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Automatic optical inspection system for the coupling efficiency of optical fiber with a coupling efficiency contour map

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This study presents a method for the inspection of optical fiber coupling efficiency and alignment system. The device is applied to the three dimensional alignment of the optical connector module of the standard Intel Light Peak. A coupling efficiency contour map for the relationships of fiber microlens off-axis, tilting, and coupling efficiency is established. The system uses CCD cameras for real-time monitoring. The coupling efficiency can be calculated from the image processing and the database comparison methods. A five-axis precision translation stage is used as the platform, which can adjust the axis offset and relative angle to obtain the case of optimal coupling efficiency. With a novel algorithm, the system can determine the direction of off-axis or tilt in order to search for the best position of coupling efficiency. Finally, the smallest movement of the translation stage can be obtained in the database of the Light Peak coupling efficiency.

Keywords: Inspection, Coupling efficiency, Alignment, Off-axis, Image processing

1 Introduction

Intel introduced optical fiber transmission in the 3C connectors of Light Peak, as published in IDF in 2009. Its connotation is to integrate optical fiber cable in most existing universal USB cables; thus, the cable can be used for transmission of electric signals and high-speed transmission of light signals. Intel also developed a new connection mode known as the converged Input/Output (CIO) interface module; the basic principle of which is that two optical fiber terminals are connected using Free Space Optical Interconnects (FSOIs). The entire CIO module comprises three connectors: the optical/electric conversion part (O/E part), a receptacle lens (Re-Lens) and a plug lens[1].

The O/E part mainly plays a role in connecting the optical/electric transceiver module (O/E Module) and optical fiber connector. Another terminal of the optical fiber is connected to the Receptacle Lens, where the front terminal has four plano-convex lenses, which play a role in aligning diffused light scattered from the optical fiber terminal. The Re-Lens also has a set of alignment bolts, which may be connected in alignment with the plug lens. The plug lens has the same number of lens group as the Re-Lens, and may form FSOIs. In addition, the plug lens has a pair of location holes, which can be connected with the location holes of the Re-Lens, in order to ensure that the optical fiber and lens on both sides can maintain the same optical axis. As a result, the lens plays a decisive role in light transmission, can optimize optical alignment quality, and helps to improve coupling efficiency[2-4]. Figure 1 is the assembly diagram of the three connectors.

The Re-Lens integrates optical alignment into the transmission hole of the host computer, while the plug lens is integrated into the transmission connectors of various 3C products. If a user improperly uses or maintains 3C products, the plug lens may cause off-axis or damage to the Re-lens. It is expected that

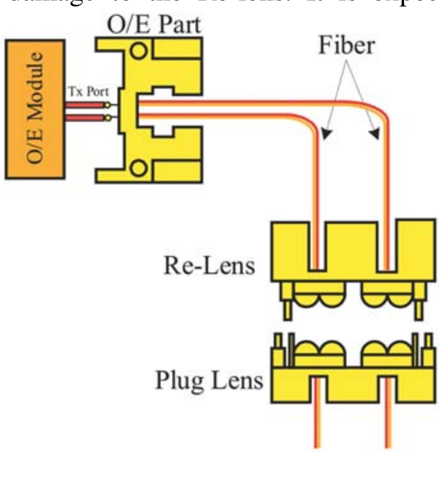


Fig. 1 — Assembly diagram of the three connectors: O/E Part, Re-Lens, Plug Lens.

when a 3C product is connected to a computer, its coupling efficiency can be detected and analyzed for communication quality[5-7].

In the optical transmission structure, the optical fiber, microlens, and coupler, have become indispensable components for optical connectors. The optical fiber not only processes quality, but the optical fiber coupling is also very important in optical fiber transmission, especially for the trend of light, thin, short, and small components. However, as these optical components become increasingly smaller, the optical fiber coupling process is faced with difficulties. The optical fiber core transmits light using the total reflection principle, thus, coupling between optical fibers must be precise and accurate in order that the loss rate in the coupled light transmission is minimized for effective transmission[8-11]. But the traditional fiber coupling methods were not suitable for assembly of the O/E part, Re-Lens, and plug lens.

Blind Search is a search method that was earliest applied in automatic alignment assembly technology, which can be generally divided into the following two forms, as based on the search path: square matrix search and spiral search. The search pattern first randomly selects the starting points and decides the stepping distance, and then conducts a global search according to the selected search method.

