac{K_2}{2}\left(\frac{x^2}{R_{2x}^2} + \frac{y^2}{R_{2y}^2}\right)\right] \quad \text{........(3)}$$

ω_{2x}, ω_{2y} are the transformed beam waists. R_{2x} and R_{2y} are the transformed radii of curvature in the X and Y directions; k_2 is the wave number in the coupling medium.

The coupling efficiency is expressed by the overlap integral (Sarker et al.,1986)

$$\eta = \frac{\left|\iint (\psi_{2L})^* \psi_f \, dxdy\right|^2}{\iint |\psi_{2L}|^2 dxdy \iint |\psi_f|^2 dxdy} \quad \text{.......(4)}$$

After subs., we get:

ABCD ray tracing matrix can be used to express w_{2x} , w_{2y} and R_{2x}, R_{2y} in terms of their counterparts before

$$\eta = \frac{4\omega_{2x}\omega_{2y}(\omega_f)^2}{\left[(\omega_f^2 + \omega_{2x}^2)^2 + \left(\frac{k_2^2\omega_f^4\omega_{2x}^4}{4R_{2x}^2}\right)\right]^{\frac{1}{2}}\left[(\omega_f^2 + \omega_{2y}^2)^2 + \left(\frac{k_2^2\omega_f^4\omega_{2y}^4}{4R_{2y}^2}\right)\right]^{\frac{1}{2}}} \quad \text{.........(5)}$$

transformations. Using a standard Gaussian beam approximation, it can be shown that for the ideal case of coupling (**Joyce and Deloach, 1980**)

$$\eta = \frac{4w_f^2 w_{2x} w_{2y}}{\left(w_{2x}^2 + w_f^2\right)\left(w_{2y}^2 + w_f^2\right)} \quad \text{.........(6)}$$

The alignment tolerance can be defined as the displacement between the two beam waists along the optical axis which results in a 1-dB loss of coupling efficiency. This is given by (**Joyce and Deloach, 1980**) as

$$\Delta z_{1dB} = \frac{1}{2}\frac{\pi}{\lambda}\left(w_l^2 + w_f^2\right) \quad \text{.........(7)}$$

For perfectly matching $w_l = w_f = w$. (here we assume $w_{2x} = w_{2y} = w_l$, Similarly, expressions for lateral and angular alignment tolerances (displacement resulting in 1-dB coupling losses)

$$r_{1dB} = 0.33(w_l^2 + w_f^2)^{\frac{1}{2}} \quad \text{.........(8)}$$

And

$$\theta_{1dB} = 60\frac{\lambda}{\pi^2}\left(\frac{1}{w_l^2} + \frac{1}{w_f^2}\right)^{\frac{1}{2}} \quad \text{.........(9)}$$

EXPERIMENTAL PROCEDURE

Besides electronic circuitry, a typical transmitter consists of a diode laser with an optical isolator, a lens and a fiber pigtail. During production, these components are positioned and affixed by laser welding. Post weld shift along with other welding defects can be minimized or even eliminated by suitable selection of the material of welding tools such as fiber ferrule, welding clips, and the substrate. It is also reported that the laser beam parameters, the deign of welding clips, and welding sequence have a very strong impact on the weld yields and hence the coupling efficiency.

