

Solder Jetting - A Versatile Packaging and Assembly Technology for Hybrid Photonics and Optoelectrical Systems

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Abstract

Solder Jetting is a versatile assembly and packaging technology for hybrid photonics and MEMS. The jetting device for liquid solder droplets ranging from 100 μm to 760 μm in diameter is manipulated in up to 6DOF independently from the complex assembly environment, thus able to reach even complex and 3D-shaped joining geometries. Creating the joint between the component and the system platform the metallic solder alloy is advantageous over standard adhesives due to better temperature, radiation and long term stability, making it favourable e.g. for high power photonics applications and also serving for electrical and thermal conductivity. In various photonics applications alignment stability up to $1.5 \pm 0.5 \mu\text{m}$ have been demonstrated.

Key words: Solder Jetting, Photonics Assembly, Hybrid Packaging

Introduction

A typical photonic system, as shown for example in fig. 1, consists of several electrical and optical components that act as light source, beam shaper, transformers, light drain and sensors. A photonic system thus mainly merges optical and electrical functionality on a system platform that needs to provide not only a stable mounting surface, but also facilities to manage wirings and thermal conduction. Increasing power and shrinking size not only require assembly tools and algorithms that go beyond the usual 3DOF technologies of hybrid electronics manufacturing, but also introduce special requirements in terms of accuracy and long term stability under various application and environment conditions.

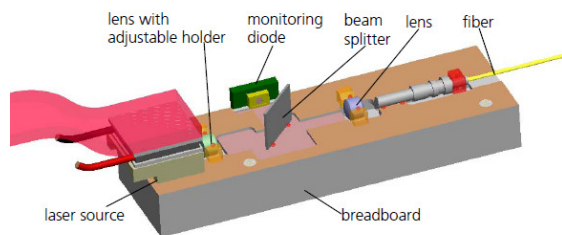


Fig. 1: Complexity of a Photonic System

A standard and easily practicable integration technology is adhesive bonding, commonly based on UV-curable polymeric adhesives and widely used especially in photonics and micro optics. Nevertheless, adhesives exhibit limiting performance in terms of electrical and thermal conductivity, vacuum compatibility as well as radiation, heat and long term stability. Thus an electronics compatible alternative with comparable flexibility, speed and precision of its application is required.

Solderjet Bumping

Soft metallic solder alloys can be such an alternative; while laser based solderjet bumping is the flexible process that places bumps of solder onto different substrates. Solderjet bumping was primarily developed for flip chip interconnections in semiconductor devices [1]. The bumping instrument is capable of handling a wide variety of solder alloys extending from indium-tin, tin-based lead free alloys to eutectic gold-tin and can be equipped to process solder spheres with a diameter ranging from 100 μm to 760 μm .

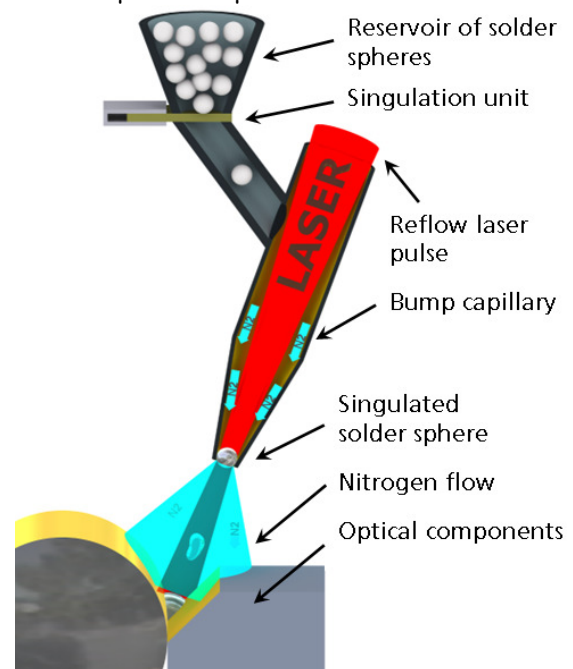


Fig. 2: Schematics of Solderjet Bumping

The principle of operation is shown in fig. 2. Spherical solder alloy preforms get singularized out of a reservoir and transferred to the bumping capillary with an inner tip diameter at its conical end that is smaller than the diameter of the solder sphere. The separated sphere is held in place there by a constantly applied pressure of N_2 within the capillary. With the solder being locked at the outlet of the capillary the bond head can be positioned near the desired joining area, e.g. by a robot or a XYZ-gantry, in all 6DOF, including angular movements (tip and tilt). The capillary thus can be positioned in complex, miniaturized and highly integrated system environments.