Before searching, it is necessary to first decide the default value of the light loss rate, by assuming that when the captured light loss rate is in line with the default value, stop searching, and vice versa. If the default value is still not satisfied after the global search is completed, then continue searching after randomly reselecting the starting points. This method is characterized by global search optimization, but suffers from the weaknesses of inaccurate, time-consuming, labor-consuming and difficult to search the minimum light loss rate.

Assume that the coupling efficiency curve function $f(\mathrm{x})$ is an approximate quadratic function and the maximum coupling efficiency to be calculated is on coordinate X*; however, the search logic of the Swann method is only based on comparison of the two test point functions and only considers the function value sequence, which is independent of their difference value.

In the optical fiber coupling process with automatic optical inspection system [Fig. 2 (a)-(b)], two optical fibers may not be accurately aligned due to various factors, such as shaking, air turbulence, or artificial collision; thus, the coupled light transmission loss rate cannot meet the optical fiber coupling standard. This study captured the light spot image, after optical fiber coupling with the CCD camera, and discussed two inaccurate alignment phenomena in the light of the alignment coupling of the microlens modules (Re-Lens and plug lens) in the light peak connectors: The optical fiber is offset from the lens axis, as shown in Fig. 2 (c); the optical fiber is tilted relative to the lens axis as shown in Fig. 2 (d). This paper also found the relationship between the optical fiber coupling efficiency trend and offset, and designed a system to test the optical fiber coupling efficiency and axis offset, in order to determine the position of optimal coupling efficiency.

2 Coupling Efficiency Database

Coupling efficiency is calculated in advance using the system according to the practical unit movement of the translation stage, where the coupling efficiency of each unit offset of each axis is saved to establish the coupling efficiency database of Light Peak, thus, in future, the offset corresponding to the coupling efficiency of each axis can be compared with the database through continuous images, while the axis position can be immediately determined by judging the offset direction according to the coupling efficiency attenuation trend[12-16].

This study adopted the search method as the database comparison method, which has simple operational steps, can quickly calculate the offset and directly move to the position of the optimal coupling efficiency, facilitates automatic testing, and saves search time. By contrast, the Swann method requires slow and minimum amount of movement Δ, until the optimal coupling efficiency is determined[17-19]. Under the condition, that the basic brightness value is known, the system calculates the brightness value of the images photographed by a camera, via image processing. Assume that the axis offset is d_k, and the system obtains coupling efficiency CE_k via images. Then CE_k is compared with the coupling efficiency CE in the Light Peak database. The corresponding offset is d, if $CE_k=CE$, then the axis offset $d_k=d$; if $CE_k \neq CE$, then the coupling efficiency scope CE_i is determined. The offset corresponding to CE_{i-1} is in the range of $d_i \sim d_{i-1}$, then the offset d_k can be calculated using the interpolation method.

$$d_k = \frac{[(CE_k - CE_{i-1})(d_i - d_{i-1})]}{CE_i - CE_{i-1}} + d_{i-1} \quad \ldots (1)$$

