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Picosecond laser welding of glasses with a large gap by a rapid oscillating scan

Hang Chen,† **Leimin Deng,**† **Jun Duan,*** **and Xiaoyan Zeng**

Wuhan National Laboratory for Optoelectronics, Huazhong University of Science and Technology, Wuhan 430074, China
**Corresponding author: duans@hust.edu.cn*

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A welding method that utilizes a picosecond laser with a small-scale rapid oscillating scan is presented in this Letter to achieve the welding of glasses with natural stacking contact (gap ≈ 10 μm). The rapid oscillating scan of the laser not only creates enough molten material to fill the gap, but also releases the internal thermal pressure during the welding process. The contraction created by condensation of the welding area can reduce the gap to less than 3 μm, which provides necessary conditions for realizing continuous welding. By using this method, a maximum joint strength up to 64 MPa can be achieved without any defects. The detail mechanism of laser welding with a rapid oscillating scan was revealed in this Letter. This research lays a good foundation for the laser welding of large-gap glass in practical engineering applications.

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Glass is an excellent material for chip packaging in the field of solar cells, implanted microelectronics, organic light emitting diode, micro-electromechanical systems, and microsensors due to its excellent chemical and physical properties such as light transmittance, insulation, corrosion resistance, and high hardness. Therefore, it has very extensive potential applications and market prospects in the automotive, aerospace, electronic semiconductor, and biomedical sciences.

At present, most of the chip's glass packaging technology in industry uses an adhesive method to achieve the purpose of sealing and mechanical strength. However, its shortcomings cannot be ignored: First, the gas emission from the adhesive can lead to device contamination and chip performance damage; then the adhesive tends to age prematurely due to photobleaching, which will reduce the sealing and lifetime of the chip; finally, the adhesive is thermal susceptible to cause degradation and expansion, which has a huge impact on chip life.

Laser micro welding provides a feasible solution to joint inner-interface of two glasses by utilizing the advantage of transparent properties. However, the long-pulse laser used for micro-welding suffers from a low absorption rate of transparent glass, so an additional absorption layer is needed to reduce the transparency of the whole interface of the bonded samples [1]. This laser welding method only melts the material of absorption layer, not the glass substrate. Therefore, its bonding strength and sealing performance is weak.

The appearance of ultrafast laser makes it possible for glass materials to absorb the laser energy through the nonlinear effect produced by its extremely high peak power density. Its applications include internal carving [2], cutting [3], and waveguide writing [4,5]. In 2005, Tamaki *et al.* [6] published a glass welding technology based on ultrafast laser and objective lens. Utilizing the nonlinear absorption characteristics of the ultrafast laser and the focusing performance of the objective lens, the laser pulse energy can be absorbed selectively in the focus position, which will produce a local melting of the glass interface and form a successful welding of the two glasses.

Since then, researchers proposed various methods to improve the mechanical strength of glass welding such as high repetition rate [7–9], double-pulse [10–12], and laser bursts [13]. The mechanical strength published in some research was even close to the glass itself. However, there are still two defects in these studies from the perspective of engineering: first, the focal length of the objective lens is very short, which limits the thickness of the upper glass, meanwhile, the accelerated speed of the stage is very low, which seriously affects the processing efficiency; secondly, these methods were based on optical contact which requires a harsh condition with a glass gap less than 1/4 wavelength [6] or even within 100 nm [14] to limit the dissipation of plasma [15]. This requirement has a great limitation in engineering applications, because it is very difficult to guarantee extensive optical contact in practical applications. Additionally, the residual stress would be also introduced in the process of welding if the local clamping method was used to obtain an optical contact. Some methods [14,16,17] were proposed for the problem which could increase the welding gap available to almost 3 μm. However, the contact gap between two glasses in natural stacks status is generally greater than 3 μm, so there is still a tough problem to realize the engineering application of ultrafast laser welding of glass.

The main reason for the difficulty in achieving laser welding of glass with a large gap is that the molten material produced by the interaction between laser and material is too limited to fill the large gap (≥ 3 μm) [16]. In addition, due to the nonlinear effect, the ultrafast laser acting area is tiny, which is inevitable to generate a strong internal thermal pressure and thermal accumulation in the welding area to cause a micro-explosion and further loss of the melt [18,19]. Moreover, the generated

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plasma is easy to dissipate at a large gap, resulting in a direct ablation effect on the glass material [20].

