A Feasibility Study on the Measurement of the PWS of Butterfly-Type Laser Module Packages Employing a Micro Polygon-Mirror and PSD

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Abstract: The measurement of the relative post-weld-shift (PWS) in the butterfly-type laser module packaging processes is very difficult because the components are very small and the space is very compact. In this paper, we develop a low cost system to study the feasibility on the on-line measurements of PWS in a butterfly-type laser module packaging process. The main components of the system are three 5 mW commercial lasers, three 2-axis position sensing detectors (PSD), and three micro mirrors. The system developed in this paper can measure the three Degrees of Freedom (DOF) of displacement of the optical fiber ferrule after PWS. The displacement measurement system is implemented on a Newport butterfly-type laser diode module package station (Model LW4200) for testing. The resolution of this system is within 1 μm and the accuracy is within 2 μm .

Keywords: Micro displacement; Micro polygon-mirror; PSD; Post weld shift (PWS); Butterfly-type laser module

1. Introduction

Figure 1. Schematic diagram of PWS measurement and compensation for the butterfly module [1]

The butterfly laser module is one of the best systems to use when considering high power output, speed, and reliability. To achieve the above advantages, a good coupling efficiency between the fiber and laser diode is necessary. One of the important factors influencing coupling efficiency is the alignment between the fiber and the laser diode. The butterfly package is assembled by a dual-beam laser welding system that connects the fiber ferrule and laser diode within the package as shown in Figure 1 [1]. A post-weld-shift (PWS) between welded components is caused by the rapid solidification of the welded region. The PWS will reduce the coupling efficiency because of the misalignment between the optical fiber and laser diodes as shown in Figure 2 [2]. To increase the accuracy of the alignment between the fiber and laser diode, online measurement of the PWS is very important. The measured values of

the PWS are used to compensate for the misalignment by plastic deformation or laser hammer. Both methods generally compensate the PWS of the X and Y axes only because the compensations of X and Y axes offer a simple and satisfied solution. Since 2 DOFs are sufficient for the measurement of the PWS, only 3 DOFs are measured in this study.

It is not easy to measure the PWS because there is not enough space for the measurement sensors. To solve this problem, many studies have been undertaken. In 1995, Valk [3] used an eddy current sensor to measure the PWS of a fiber pig tail TO-Can. Hsu et al. [1, 2, 4] used a laser displacement meter to analyze the PWS of

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Figure 2. Coupling efficiency as a function of X, Y, and Z directions [2].

a TO-Can, and used a CCD camera to analyze the PWS of butterfly packaging in 2004–2006. In 2007, Chen [5] used a pyramid-polygon-mirror, laser diodes, and a 2-axis PSD to measure the 6 DOF motion errors of rotary parts. In 2008, Hsu [6] used a high-magnification camera with image capturing system to measure the PWS on-line. In 2010, Liu [7] used a capacitance displacement meter to measure the PWS on-line. Unfortunately,, most of these are quite expensive [1, 2, 4, 6, 7] or require too large a space [5, 8–11] compared with a laser module.

A low cost system is developed in this paper to study the feasibility on the online measurement of 3 DOFs of the PWS in the butterfly-type laser module packaging process.

2. Mechanism of the Displacement Measuring System

This system is designed for measuring the 3 components of displacement (1 rotation and 2 translations) of the ferrule with the optical fiber after PWS. Three 5 mW/ 650 nm commercial lasers, three 2-axis position sensing detectors (PSD), and three micro polygon-mirrors are the main components of this system.

Figure 3. Schematic of the displacement measuring system.

2.1 Concept of the displacement measuring system

As shown in Figure 3, there are three main components in the displacement measuring system: the laser source, the micro polygon-mirror, and the PSD. The laser source and PSD are fixed to the frame. The micro polygon-mirror is placed on a carrier and the carrier is fixed at the ferrule tube. The micro polygon-mirror reflects the laser beam onto the PSD. By tracking the motion of the reflected laser spot, the displacement of the measured object can be calculated. Each 2-axis PSD can offer two signals. Three laser sources, three micro polygon-mirrors, and three PSDs are required to measure 6 DOF displacements of the motion of the object in space.