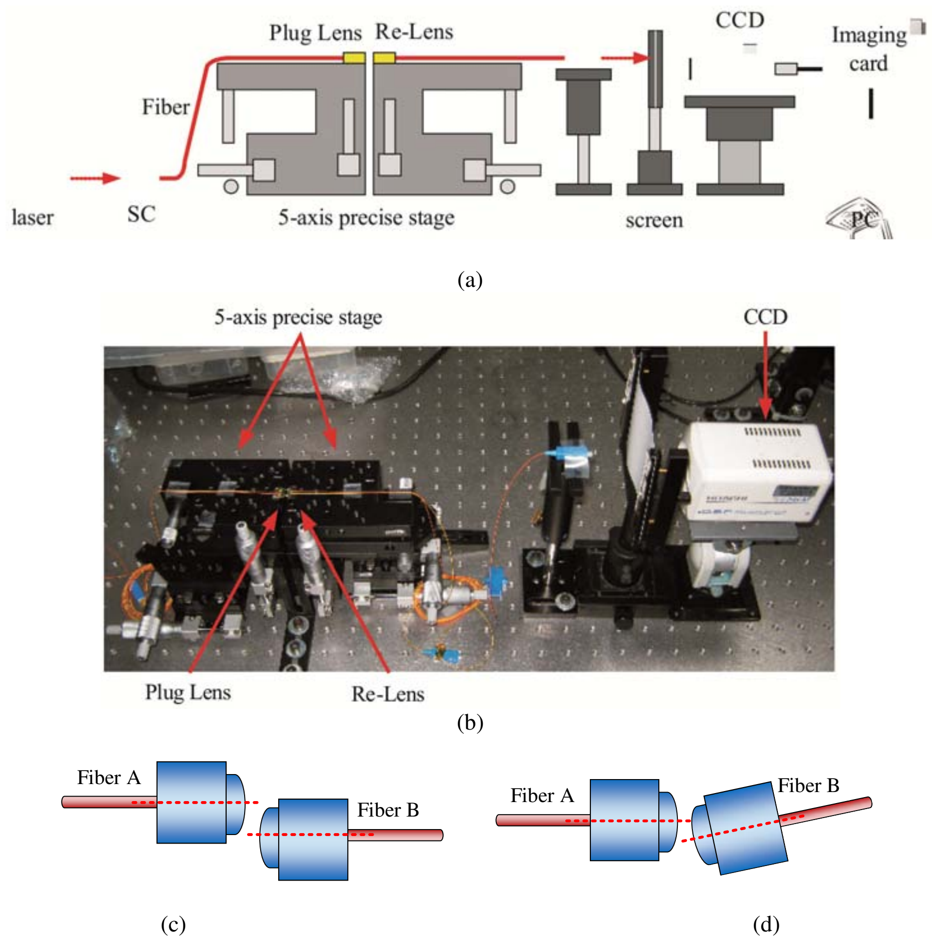


Fig. 2 — (a) An optical fiber coupling process with automatic optical inspection system; (b) the entire experimental structure (c) the optical fiber is offset from the lens axis; (d) the optical fiber is tilted relative to the lens axis.

According to this method, when the system obtains coupling efficiency CE_k, the axis offset d_k in case of offset from X, Y and Z axis or the tilt angle θ_x and θ_y is calculated, as per Eqs (2)~(6).

$$\text{X axis offset}\begin{cases}\text{if } CE_k = CE_X \Rightarrow d_k = d_X \\ \text{else } CE_{i-1} < CE_k < CE_i \Rightarrow d_k \\ \quad = \dfrac{[(CE_k - CE_{i-1})(d_i - d_{i-1})]}{CE_i - CE_{i\text{-}1}} + d_{i-1}\end{cases} \quad \ldots(2)$$

$$\text{Y axis offset}\begin{cases}\text{if } CE_k = CE_Y \Rightarrow d_k = d_Y \\ \text{else } CE_{i-1} < CE_k < CE_i \Rightarrow d_k \\ \quad = \dfrac{[(CE_k - CE_{i-1})(d_i - d_{i-1})]}{CE_i - CE_{i-1}} + d_{i-1}\end{cases} \quad \ldots(3)$$

$$\text{Z axis offset}\begin{cases}\text{if } CE_k = CE_Z \Rightarrow d_k = d_Z \\ \text{else } CE_{i-1} < CE_k < CE_i \Rightarrow d_k \\ \quad = \dfrac{[(CE_k - CE_{i-1})(d_i - d_{i-1})]}{CE_i - CE_{i\text{-}1}} + d_{i-1}\end{cases} \quad \ldots(4)$$

$$\theta_x \text{ offset}\begin{cases}\text{if } CE_k = CE_{Tx} \Rightarrow d_k = d_{Tx} \\ \text{else } CE_{i-1} < CE_k < CE_i \Rightarrow d_k \\ \quad = \dfrac{[(CE_k - CE_{i-1})(d_i - d_{i-1})]}{CE_i - CE_{i\text{-}1}} + d_{i-1}\end{cases} \quad \ldots(5)$$

$$\theta_y \text{ offset}\begin{cases} \text{if } CE_k = CE_{Ty} \Rightarrow d_k = d_{Ty} \\ \text{else } CE_{i-1} < CE_k < CE_i \Rightarrow d_k \\ \quad = \dfrac{[(CE_k - CE_{i-1})(d_i - d_{i-1})]}{CE_i - CE_{i-1}} + d_{i-1} \end{cases} \quad \ldots(6)$$

where CE_X, CE_Y, CE_Z, CE_{TX} and CE_{TY} is the coupling efficiency database, respectively, in the case of offset from X, Y and Z axis, and the tilt angle of θ_x and θ_y. d_X, d_Y, d_Z, d_{TX} and d_{TY} are the corresponding offset, respectively.