Once the desired capillary position is reached and the photonic components have been adjusted the solder gets melted by a fiber coupled laser pulse. The current system uses a Nd:YAG laser with pulse widths up to 25 ms and pulse energies up to 5 J depending on both solder alloy and volume. The liquid solder is then pressed out of the capillary by the N_2 pressure, flying towards the designated joining area within a localized nitrogen atmosphere created by the flow of nitrogen being exhaled from the now open capillary which also allows for the preheating of the substrate due to the laser beam now routed through. Depending on solder sphere diameter, required accuracy and nitrogen pressure free flight bumping distances range from twice the sphere diameter up to approx. 6 mm. The liquid solder hits the joining surfaces and forms the joint by partially transferring its stored thermal energy and creating the intermetallic phases during resolidification if a wettable layer is available at the joining surface. Laminar contact of the liquid solder with both parts increases thermal contact; enhancing wettability and solder spreading. The solder joint geometry formation is not limited to planar or horizontal surfaces, but can be shaped in complex geometries as long as the liquid solder can reach the wetting surfaces on both parts to be joined. Bump application was demonstrated even on vertical surfaces and with joining gaps up to 100 μm apparent [2].

The capability of solderjet bumping to operate in a flux less mode prevents contamination of optical components and corrosion, thus leading to better vacuum compatibility and a higher processing speed rendering subsequent cleaning unnecessary. It provides a short cycle time compared to UV-curing adhesives due to the free flight time of application typically less than 10 ms and the fast freezing and down-cooling of the solder in less than 100 ms, depending on substrate material, solder alloy and bumping parameters. Bumping frequencies up to 10 Hz can be reached which is much faster than the positioning of the bumping capillary.

Pre-Requisites and Materials Selection

Using a metallic soft solder alloy and the joint creation being the formation of intermetallic phases requires a wettable metallization on the components to be joined. Good adherence of this metallization is necessary for mechanical stability, while non-oxidization is mandatory for flux free processing. A typical metallization system for such purposes is shown in fig. 3. The sputtered three layer metallization consists of Titanium as an adhesion promoter, Platinum as a diffusion barrier and a covering Gold flash acting as a wetting surface. The overall thickness of this metallization system is approx. 0.5 μm

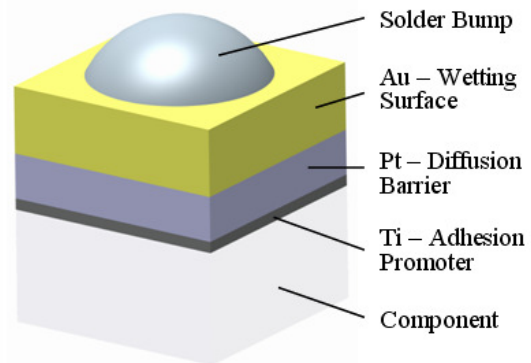


Fig. 3: Metallization System (not drawn to Scale)

Onto this metallization a wide variety of solder alloys can be bumped. Table 1 lists the most common soft solder alloys [3, 4] that span a reflow temperature from 138° C to 278° C. It has to be considered that typically, while exhibiting higher strength than adhesives, solder alloys are less elastic and thus have a limited capability for compensating stress that occurs due to CTE mismatch induced thermal expansion between the components to be joined. In a limited range this can be controlled by proper solder alloy and volume selection, but more regular specific design rules have to be applied.

Tab. 1: Soft Solder Alloys Properties

	Solidus/ Liquidus	Young's Modulus	Yield Strength	Thermal Conduc- tivity	Coefficient of thermal Expansion
	°C	GPa	MPa	W m ⁻¹ K ⁻¹	10 ⁻⁶ K ⁻¹
Au80Sn20	278	59..68	275	57	16
Sn3Ag0.5Cu	217/ 221	44	45	56.3	22.4
Sn58Bi	138	11.9	49.1	19	14.3
Sn3.5Ag	221	26.2	26.7	33	20.4
Indium	156	10.6	2.6	81.6	32.1

Process Parameters and Performance

a) Solder Reflow

Within the capillary the solder sphere gets molten by the laser that is routed through. The laser energy can be adjusted by pulse duration and laser current (fig. 4), resulting in a wide range for thermal energy that is stored within the molten solder drop, being depended from absorption. Melting takes place in approx. 5 ms to 10 ms, thus with pulse lengths up to 25 ms it is possible to illuminate the joining area by the laser in the remaining time of the pulse.