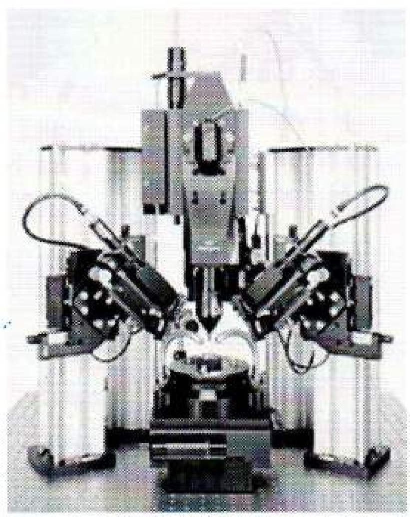

Fig.2 a photo for the laser weld system

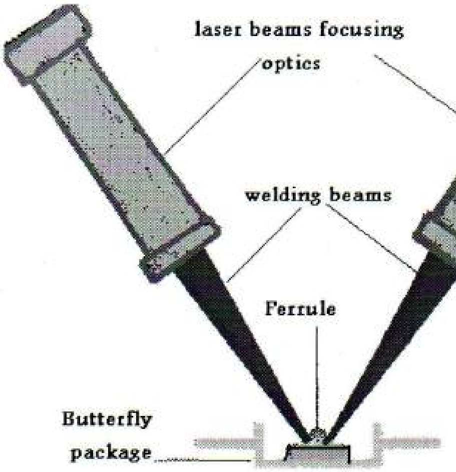

Fig. 3 Dual laser beam weld for butterfly module

During the alignment of a laser diode module, the system continuously measures the output power of the diode laser at the free end of the fibers to determine coupling efficiency. A machine vision system pre-positions the housing, which eliminates or reduces blind searches for first light. After the system locates the light in the fiber, alignment routines determine the optimum coupling position. The coupling parts are then fixed using two or three simultaneous laser beams from Nd: YAG laser. Normally for butterfly type modules the system is equipped with two beams as shown in the fig. (2) and illustrated in fig. (3). The change of coupling power with the displacement in x and y directions is depicted in fig.(4). The laser pulse energy and duration as well as the sequence of the spot welds have to be adjusted to compensate the expected deformation and guarantee a well-performing welding joint without introducing unnecessary heat. The spot welds are placed symmetrically to reduce thermal influence, this process compensates for the stress introduced by the welds. The alignment process for all components and the spot-weld quality are monitored by CCD cameras on the welding optics. The welding laser includes a pilot laser beam, which simplifies positioning the spots and the development of the welding process. Fig.(5) shows the active alignment process done by laser weld system(LW4000S). During the active alignment and scanning process the coupled power is monitored continuously by the optical meter

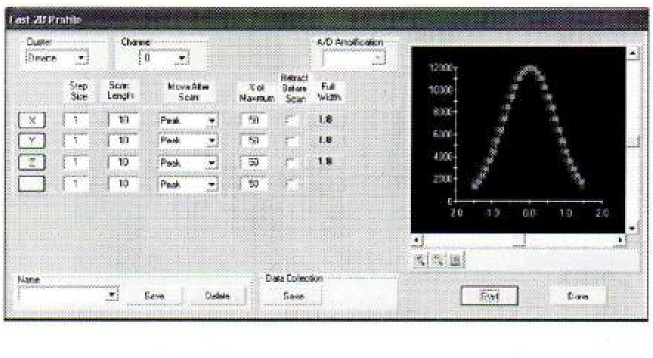

Fig. 4 Fast alignment 2D profile

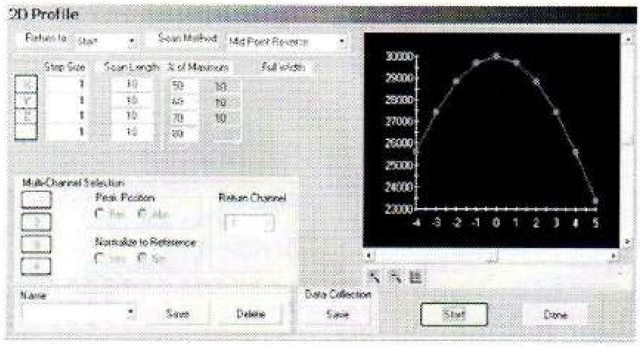

Fig. 5 2D profile of the alignment

RESULTS AND DISCUSSION:

Theoretical calculation of coupling efficiency with lateral offset for the case of confocal ball lens coupling is shown in fig.(6). Experimentally we found tat the obtained coupling efficiency can reach a 75% at optimum position (around 5μm) for the working distance.