3 Direction Judgement

First, the current coupling efficiency CE_k at any position is calculated, and a single axis of the five-axis precision translation stage is specified to rotate positively. After rotation for a short distance, the coupling efficiency CE_{k+1} and offset d_{k+1} are calculated. If $CE_k > CE_{k+1}$, the current position can be judged as a positive offset, and the axis of the five-axis precision translation stage should be negatively rotated by the distance of d_{k+1}. On the contrary, if $CE_k < CE_{k+1}$, the current position can be judged as a negative offset, and the axis of the five-axis precision translation stage should be positively rotated by the distance of d_{k+1}, as shown in Fig. 3(a): the horizontal axis is the offset and longitudinal axis is the coupling efficiency.

If the current coupling efficiency CE_k is in the negative axial position, and falls at the position of the positive axial coupling efficiency CE_{k+1} after positive axial rotation for a short distance, then the first case is when the coupling efficiency is increased, namely $CE_k < CE_{k+1}$, which will be misjudged when the position after positive axial rotation falls at the position of the negative axial coupling efficiency CE_{k+1}. Under the circumstances, after guiding offset d_1 according to the procedure, the position of the optimal coupling efficiency fails to be reached, instead, the coupling efficiency is reduced to the CE_{k+2} position. Then it is judged that $CE_{k+1} > CE_{k+2}$ is in the positive axial direction, the offset d_2 is calculated, and the axis is regressed to the position of the optimal coupling efficiency as shown in Fig. 3(b).

The second case is when coupling efficiency is decreased, namely $CE_k > CE_{k+1}$, the negative axial direction is rotated to the positive axial direction; however, it is still judged as the positive axial direction in accordance with the design rules. After the offset is obtained, the axis can be regressed to the position of the optimal coupling efficiency [Fig. 3 (c)].

Assume that the coupling efficiency function is approximately smooth, then it can be approximated using a polynomial, and the approximate polynomial can be used to estimate the coordinate position of the

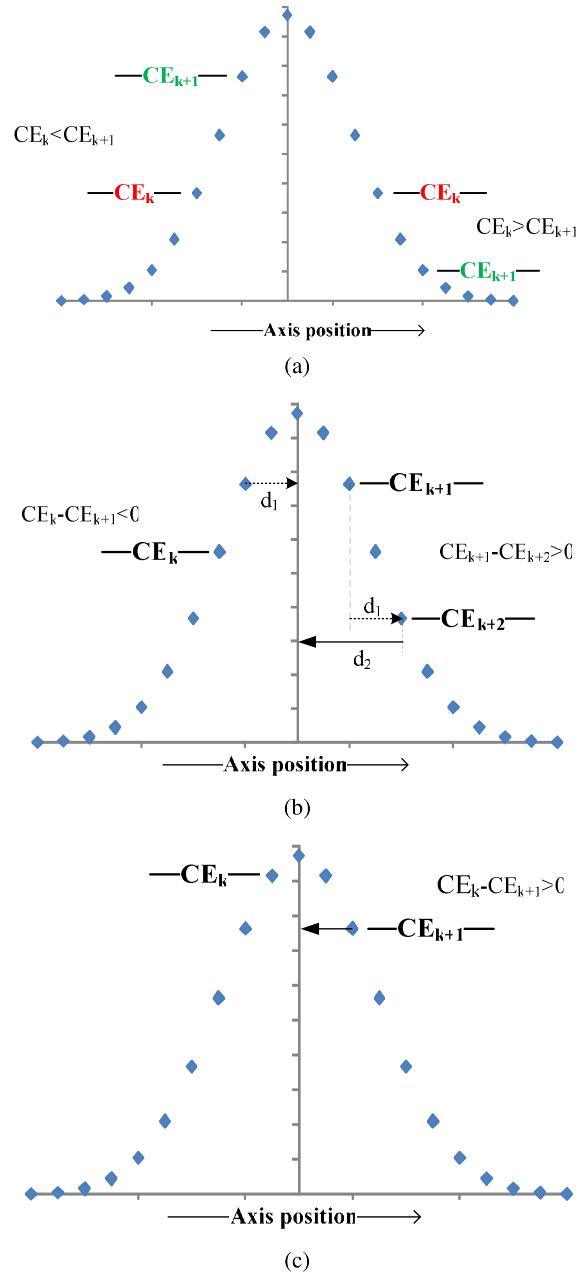


Fig. 3 — (a) A negative offset, and the axis of the five-axis precision translation stage should be positively rotated by the distance of d_{k+1}; (b) the axis is regressed to the position of the optimal coupling efficiency; (c) negative axial direction is rotated to the positive axial direction.