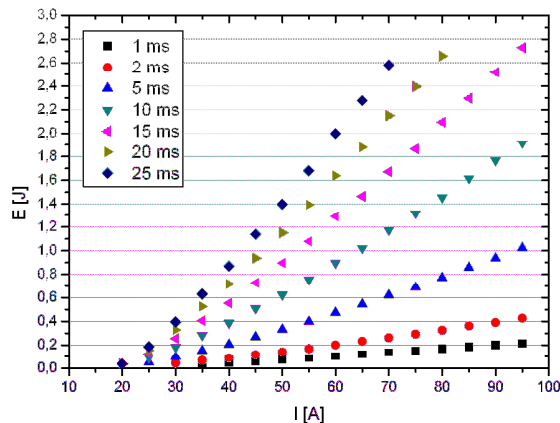


Fig. 4: Reflow Energy as a Function of Laser Current and Pulse Duration

Main goal for reflow parameterisation is to select the proper thermal energy that is necessary to wet on both components to be joined. This often has to be a compromise. On one side is the optical component made of glass, a brittle material that has low thermal conductivity, requiring only low amounts of thermal energy to wet the solder onto the respective metallization and to prevent the material from being damaged (fig. 5). On the other side there is a system platform often made of medium to good heat conducting materials such as metals or ceramics. These require rather high amounts of thermal energy deposited within the applied liquid solder bump. The compromise is to find the process window that fits both requirements. It narrows if there is a large difference in heat conductivity between both the components to be joined.

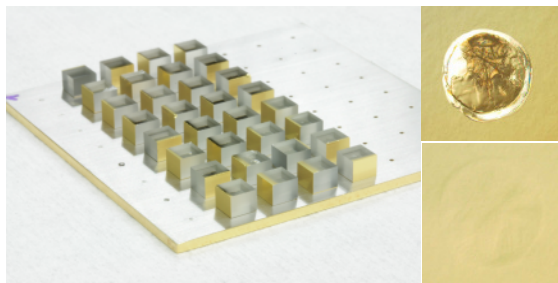


Fig. 5: Test Vehicle for Reflow Parameterisation and different Damage due to Solder Application

b) Targeting Accuracy

Complex assembly environments at high integration levels require the application of solder bumps in locations difficult to reach. Thus one objective of solderjet bumping is to increase the bump distance as much as possible, enhancing flexibility for the placement and orientation of the bumping capillary (length beyond bond head max. 15 mm, diameter < 3 mm, tapered tip) with respect to the assembly environment. Fig. 6 shows a setup used to determine the influence of process parameters on targeting accuracy that is quantified as a displacement between the targeted position and the actual placement of the solder bump. Metalized glass slides with fs-Ti:Saphir laser structured cross-hair for referencing the targeted positions were used as targets. Manipulation and positioning of the solderjet capillary is accomplished using the pilot laser of the bump head, an observation camera and a 6DOF robot.

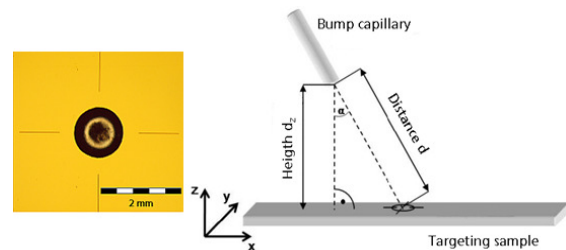


Fig. 6: Test Target and variable Parameters

An experiment was conducted using solder spheres made of Sn96.5Ag3.0Cu0.5 alloy with diameters of 400 μm . Prior experiments defined constraints to the parametric levels to be investigated. Laser pulse width and current are restricted to an upper limit due to possible damage to the target substrate or component and due to wetting of the solder to the capillary. To a lower limit they are restricted for providing sufficient energy for reflow of the solder spheres to be jetted out of the capillary. Bond level height, i.e. the distance of capillary to target, and angle of incidence are delimited by geometrical considerations of typical components and joining geometries.