Although increasing the pulse number or single-pulse energy can be used to expand the heat affected zone (HAZ) to obtain more melting effect, the increase in pulse number will only cause the HAZ to develop vertically along the optical axis and cannot enter the weld gap. On the other hand, the increase in single-pulse energy will lead to ablation or even fracture of the glass due to excessive local heat accumulation [16,21]. Therefore, increasing the number of pulses and single-pulse energy cannot solve these problems.

In this Letter, a novel welding method named a rapidly oscillating scan is proposed based on a picosecond laser. A laser pulse with low energy density is focused in the contact surface between two glasses; then the laser focusing spot with diameter *d* moves along the path of concentric circles rapidly and repeatedly. In this process, the glass material absorbs laser energy through a nonlinear effect, as shown in Fig. 1(a). In this way, a local liquid pool of material with a radius of *R* is generated by melting gradually through heat accumulation [22]. The advantages of this welding method are as follows: it can reduce the heat accumulation of vertical direction to avoid laser energy consumption and generate a liquid pool that expands horizontally along the joining interface, which is beneficial to produce enough filling melt to join the gap between two glasses; secondly, the laser multiple scanning with low pulse energy density can effectively avoid the ablation or even fragmentation of glass; finally, the oscillations of the laser will stir the liquid pool to release the internal heat pressure that may cause micro-explosion.

The experiments were performed using a Nd:YVO$_4$ picosecond laser from Edgewave, which emits 10 ps pulses of 1064 nm light at a repetition rate of 1 MHz (the energy of a single pulse is 12 μJ). The laser beam was focused by a high-speed scanning galvanometer with a focal length of 103 mm [shown in Fig. 1(b)] to produce a focal spot of 20 μm diameter, which can form a welding line with a width about 28 μm. In order to enable all welding lines to melt together, the scan line spacing *s* was set to 0.01 mm. In addition, the scanning speed was set as 1000 mm/s, and the number of scanning was 150 times. The welding method was stacking soda-lime glasses naturally in the form of a dislocation lap without any external force, as shown in Fig. 1(c), and the contact gap was about 10 μm measured by a microscope. Since the depth of focus is longer, the laser was focused at the contact gap and moved back-and-forth rapidly and repeatedly in a concentric trajectory [Fig. 1(a)]; the laser can act on the upper and lower layers of glass at the same time. A Shimadzu AG-100KN universal material testing machine was used to test the joint strength of welding samples by measuring the force needed to break the weld seam in the push configuration and dividing by the total area of several welding areas [23], and the joint strength value took an average of three measurement results to reduce the measurement error.

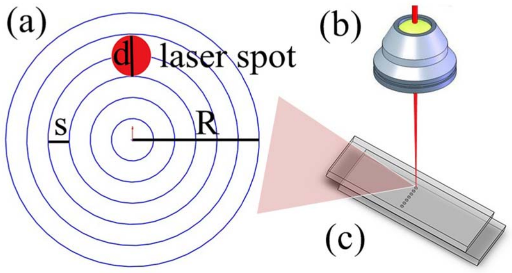

Fig. 1. Schematic diagram of the welding method. (a) Diagram of the welding path where *d* is the diameter of the spot, *R* is the radius of the welding area, and *s* is the interval of each ring in the path; (b) high-speed scanning galvanometer; (c) misplaced sample and the method used for the welding area on it is shown in (a).

Figure 2 shows the microstructure of the glass weld area with radius *R* of 0.3 mm obtained by a transmission microscope and scanning electron microscope (SEM), respectively, where (a) is the top view, and (b) is the transverse image. As can be seen, the melt does fill the gap. Quite different with the dual-structured internal modification which consists of a teardrop-shaped inner structure and an elliptical outer structure obtained by the previous ultrafast laser welding method [24], the modified region obtained by the method in this Letter is similar to an ellipse without an internal plasma ablation zone, and the contact gap reduced from 10 to 2.8 μm after welding. The relationship between *R* and the joint strength of the welding seam is shown in Fig. 3. As *R* increases from 0.05 to 0.3 mm, the joint strength of the welding seam increases from 30 MPa to the maximum value of 64 MPa; however, a further increase of *R* will cause a decrease of the weld joint strength. This section will be discussed in detail later in this Letter.