2.2 The micro polygon-mirror

The micro polygon-mirror is fabricated by grinding the tip of a 125 μm diameter optical glass fiber on a grinding machine, developed by the author, as shown in Figures 4 and 5. The desired profile of the micro

polygon-mirror is produced by controlling the parameters of the material removal rate (MRR) of the optical fiber. A thin gold film is coated on the surface of the micro polygon-mirror to increase the reflectance.

Two kinds of the micro mirrors were developed: the polygon mirror shown in Figure 5(a), and the single-plane mirror shown in Figure 5(b). The polygon-mirror is helpful in finding the edge of the optical fiber if a high-magnification camera with image capturing system [6] is used. However, the measurement space is limited and only one optical microscope can be installed. One optical microscope can not observe the PWS of translations of X and Y axes and rotation of Y axis simultaneously. According to Snell's Law, the micro mirror will reflect the laser light source as a spot on the PSD. A sufficient and clear spot will provide better accuracy of PSD. As the reflection planes increase, the area of reflection decreases. The reflected laser spot, shown in Figure 6, will become small and blurred to be identified by the PSD. A single-plane mirror is used in this study as shown in Figure 5(b).

Figure 4. An optical fiber grinding machine.

(a)

(b)

Figure 5. The micro mirrors: (a) Polygon mirror and (b) Single-plane mirror.

Figure 6. The reflection results with different polygon-mirrors (a) 6 reflection planes (b) 20 reflection planes.

Figure 7. Carrier for Micro Mirrors.

Figure 8. Carrier with micro mirrors on station.

Figure 9. Three PSDs on the Station.

2.3 The carrier for Micro Mirrors

A tungsten carbide carrier has been designed for setting the micro polygon-mirrors. The semicircle profile is produced by wire cutting, and there are nine holes on the surface of the carrier that were fabricated by micro EDM. Three holes in a group with incline angles 45° , 90° , and 135° are located at the middle and on each side of the carrier, as shown in Figure 7. The polygon-mirrors are set on the carrier and then placed on the ferrule as shown in Figure 8. Figure 9 shows three PSDs placed on the Newport butterfly-type laser diode module package station (Model LW4200).

3. The mathematical model

3.1 The definition of displacement

Although only 3 DOFs are measured in this study, a general 6 DOFs solution is derived. The coordinate system $X_0Y_0Z_0$ is defined as the original coordinate system before displacement occurs. The coordinate system $X_nY_nZ_n$ defines the new coordinate system after displacement has occurred. In general, a rigid body displacement in a 3D space has 6 DOFs. The Euler angles (ϕ , θ , ψ) and the translation vector components (a , b , c) are commonly used to define the displacement between the new coordinate system and original coordinate system, as shown in Figure 10.

Figure 10. Definition of coordinate systems.

Figure 11. Euler angle system (3, 2, 3) [12].

3.2 Coordinate transformation matrix

The relationship between the coordinate system $X_0Y_0Z_0$ and the coordinate system $X_nY_nZ_n$ is shown in Figure 11 [12]. First, translate $X_0Y_0Z_0$ to $X'Y'Z'$ by (a, b, c) . Then, the (3, 2, 3) Euler angle convention is used as follows. Rotate $X'Y'Z'$ about Z' by ϕ and get $X''Y''Z''$. Rotate $X''Y''Z''$ about Y'' by θ and get $X'''Y'''Z'''$. Rotate $X'''Y'''Z'''$ about Z''' by ψ and get $X_nY_nZ_n$. The relation between $X_0Y_0Z_0$ and $X_nY_nZ_n$ can be represented by the coordinate transformation matrix nD_0 as below.