Radial displacement is measured by means of a microscope and image processing for the calculation of the shift between the center of the circular solder bump and the provided cross-hair target structure. The micrographs also allow for a rating of the solder bumps concerning deviation of shape and damaging of the substrate material. As depicted in Table 2 the factors nitrogen pressure, bond level height and angle of incidence can be considered significant in terms of the response variable of a test according to Design of Experiment (DoE) rules. All coefficients are positive, thus minimizing the values within the boundaries given by the design of experiments will minimize the displacement. Both laser current and pulse width are not significant. Although the second order

model and the resulting data do not sufficiently match in the lack-of-fit test, i.e. there are disturbance variables yet unaccounted for and statistical spread has to be reduced, an optimization of the reduced regression equation can be calculated. This optimization provides the parameters as shown in Table 3 and predicts a minimized radial displacement of $(55 \pm 10) \mu\text{m}$. In general terms a good approximation is that the targeting accuracy of solderjet bumping is in the range of 10 % of the used solder sphere diameter.

Tab. 2: DoE Significance of Process Parameters*

Factor	Correlation Coefficient
Laser Current	0.087
Pulse Width	0.024
N ₂ Pressure	0.178
Bond Height Level	0.256
Angle of Incidence	0.248

*400 μm Spheres

Tab. 3: DoE Optimized Process Parameters*

Factor	Set 1		Set 2	
Laser Current	50 A	Pulse Energy : 2.25 J	50 A	Pulse Energy: 1.44 J
Pulse Width	25 ms		15 ms	
N ₂ Pressure	25 mbar		20 mbar	
Bond Height Level	1.5 mm		1.5 mm	
Angle of incidence	0°		15°	
Radial Displacement	42 μm		91 μm	

*400 μm Spheres

c) Joint Strength

To provide a strength test vehicle for shear force measurements prisms made of Borofloat BF33 glass, having dimensions of $4 \times 4 \times 2.7 \text{ mm}^3$, were soldered to ceramic system platforms. The Borofloat prisms are metalized using the thin film system Ti/Pt/Au already described. Both LTCC (Low Temperature Cofired Ceramics) and Alumina were processed to provide platforms with 48 evenly distributed cross shaped land patterns made of screen printed Au-and AgPd-thick-film metallization similar to wiring used in hybrid electronics. Fig. 7 and 8 show the shear force test setup using an LTCC platform. The capillary is positioned with an angle of incidence of 22.5° , 400 μm solder spheres made of Sn96.5Ag3.0Cu0.5 alloy were used.

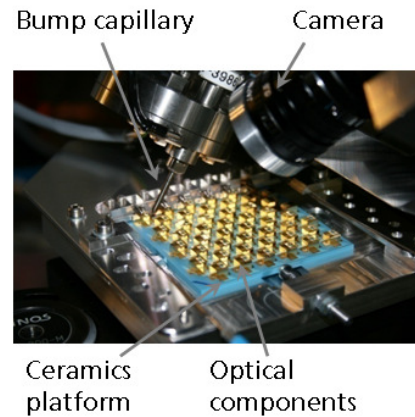


Fig. 7: Shear Test Platform Overview

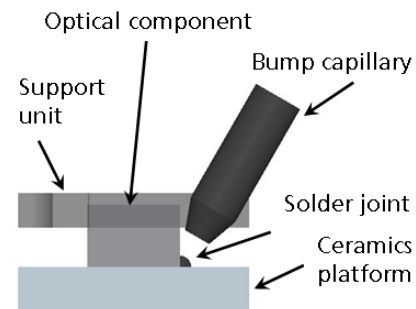


Fig. 8: Shear Test Platform Layout

For LTCC with AgPd metallization laser current and nitrogen pressure were found to be significant factors, while pulse width, also being important, was set constant to 5 ms due to damage to the substrate at higher levels. The reduced regression equation exhibits two main effects, the two-factor-interaction of laser current and nitrogen pressure and the second order term for nitrogen pressure. A local maximum can be found at the edge of the parameter space, but a further increase of laser current while decreasing the pressure is not feasible due to wetting of the capillary. As shown in table 4 the shear force ranges from 11.4 N to 14.3 N. An optimized shear force of 14.6 N was achieved, representing the strength of two joints made by 400 μm spheres.