The experimental results above show that the rapid oscillatory scan method not only can realize the welding of glass with a large gap, but also achieves good quality welding seam and high joint strength without an internal plasma ablation zone, microcracks, and bubble defects.

In the rapid oscillating scan process, due to low laser power density and the short interaction time of the laser and glass because of the fast scanning speed, the energy deposition at

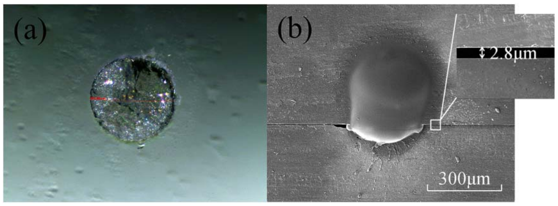

Fig. 2. Microstructure of the glass weld area with radius *R* of 0.3 mm. (a) Top view by a transmission microscope and (b) the transverse SEM image.

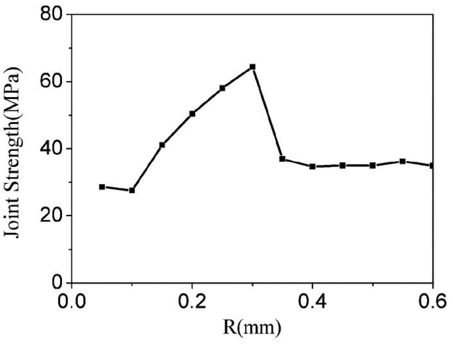

Fig. 3. Relation between *R* and the joint strength of the welding seam.

each scanning process is relatively mild. Then during the subsequent laser scanning period, the laser energy is likely to be dispersed due to the scattering and refraction effects in the modified area. Under this circumstance, the generated temperature gradient and internal thermal pressure are relatively small, which is beneficial for the melting effect, avoiding ablating and micro-explosion.

Secondly, the plasma formed during the welding will also have a shielding effect on the subsequent laser. This effect not only prevents the laser from directly acting on the material to produce ablating effect, but also absorbs laser energy and transfers it to the surrounding materials to further enhance the melting effect. After multiple scans, the laser action area heats up and melts, and the obtained molten material enters the gap under the gravity and internal thermal pressure to realize the gap bridge.

In addition, based on the numerical model of instantaneous point source given in Ref. [24] and the relevant parameters of the soda-lime glass in Table 1, as well as the set picosecond laser scanning welding parameters, the temperature at the initial point of the welding area with different sizes of R can be calculated when the initial point is again exposed to the laser radiation, as shown in Fig. 4. The calculated results show that the laser focus moves back-and-forth rapidly and repeatedly in a certain size of welding area, and can keep the liquid pool temperature above the melting temperature. It is because each interaction point can radiate heat outward to make the whole region reach a thermal equilibrium with a relatively gentle temperature gradient. In this case, the glass material inside the welding area still remains a molten state to form a region-scale liquid pool. Moreover, the rapidly oscillating scanning welding can also prevent laser energy from continuously accumulating at one point to result in the heat affected zone developing longitudinally along the optical axis and, instead, make the liquid pool expand horizontally to obtain enough melt filling the large gap.

Table 1. Physical Parameters of a Soda-Lime Glass

Properties	Unit	Reference value
Density	g/cm^3	2.53
Refractive index	—	1.520
Heat capacity	J/mol·K	48
Young's modulus	GPa	74
Shear modulus	GPa	29.8
Coefficient of thermal expansion	ppm/K	9.5

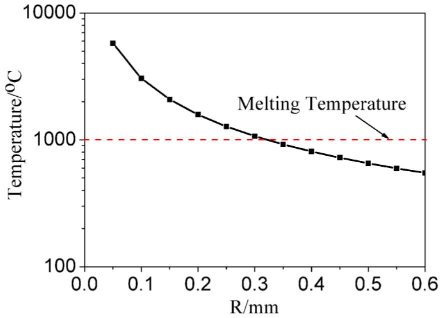

Fig. 4. Calculated temperature at the initial point based on the mathematical model of the instantaneous point source, when it is exposed to the laser again under different radii R.

Finally, the liquid pool can be stirred by a laser beam as electromagnetic, mechanical, and thermal effects generated by reactions of laser and glass material to reduce or even eliminate the defects such as melt material splashes, microcracks, and bubbles. [21], which is beneficial to obtain a high-quality weld structure (shown in Fig. 2).