$$\begin{aligned} [x_n \ y_n \ z_n \ 1]^T &= [x_0 \ y_0 \ z_0 \ 1]^T [{}^nD_0]^T \\ [{}^nD_0] &= \text{Rot}(\vec{Z}''', \psi) \text{Rot}(\vec{Y}'', \theta) \text{Rot}(\vec{Z}', \phi) \\ &\quad \text{Trans}(a, b, c) \end{aligned} \quad (1)$$

$$[{}^0D_n] = [{}^nD_0]^{-1} \quad (2)$$

The definition of the coordinate axes of the reflection mirror coordinate system is $X_rY_rZ_r$, as shown in Figure 12. The Y_r axis is perpendicular to the plane of the reflection mirror. The Euler angles are defined as (α, β, γ) and the translation vector components are (d, e, f) . The relation between coordinate system $X_rY_rZ_r$ and coordinate system $X_nY_nZ_n$ can be represented as

$$\begin{aligned} [x_n \ y_n \ z_n \ 1]^T &= [x_r \ y_r \ z_r \ 1]^T [{}^nD_r]^T \\ [{}^nD_r] &= \text{Trans}(-d, -e, -f) \\ &\quad \text{Rot}(\vec{Z}_n, -\alpha) \text{Rot}(\vec{Y}_r, -\beta) \text{Rot}(\vec{Z}_r, -\gamma) \end{aligned} \quad (3)$$

$$[{}^0D_r] = [{}^0D_n][{}^nD_r] \quad (4)$$

Figure 12. Mirror Coordinate system $X_rY_rZ_r$.

Similarly, the coordinate system of the PSD, $X_dY_dZ_d$, can be defined by the Euler angles (σ, ρ, τ) , translation vector components (g, h, i) , and coordinate transform matrix 0D_d

$$\begin{aligned} [{}^0D_d] &= \text{Trans}(-g, -h, -i) \\ &\quad \text{Rot}(\vec{Z}_0, -\sigma) \text{Rot}(\vec{Y}_d, -\rho) \text{Rot}(\vec{Z}_d, -\tau) \end{aligned} \quad (5)$$

Figure 13. Relation between Laser source and the reflection plane

3.3 Coordinates of the reflected laser spot

The reflection plane of the micro polygon-mirror is much smaller than the laser spot from the laser pointer, as shown in Figure 13. The center of the reflection plane is set as the position of the laser source. 0R are the coordinates before displacement occurs and ${}^0R'$ are the coordinates after displacement occurs. The relation between the coordinate system 0R and the coordinate system ${}^0R'$ can be represented using a coordinate transform matrix 0D_n

$${}^0R' = [{}^0D_n] {}^0R = [x_{r'} \ y_{r'} \ z_{r'} \ 1]^T \quad (6)$$

Define $\vec{v}_r = [v_{rx} \ v_{ry} \ v_{rz} \ 0]^T$ as the unit normal vector of the reflection plane. According to the coordinate transformation method, the relation is as below.

$$\vec{v}_r = [{}^0D_r] [0 \ 1 \ 0 \ 1]^T - [{}^0D_r] [0 \ 0 \ 0 \ 1]^T \quad (7)$$

Since the angle of incidence is equal to the reflection angle, the unit vector of the reflected laser $\vec{v}_{out}$ is derived as below.

$$\vec{v}_{out} = \vec{v}_{in} - 2(\vec{v}_{in} \cdot \vec{v}_r)\vec{v}_r = [v_{outx} \ v_{outy} \ v_{outz} \ 0]^T \quad (8)$$

where l is the distance that the laser moves. The parametric equation of the reflected laser light is given below.

$$\begin{cases} x = x_{r'} + lv_{outx} \\ y = y_{r'} + lv_{outy} \\ z = z_{r'} + lv_{outz} \end{cases}, \quad l \in R \quad (9)$$

Defining $\vec{v}_s = [v_{sx} \ v_{sy} \ v_{sz} \ 0]^T$ as the unit normal vector of the PSD plane we have

$$\vec{v}_s = [{}^0D_d] [0 \ 0 \ 1 \ 1]^T - [{}^0D_d] [0 \ 0 \ 0 \ 1]^T \quad (10)$$