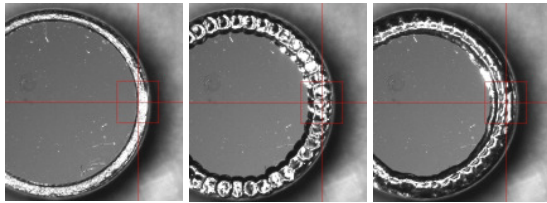
The results for Alumina with AgPd metallization are not distributed normal and thus power transformed for further analysis. For this substrate laser current, nitrogen pressure and bond height level were found to be significant. Again pulse width had to be set to 5 ms to avoid damage to the substrate. The reduced regression equation also contains the two-factor-interaction of laser current and distance as well as the second order terms of laser current and distance. Table 4 shows the achieved shear forces ranging from 10.2 N to 15.4 N. A local maximum exists at the edge of the parameter space that leads to an optimized shear force of 15.6 N, again for two 400 μm spheres. A further increase of the laser pulse current is not feasible due to wetting of solder at the tip of the capillary.

Tab. 4: DoE Optimized Shear Strength*

Substrate/ Metallization	Laser Current	Pulse Width	Optimized Shear Force
LTCC-AgPd	62 A	5 ms	14.6 N
	Pulse Energy: 0.5 J		
Al ₂ O ₃ -AgPd	62 A	5 ms	15.6 N
	Pulse Energy: 0.5 J		
LTCC-Au	61 A	23 ms	17.3 N
	Pulse energy: 1.87 J		
Al ₂ O ₃ -Au	61 A	17 ms	15.4 N
	Pulse energy: 1.46 J		

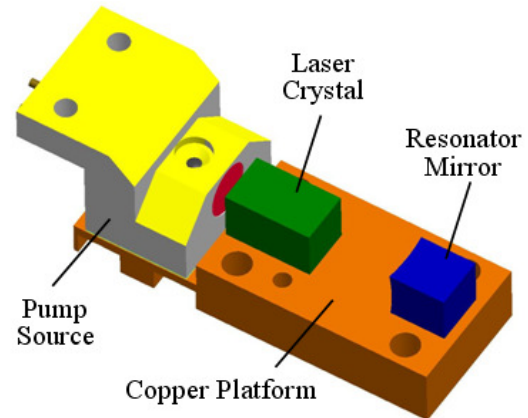
*400 μ m Spheres**d) Joint Hermeticity**

Subsequently applying bumps that overlap each other can be used to create hermetically sealed packages that are often required in photonics applications. In contrast to [5] the hermetic sealing done by solderjet bumping can be created in only one reflow step (per solder drop) when the sealing window is already apparent, thus rendering an second reflow step unnecessary or at least optional. Helium leakage rates for a sealing as shown in fig. 9 (window diameter 1 mm) of 10^{-8} mbar $\cdot$ l/s to $<4 \cdot 10^{-9}$ mbar $\cdot$ l/s have been demonstrated.

**Fig. 9: Window hermetically Soldered into Stainless Steel Capillary****e) Accuracy**

The most crucial performance parameter in photonics assembly is the accuracy after joining. By passive alignment assembly accuracies up to 10 μ m can be reached while by active alignment the achievable accuracy goes down into the sub-micron range. Nevertheless, after alignment the position has to be fixated by the subsequent joining procedure. Misalignment due to joining might be pre-compensated for, if a systematic portion within the accuracy is occurring, while reproducibility cannot be compensated for and thus is a measure for absolute achievable accuracy.

In case of solderjet bumping misalignment occurs due to wetting behaviour, phase change phenomena between liquid and solid solder state and negative thermal expansion during down-cooling of the solder from liquidus temperature to room temperature. Solder volume reduction due to this is usually in the range of 1 % to 2 % and thus comparable to low shrinkage polymeric adhesives.

**Fig. 10: Miniaturized Laser Module with Crystal and Mirror on Copper Platform**

An application example where misalignment due to solderjet bumping can be demonstrated is a miniaturized laser module as shown in fig. 10, wherein the outcoupling resonator mirror needs to be aligned with respect to the laser crystal and fixated on a copper platform with submicron accuracy. Due to the prior unknown optimum alignment state different distances and tip/ tilt states of the resonator mirror might be present, making it necessary to predict the misalignment that can be expected. In an experiment therefore the mirror-platform distance was varied from 10 μ m to 100 μ m, consequently representing different joining gap that the applied solder has to fill. A special joining geometry as described in section a) has been used, making it possible to create a joint between the two different materials glass and copper (fig. 11), while a chromatic aberration sensor detected the motion of the mirror during soldering in a non-contact mode.