According to the calculated results in Fig. 4, the radius of the welding area has a great influence on the temperature of the initial point, while the temperature will affect the viscosity of glass. Since the viscosity of the glass in the molten state is 10^4 dPas [24], the temperature of the soda-lime glass in the molten status calculated based on Охотин equation [25] at this time is about 1009 deg, which is the melting temperature. When the radius of the welding area is 0.3 mm, the calculated initial temperature at the starting point of ps laser re-radiation is 1069 deg. This means that the entire laser scanning area is still in a molten state at this time, forming a liquid pool with good fluidity. However, when the radius of the welding area increases to 0.35 mm, the calculated temperature at the initial point decreases to 922 deg. The viscosity at this time is about 10^5 dPas, which increases an order of magnitude. In this case, the fluidity of a partial liquid pool becomes poor, resulting in the generation of some defects such as micro-cracks and bubbles, which may be the main reason of joint strength drop. If the radius continues to increase, the unstable part of the liquid pool will become larger and larger, but there will always be part of an active liquid pool, which may be the reason why the joint strength remains basically constant. However, when the radius is less than 0.3 mm, the temperature of the liquid pool will increase due to the increase of laser energy deposition, resulting in an increase in internal thermal pressure and gas, as well as a weakening of the stirring effect, which is bound to cause partial melt loss such as splashes and gasification. As a result, the joint strength becomes degraded due to the molten filler reduction, just as depicted in Fig. 3.

The method in this Letter not only achieves laser welding of glass with a large gap, but also has an effect of narrowing the contact gap after re-condensation in the welding area, as shown in Fig. 2. This is because during the solidification of the melt, the surface tension will produce an internal solidification shrinkage effect to reduce the contact gap between the two glasses. This contraction effect is a very favorable effect for sealing welding of glass with a large gap, because a narrow contact gap can restrain the heat pressure release and plasma dissipation, as well as reduce the need for molten filler. Figure 5(a) shows a line weld seam obtained by a picosecond laser after reducing the contact gap to less than 3 μm from 10 μm through the rapid oscillating scanning method. It can be seen that there is less spatter around the weld seam, and the whole is more transparent, which indicates that the quality of the weld seam is better. The microstructure of the separated weld observed by SEM is found that the melt is condensed into a whole and relatively compact [as shown in Fig. 5(c)], and the joint strength of the weld seam can reach 25.4 MPa. While in the line welding of glass with a large gap directly, not only does the splash increase a lot, but also the melt is not enough to fill the gap [shown in Fig. 5(b)], and there are many microparticles inside its loose microstructure [as shown in Fig. 5(d)], resulting in an invalid welding.

To sum up, this Letter has proposed a method for welding glasses with a large gap, based on rapid oscillation scanning of a picosecond laser, which breaks the barriers of optical contact

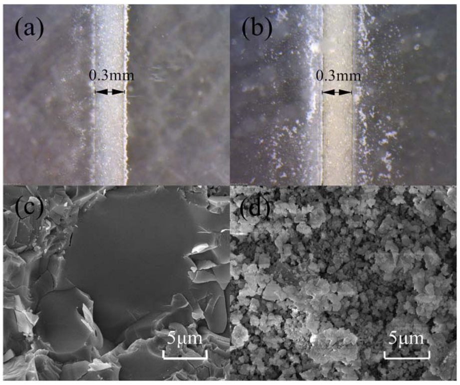

Fig. 5. Top view of the weld line and microstructure under different conditions where (a) and (b) are the welding seam observed through a layer of glass by a microscope, and (c) and (d) are the welding seam photographed by SEM after the sample split apart. (a) and (c) are the condition of the narrowing gap; (b) and (d) are the conditions of natural stacked.

condition and realizes the welding of glass with a 10 μm contact gap successfully. The weld had no defects and a joint strength up to 64 MPa in the state of natural stacked, which greatly reduces the requirement of the glass contact gap and surface roughness, as well as focusing precision. The rapid oscillation scanning mechanism of a picosecond laser was also revealed, and the relationship between the joint strength and welding zone radius *R* was also studied in this Letter. In addition, this method can also effectively reduce the glass contact gap, which lays a foundation for the realization of high-performance continuous welds and large-range sealing welding, and has an important influence on the engineering application of glass welding technology.

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[†]These authors contributed equally to this Letter.

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