The coordinates of the center of the PSD are ${}^0S = [x_s \ y_s \ z_s \ 1]^T$. The surface equation can be derived from the unit normal vector and a point on the surface. Therefore, the surface equation of the PSD is obtained as below.

$$v_{sx}(x - x_s) + v_{sy}(y - y_s) + v_{sz}(z - z_s) = 0 \quad (11)$$

Combining equations (7) and (9), the reflection point on the PSD 0T and l_{out} can be derived as below.

$$l_{out} = \frac{v_{sx}(x - x_{r'}) + v_{sy}(y - y_{r'}) + v_{sz}(z - z_{r'})}{v_{sx}v_{outx} + v_{sy}v_{outy} + v_{sz}v_{outz}} \quad (12)$$

The coordinates of the reflection point of the PSD $[x_t \ y_t \ z_t \ 1]^T$ are

$${}^0T = \begin{bmatrix} x_t \\ y_t \\ z_t \\ 1 \end{bmatrix}_{X_0Y_0Z_0} = \begin{bmatrix} x_{r'} + l_{out}v_{outx} \\ y_{r'} + l_{out}v_{outy} \\ z_{r'} + l_{out}v_{outz} \\ 1 \end{bmatrix} \quad (13)$$

The coordinates of 0T can be transformed to the coordinate system of the PSD through the coordinate transformation matrix $[{}^dD_0]$, and should be equal to the data (x_{pi}, y_{pi}) read from the 2-axis PSD. The displacement parameters can be solved by numerical methods.

$$f_i(\phi, \theta, \psi, a, b, c) = 0, \quad i = 1, 2, \dots, 6 \quad (14)$$

The Taylor series of equation (14) is as below.

$$\begin{aligned} & f_i(\phi + h_1, \theta + h_2, \psi + h_3, a + h_4, b + h_5, c + h_6) \\ &= f_i(\phi, \theta, \psi, a, b, c) + \frac{\partial f_i}{\partial \phi} h_1 + \frac{\partial f_i}{\partial \theta} h_2 + \frac{\partial f_i}{\partial \psi} h_3 \\ &+ \frac{\partial f_i}{\partial a} h_4 + \frac{\partial f_i}{\partial b} h_5 + \frac{\partial f_i}{\partial c} h_6 \approx 0 \end{aligned} \quad (15)$$

where $i = 1, 2, \dots, 6$

Equation (15) could be shown as matrix form, $\mathbf{JH} = \mathbf{F}$, as follows.

$$\begin{bmatrix} \frac{\partial f_1}{\partial \phi} & \frac{\partial f_1}{\partial \theta} & \frac{\partial f_1}{\partial \psi} & \frac{\partial f_1}{\partial a} & \frac{\partial f_1}{\partial b} & \frac{\partial f_1}{\partial c} \\ \frac{\partial f_2}{\partial \phi} & \frac{\partial f_2}{\partial \theta} & \frac{\partial f_2}{\partial \psi} & \frac{\partial f_2}{\partial a} & \frac{\partial f_2}{\partial b} & \frac{\partial f_2}{\partial c} \\ \frac{\partial f_3}{\partial \phi} & \frac{\partial f_3}{\partial \theta} & \frac{\partial f_3}{\partial \psi} & \frac{\partial f_3}{\partial a} & \frac{\partial f_3}{\partial b} & \frac{\partial f_3}{\partial c} \\ \frac{\partial f_4}{\partial \phi} & \frac{\partial f_4}{\partial \theta} & \frac{\partial f_4}{\partial \psi} & \frac{\partial f_4}{\partial a} & \frac{\partial f_4}{\partial b} & \frac{\partial f_4}{\partial c} \\ \frac{\partial f_5}{\partial \phi} & \frac{\partial f_5}{\partial \theta} & \frac{\partial f_5}{\partial \psi} & \frac{\partial f_5}{\partial a} & \frac{\partial f_5}{\partial b} & \frac{\partial f_5}{\partial c} \\ \frac{\partial f_6}{\partial \phi} & \frac{\partial f_6}{\partial \theta} & \frac{\partial f_6}{\partial \psi} & \frac{\partial f_6}{\partial a} & \frac{\partial f_6}{\partial b} & \frac{\partial f_6}{\partial c} \end{bmatrix} \begin{bmatrix} h_1 \\ h_2 \\ h_3 \\ h_4 \\ h_5 \\ h_6 \end{bmatrix} = \begin{bmatrix} -f_1 \\ -f_2 \\ -f_3 \\ -f_4 \\ -f_5 \\ -f_6 \end{bmatrix} \quad (16)$$