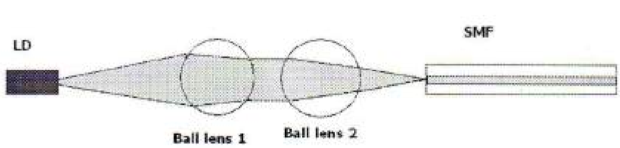

Fig.6 Confocal ball lens coupling

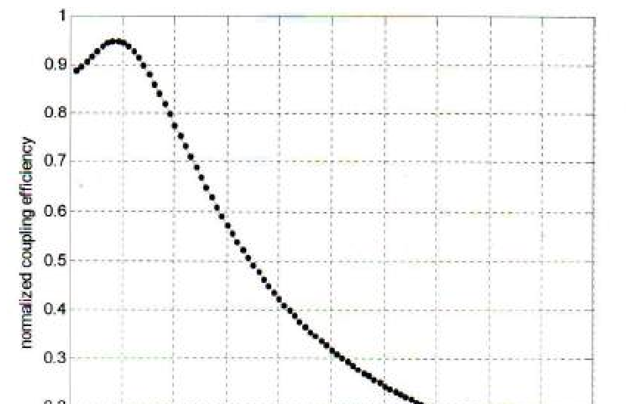

Fig. 7 Coupling efficiency vs. lateral offset (theoretical calculation)

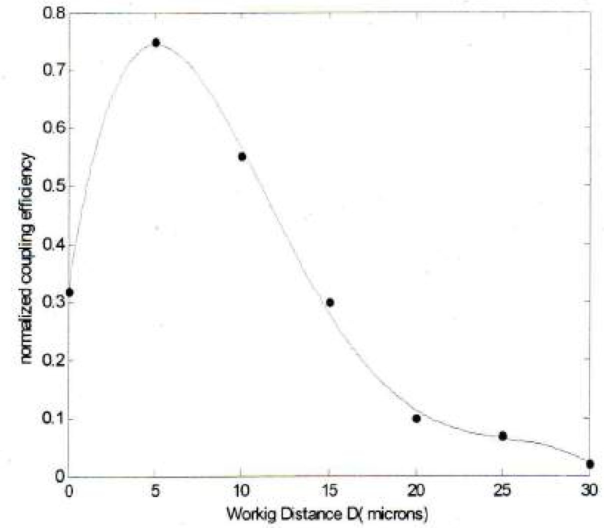

Fig. 8 Coupling efficiency vs. working distance (Experiment)

The effect of the change of beam waist size on both lateral and angular misalignment tolerances is calculated and plotted in figure (9). It is clear that there is an optimum spot size at which both the tolerance in angular and lateral misalignments is maximum.

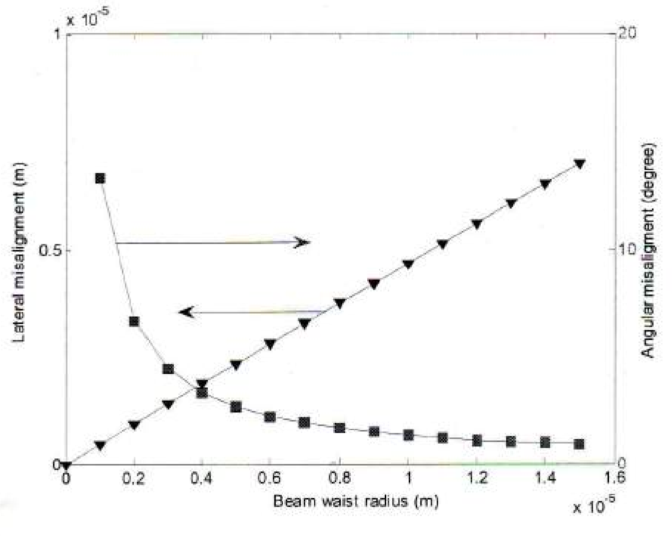

Fig.9 The effect of beam waist size on lateral an angular misalignment tolerances

It has been found that for both materials Kovar™ and Stainless steel 304, the required power density for welding is in the range of ($10^5 w/cm^2$). A linear relationship is obtained for the change of spot weld dimensions with pulse energy and power density as shown in figs.(10&11) and Fig (12) respectively.