optimal coupling efficiency. The simplest polynomial interpolation is the quadratic approximation method, such as the three coordinate points; x_1, x_2, and x_3, and relative function values f_1, f_2, and f_3 in Fig. 4. After the three constants *a, b,* and *c,* of the quadratic polynomial function are determined, the quadratic function $f(x)$ can be expressed as:

$$f(x) = a + bx + cx^2 \quad \ldots(7)$$

After the three points and their function values are obtained, the constants *a, b,* and *c* are calculated, thus, the quadratic function can be established. Where, the constants *a, b,* and *c* are calculated, as follows:

$$c = \frac{(f_3 - f_1)/(x_3 - x_1) - (f_2 - f_1)/(x_2 - x_1)}{(x_3 - x_2)} \quad \ldots(8)$$

$$b = \frac{f_2 - f_1}{x_2 - x_1} - c(x_1 + x_2) \quad \ldots(9)$$

$$a = f_1 - bx_1 - cx_1^2 \quad \ldots(10)$$

After quadratic function $f(x)$ is established, the coordinate position X* of the optimal coupling efficiency can be calculated, as per the following equation:

$$x^* = -\frac{b}{2c} \quad \ldots(11)$$

Planar alignment in automatic optical fiber alignment is of uniform round contour distribution[20-22]. In theory, the optical fiber transmitting terminal is a point light source. In terms of optical geometry, light scattered from a point light source shall be round, and remain round after expansion under the same distance, that is, when the transmitting terminal moves in a plane, the receiving terminal also reflects the round contour light loss rate[23,24].

In individual cases, X and Y axis are searched with the quadratic approximation method; by first searching the best position of the X axis and then searching the best position of the Y axis, in order to determine the best position of the plane. Then assume that this point is the best coupling efficiency point of the plane.

Plug lens and Re-Lens axis alignment is simulated using optical simulation software Zemax. The coupling efficiency loss trend diagram is simulated, respectively, by the offset from the X axis only and the Y axis only of the plug lens. Where, the horizontal axis represents the offset from the X axis, while the longitudinal axis represents the offset from the Y axis. In this way, the coupling efficiency contour map is obtained as shown in Fig. 5.

In the coupling efficiency contour map of X axis to Y axis, when the axial offset is increased, the coupling efficiency is reduced. Based on this feature, the optimal coupling efficiency position, namely, the original point position in Fig. 5 is obtained in the 2D coupling efficiency contour map.

If the axis position of the plug lens is (x_n, y_n), the first positive offset of a short distance d_{mx} towards the X axis is specified, if the coupling efficiency is increased, it can be known that (x_n,y_n) is in the left half-plane; if the coupling efficiency is decreased, it can be known that (x_n,y_n) is in the right half-plane.

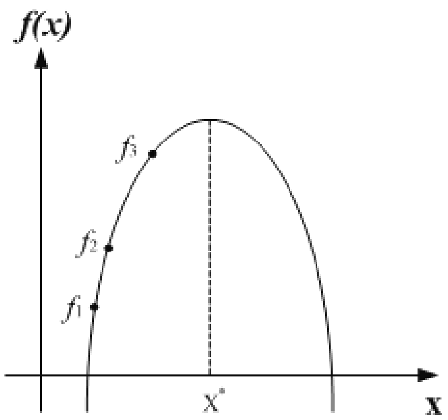


Fig. 4 — Quadratic approximation method and relative functional values f_1, f_2, and f_3