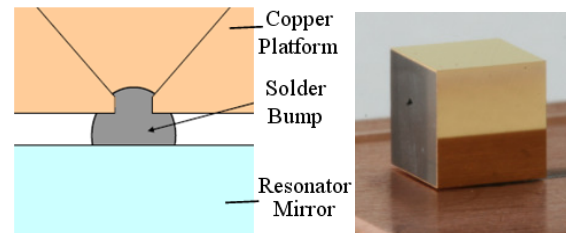
**Fig. 11: 3³ mm³ Laser Mirror mounted on Copper Platform with variable Gaps**

Fig. 12 illustrates, that the mean value of misalignment has a linear dependence from the joining gap as it can be expected from theory. If the actual joining gap is known after positioning of the component it is the value that can be compensated for. The remaining uncertainty of $\sigma = 0.6 \mu$ m to 0.8μ m then is the achievable accuracy.

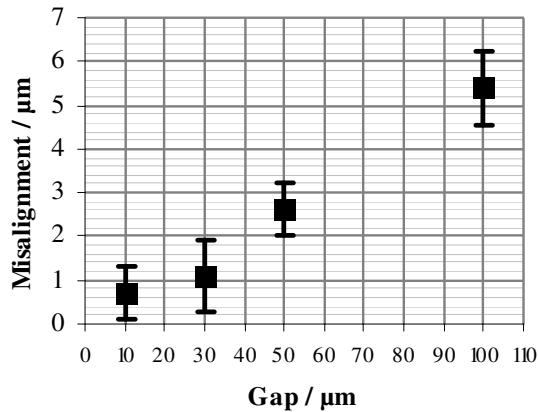


Fig. 12: Misalignment as a Function of the Joining Gap

Photonics Assembly Example

In fig. 13 a typical photonics assembly is shown where soldering is required to replace polymeric adhesives since the high power laser module leads to a high radiation load in use. Also the laser manufacturer prohibits their use due to out-gassing and facets contamination concerns. Fluxless solderjet bumping was applied to mount a multimode fiber in front of the laser facet, using one solder sphere made of Sn96.5Ag3.0Cu0.5 alloy that embeds the metallized fiber completely at a distance between 50 μm and 100 μm to the support structure. According to the accuracy experiment depicted in the prior section a misalignment in the range of 2 μm to 5 μm can be expected for such an arrangement, being sufficient for a multimode coupling of the fiber.

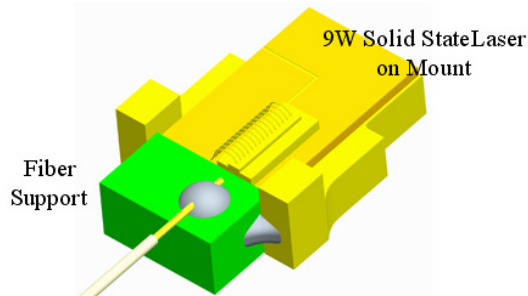


Fig. 13: Fiber Coupled High Power Solid State Laser Module

The fibers were prepared by means of stripping before being put into a batch metallization system that is able to process up to 400 fibers in parallel during PVD sputtering. After metallization of both sides (two sputter runs) cleaving took place providing even better result for the metallized fibers than cleaving bare glass fibers. During assembly the fiber was manipulated by means of a gripper with integrated rotation unit to provide polarization alignment. A solder bump with a diameter of 760 μm was placed after optimal alignment approximately 0.5 mm away from the fiber facet. Monitoring the coupling efficiency during the

joining procedure no significant drop was observed. Fig. 14 illustrates how the fiber with an outer diameter of approx. 125 μm is fully embedded within the solder at a distance of 50 μm to the support structure.

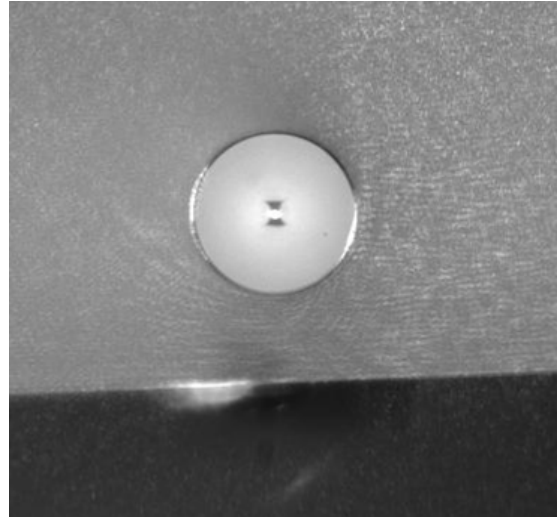


Fig. 14: Detailed View of the Polarization Maintaining Fiber embedded within Solder