Increasing the number of laser pulse shoot leads to the increase in both laser spot weld depth fig.(14) and also the increase of weld width, therefore an optimization is necessary to get good weld depth and reduced heat affected zone (HAZ). It is also found that for the same pulse energy, the weld width is increased by increasing the pulse duration as depicted in fig.(14). Another important parameter is focusing position of the laser beam with respect to the surface of workpiece; here the weld width and depth can be also optimized by changing the focusing position leading to the desired ratio of weld width to weld depth.

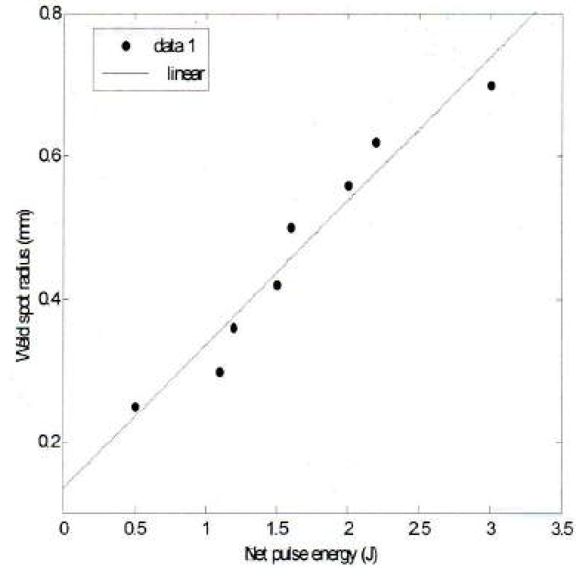

Fig.10 The effect of pulse energy on the weld spot radius (for Kovar)

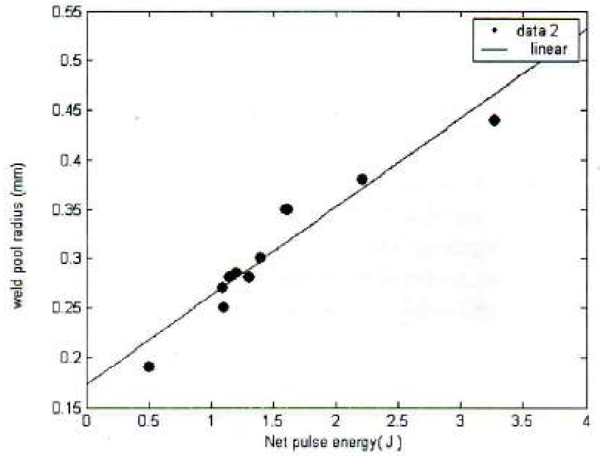

Fig.11 The effect of pulse energy on the weld spot radius (for stainless steel)