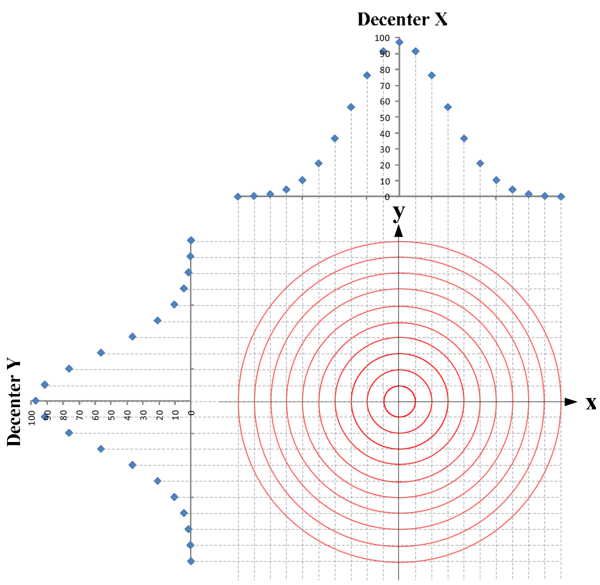


Fig. 5 — Coupling efficiency contour map of X-Y offset

The offset d_{kx} is calculated by comparison with the X-axis database, and is regressed in the opposite direction. If the coupling efficiency is lower than the desired coupling efficiency threshold value, then it is judged to have offset from the Y axis. The optimal coupling efficiency position on the X axis is calculated using the quadratic approximation method. If the coupling efficiency is increased after positive offset of a short distance d_{my} towards the Y axis, then it can be known that (x_n,y_n) is in the lower half-plane; if the coupling efficiency is decreased, then it can be known that (x_n,y_n) is in the upper half-plane. The offset d_{ky} is calculated by comparison with the Y axis database, and is regressed in the opposite direction, in order that the optimal coupling efficiency position of the XY plane is obtained.

When (x_n,y_n) is in different quadrants, the approach for finding the optimal coupling efficiency will be different; however, the judgment method is the same. There are four approaches as shown in Fig. 6.

If axis of the plug lens is first tilted downward by $\theta°$, then the coupling efficiency loss trend diagram is simulated, respectively, by the offset from X axis and Y axis only. Where, the horizontal axis represents the offset from the X axis, while the longitudinal axis represents the offset from the Y axis. In this way, the coupling efficiency contour map is obtained, as shown in Fig. 7(a). As can be seen from the