The complete module (fig. 16) was subject to long term stability tests. Coupling efficiency at full power level (9 W) has been monitored over time (100 h) and calculated as relative changes with respect to the start value (fig. 15). With measures in the ranges of 1 % being standard for polymer adhesive assemblies the prototypes of the soldered assemblies provide similar performance, but having the advantage of absence of any organics near the laser facet.

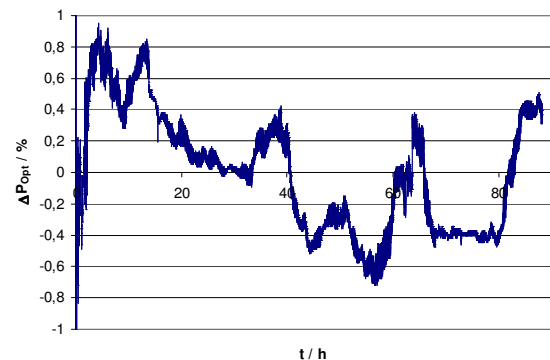


Fig. 15: Relative Change of Coupling Efficiency over Time

A problem occurring during assembly is the stress that is applied by the solder volume to the polarization maintaining fiber. Significant loss was observed in terms of polarization ratio when a certain angular position of the stress rods around the fiber core in relation to the support structure was present. This can be addressed to the direction of the stress that the solder is applying, while in other angular positions the effect was significantly lower. The effect of stress depended polarization state and ratio and needs further investigations.

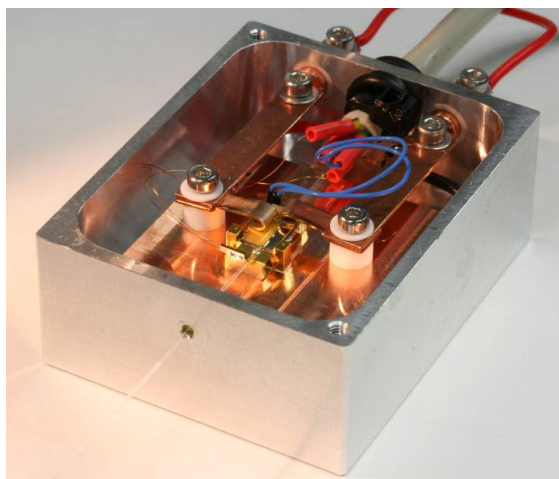


Fig. 15: Assembled Fiber Coupled High Power Laser Module

Summary and Outlook

Solderjet bumping has been described to be a versatile and flexible technology for the assembly of miniaturized optoelectronic and photonic system. Despite the mandatory additional effort to prepare components to be joined by metallization the solder material itself provides good properties in terms of conductivity and stability. Using the possibility to parameterize the process in a wide range solderjet bumping can be adapted to various assembly tasks. Main emphasis is on joining of miniaturized and 3D shaped optical and electrooptical components to other components, metallic mounts or ceramic platforms. Even hermeticity can be accomplished. Using small spheres in the range of 100 μm to 760 μm strong joints can be achieved that are superior over adhesive joints. Repeatability in terms of misalignment in the sub-micron range has been demonstrated. Nevertheless, the overall accuracy depends on solder joint geometry as well as the joining gap the solder has to overlap.

The high flexibility of the technology enables for fully automatic assembly processes in complex environments. A further addressable investigation topic is the stress that is induced by the solder and the capability of subsequently setting bumps for fine alignment by introducing specific tension states. Another issue is long term stability in presence of permanent stress. Even below the plastic limit of bulk solder creeping effects can occur and thus influence its performance. Also intermetallic diffusion and phase changes are different to what is known from standard reflow soldering in electronics due to the short laser beam reflow. Most important is a better understanding of the wetting and resolidification process in order to optimize and minimize misalignment during solderjet bumping, which is still at the limit for some micro optical and photonic applications. Nevertheless solder bumping technology has a substantial potential for fast varying, high precise

assembly processes in micro optics and micro system technology, where multifunctional and high accuracy packaging techniques are required.

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