If the inverse of matrix $\mathbf{J}$ exists, the vector $\mathbf{H}$ is calculated as follows.

$$\mathbf{H} = \begin{bmatrix} h_1 \\ h_2 \\ h_3 \\ h_4 \\ h_5 \\ h_6 \end{bmatrix} = \mathbf{J}^{-1}\mathbf{F} \quad (17)$$

An iterative method is used to calculate the PWS as follows, and can be solved with Wolfram Mathematica software.

$$\begin{bmatrix} \phi \\ \theta \\ \psi \\ a \\ b \\ c \end{bmatrix}_{i+1} = \begin{bmatrix} \phi \\ \theta \\ \psi \\ a \\ b \\ c \end{bmatrix}_i + \mathbf{H} = \begin{bmatrix} \phi \\ \theta \\ \psi \\ a \\ b \\ c \end{bmatrix}_i + \mathbf{J}_i^{-1} \begin{bmatrix} -f_1 \\ -f_2 \\ -f_3 \\ -f_4 \\ -f_5 \\ -f_6 \end{bmatrix} \quad (18)$$

4. Calibration and repeatability

The Newport butterfly-type laser diode module package station (Model LW4200) is used to calibrate and test the repeatability of the displacement measuring system. The resolutions of both the Z_0 and X_0 coupling stages of this system are within $0.01 \mu\text{m}$, and the accuracy is within $0.2 \mu\text{m}$. Three reflection mirrors and three PSDs are setup in the package station as shown in Figure 8 and Figure 9. PSD1 is toward to the $+X_0$ axis and receives the reflected ray from Mirror1. PSD2 is toward to the $-Z_0$ axis and receives the reflected ray from Mirror2. PSD3 is toward to the $-X_0$ axis and receives the reflected ray from Mirror3. All the PSDs are normal to the X_0Z_0 plane. The coordinate parameters of mirrors and PSDs are shown in Table 1 and 2.

Table 1. Coordinate parameters of mirrors

	Mirror1	Mirror2	Mirror3
α	15°	0°	-15°
β	0°	90°	0°
γ	0°	60°	0°

Table 2. Coordinate parameters of PSDs

	PSD1	PSD2	PSD3
σ	0°	0°	0°
ρ	90°	180°	-90°
τ	0°	0°	0°

The testing method involves moving the coupling stage one axis at a time. Since the allowable PWS is $\pm 2 \mu\text{m}$, the testing displacement ranges from $0 \mu\text{m}$ to $40 \mu\text{m}$. Every $5 \mu\text{m}$, the output voltage from the PSD amplifier is recorded; this is repeated several times. The least squares method is used to find the testing results. Taking the testing experiments of the Z_0 axis as an example, only the variations of both x axes of the PSD1 and PSD3 are tested and calibrated since the variations of the y axes are small enough to be neglected. The repeatability, the average of the standard deviations at different positions, is $0.8 \mu\text{m}$ as shown in Figure 14. The calibrating curve is shown in Figure 15. The calibrating curve can be used to calculate the displacement from the output voltage of the PSD.

Figure 14. Repeatability test of PSD1

(a)

(b)

Figure 15. Calibrating curve of the X axis of the (a) PSD1 and (b) PSD3

Figure 16. Repeatability test of PSD2

The standard deviation of the repeatability test of the PSD2 is $4 \mu\text{m}$, as shown in Figure 16. This value is much higher than that of the PSD1 and PSD3. It is found

that the length of the micro polygon-mirror 2 is also much longer than the other two. A small disturbance from the environment will induce a slight vibration on mirror 2, thereby reducing the repeatability.