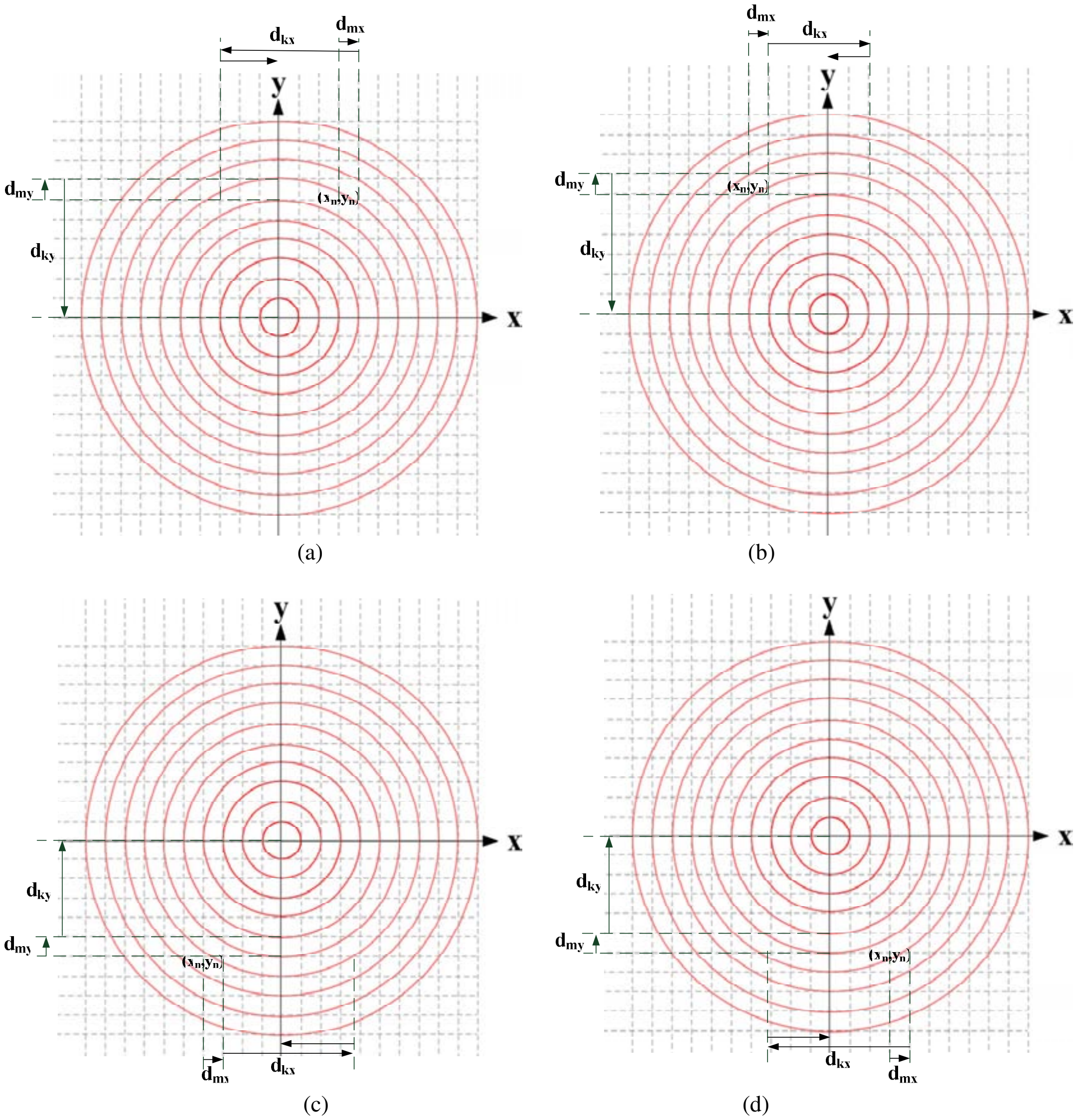


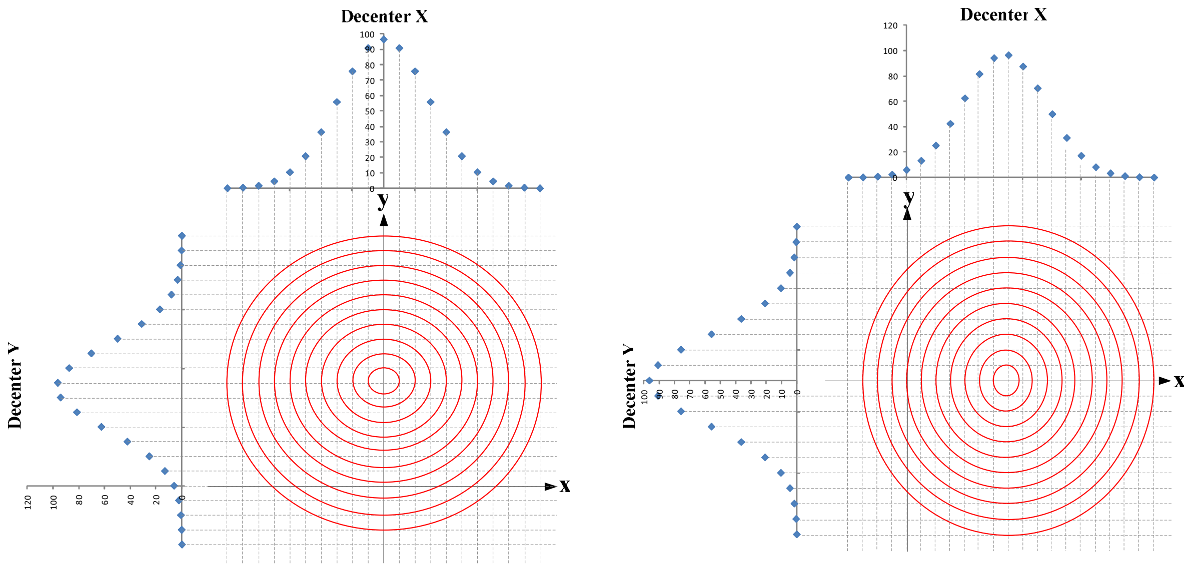
Fig. 6 — Approach for finding the optimal coupling efficiency in different quadrants: (a) quadrant I; (b) quadrant II; (c) quadrant III; and (d) quadrant IV.

comparison with the coupling efficiency contour map without tilt, the optimal coupling efficiency is not at the original point, but moves upward to d_{ty}. Based on this feature, whether the axis of the plug lens is tilted is judged.