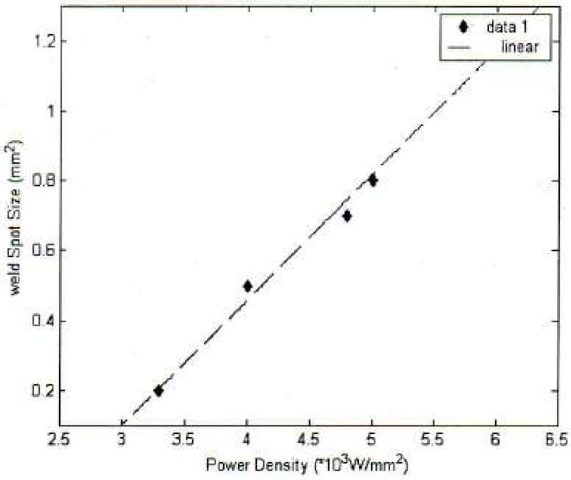

Fig.12 The effect of power density of the laser beam on weld spot area

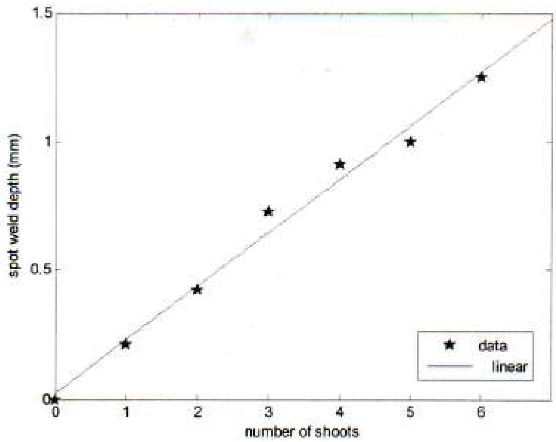

Fig.13 The change of spot weld depth with number of pulse shoots

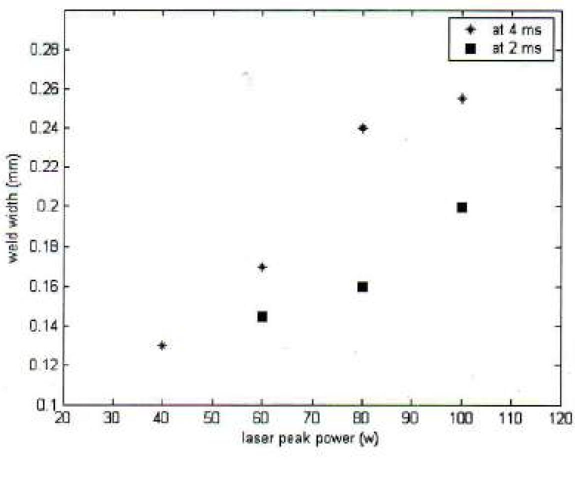

Fig. 14 The effect of changing the pulse duration on the relation between peak power and weld width

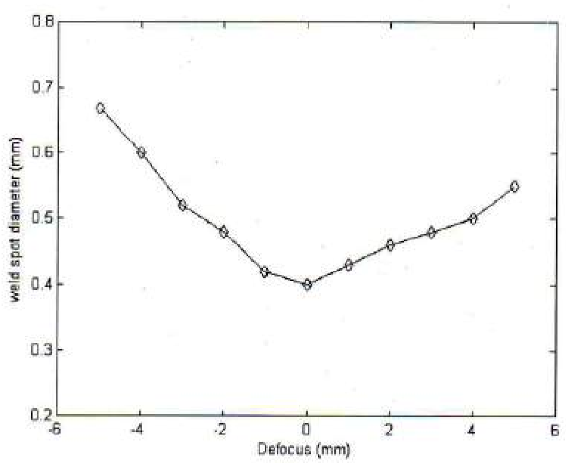

Fig.15 The change in weld width with changing the position of the workpiece from the focus point

CONCLUSION

Laser welding with dual simultaneous laser pulses proved to be an effective tool for coupling and packaging miniaturized optoelectronic devices. Laser weld system (LW4000S) used for alignment, coupling and packaging 1550 nm laser diode module using confocal two ball lenses coupling configuration. Theoretical calculations for the coupling efficiency are given along with the results obtained experimentally and by simulation. Results of effect of laser welding beam parameters on the weld dimensions show the great effect of the pulse energy, duration and peak power on both the weld width and depth, where an optimization selection of the beam parameters is necessary to optimize the ratio of weld width and weld depth to get good welds with small heat affected zones (HAZ) which is highly desired when welding very small sensitive optical components.

Kovar™ and Stainless steel material proved to be suitable as the base material for welding tools, although Kovar™ showed better interaction for this application.

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