Similar to the linear displacement, the rotating test is also carried out by changing the rotary axis θ_y from -0.15° to 0.05° by increments of 0.004° . The test shows that the curves of the rotation angle and voltage are almost linear, as shown in Figure 17. This means that the PSD is suitable for measuring small rotational displacements.

Figure 17. Relation between rotation angle and voltage at rotary axis θ_y .

Figure 18. Tilt of the reflection plane.

5. Results of the displacement test

The Newport butterfly-type laser diode module package station (Model LW4200) has a three-axis stage to adjust the ferrule translation along the X_0 and Z_0 axes, and rotation about the Y_0 axis. The stage is moved along each axis one at a time, and readings of all three PSDs are taken simultaneously. Due to the geometry of the system, the reading of PSD 1 should be zero when the stage is moved along the X_0 axis. Likewise, when the stage moves along the Z_0 axis, the reading of PSD 2 should be zero.

The translation results are shown in Tables 3 and 4. The results show that PSD1 and PSD2 fit the displacement measurement, but PSD3 is not satisfactory. The tilt of the reflection plane will induce displacement measurement error in the PSD3, as shown in Figure 18.

The results of the rotation test are shown in Table 5. The results are all reasonable for PSD1, PSD2, and PSD3.

Table 3. Stage movement along X_0 axis.

X axis (μm)	PSD1 (μm)	PSD2 (μm)	PSD3 (μm)
0	0.0	0.0	0.0
5	0.0	-4.9	1.4
10	0.0	-9.8	-4.2
15	-1.8	-14.7	-5.6
20	-1.8	-21.3	-8.4
25	-1.8	-26.2	-11.2
30	-3.6	-31.1	-14.2
35	-3.6	-34.4	-15.4
40	-5.4	-41.0	-18.2
45	-5.4	-45	-22.4
50	-5.4	-49.1	-25.2

Table 4. Stage movement along Z_0 axis.

Z axis (μm)	PSD1 (μm)	PSD2 (μm)	PSD3 (μm)
0	0.0	0.0	0
-5	7.3	0.0	-4.9
-10	12.7	6.6	-9.8
-15	18.2	-3.3	-14.7
-20	21.8	-4.9	-19.6
-25	27.2	-6.6	-25.2
-30	32.7	0.8	-29.4
-35	36.3	-1.6	-36.4
-40	41.7	-4.9	-39.2
-45	47.2	-4.9	-44.8
-50	50.8	-3.3	-49.7

Table 5. Stage rotation about Y_0 axis.

θ (degree)	PSD1 (μm)	PSD2 (μm)	PSD3 (μm)
-0.05	-29.0	-41.7	-18.2
-0.04	-23.6	-32.7	-14.0
-0.03	-18.2	-25.4	-11.2
-0.02	-10.9	-18.2	-7.0
-0.01	-5.4	-9.1	-2.8
0	0.0	0.0	0.0
0.01	5.4	7.3	4.2
0.02	11.8	14.5	8.4
0.03	18.2	23.6	13.3
0.04	23.6	32.7	16.8
0.05	29.0	39.9	19.6

6. Conclusion

The technology of fabricating micro polygon mirrors at the tip of a 125 μm optical glass fiber has been successfully established in this paper. Using commercial 5 mW lasers, commercial position sensing detectors (PSD), and micro polygon mirrors, a low cost displacement measurement system has been developed to study the feasibility on online measurement of the relative PWS in a butterfly-type laser module packaging process. The system developed in this paper has the potential to measure 3 DOFs of the relative displacement of the optical fiber ferrule after post weld shift. The resolution of this system is within 1 μm and the accuracy is around 2 μm . It is good enough as the information for the following compensating process after PWS. It is possible to improve the accuracy of this system by fine-tuning the position and angle of the PSD and reducing the stem length of the micro polygon mirror, but is a very time consuming work. Future study may concentrate on this issue. Furthermore, we believe that the technology of this measurement system can also be applied to observe the displacements of other micro and/or meso scale products.

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