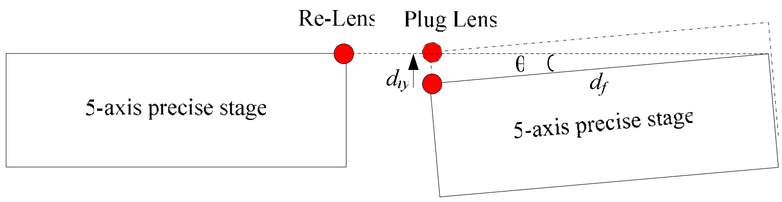
After the distance d_{ty} from the optimal coupling efficiency position to the original point and the length d_f of the five-axis precision translation stage are obtained, tilt angle θ can be calculated as per Eq. (12) and shown in Fig. 7(b).

$$\theta = \sin^{-1}\left(\frac{d_{ty}}{d_f}\right) \quad \ldots(12)$$

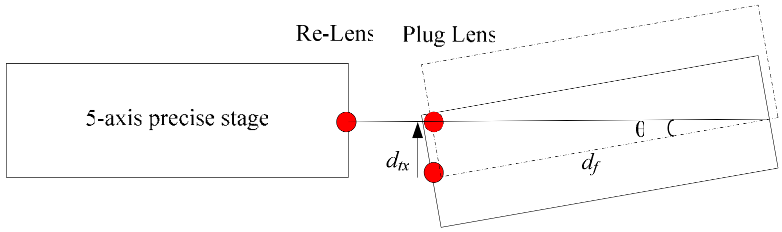
If the axis of the plug lens is first tilted leftwards by θ°, then the coupling efficiency loss trend diagram is simulated, respectively, by the offset from X axis and Y axis only. Where, the horizontal axis represents the offset from the X axis, while the longitudinal axis represents the offset from the Y axis. In this way, the coupling efficiency contour map is obtained, as shown in Fig. 7(c). As can be seen from the comparison with the coupling efficiency contour map without tilt, the optimal coupling efficiency is not at the original point, but moves rightwards to d_{tx}. Based on this feature, whether the axis of the plug lens is tilted is judged[25,26].



(b)



(c)



(d)

Fig. 7 — (a) Horizontal axis represents the offset from the X axis, while the longitudinal axis represents the offset from the Y axis; (b) tilt angle θ can be calculated; (c) the longitudinal axis represents the offset from the Y axis; and (d) dislocation d_f of the five-axis precision translation stage are obtained.

After distance d_{tx} from the optimal coupling efficiency position to the original point, and dislocation d_f of the five-axis precision translation stage are obtained, tilt angle θ can be calculated, as per Eq. (13), and shown in Fig. 7(d).

$$\theta = \sin^{-1}\left(\frac{d_{tx}}{d_f}\right) \quad \ldots(13)$$

First, after off-axis correction with a two-dimensional XY plane, the position of coupling efficiency (x_i, y_i) is reached. If (x_i, y_i) is on the +Y axis of the coupling efficiency contour map, then it can be judged that axis of the plug lens is tilted downwards by θ°; if (x_i, y_i) is on the -Y axis of the coupling efficiency contour map, then it can be judged that axis of the plug lens is tilted upwards by θ°; if (x_i, y_i) is on the +X axis of the coupling efficiency contour map, then it can be judged that axis of the plug lens is tilted leftwards by θ°; if (x_i, y_i) is on the -X axis of the coupling efficiency contour map, then it can be judged that axis of the plug lens is tilted rightwards by θ°. Then the best coupling efficiency and its position can be obtained after regression of θ° in opposite direction and adjustment of offset d_t in the opposite direction.

4 Experimental Results

Plug lens and Re-Lens are connected with optical fibers through optical fiber connectors, respectively. A laser light device is in the input terminal of the optical fiber connector, and the laser light is transmitted through the optical fiber. The plug lens diffuse and transmit a parallel laser, while the Re-Lens focuses and couples the laser into an optical fiber, and finally, the output terminal of the optical fiber connector projects the laser onto the screen. The CCD camera captures screen images, which are converted to digital signals by the image capture card, sent to the computer and detected by self-designed program, as shown in the entire experimental structure in Fig. 2(b).

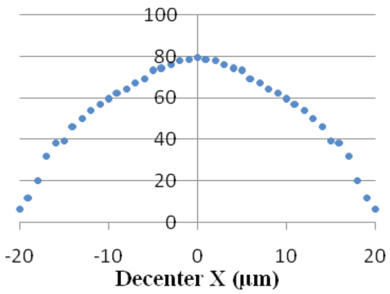
First, it is necessary to adjust the height and parallelism of two five-axis precision platforms, with the plug lens in the same axis as the Re-Lens. Here, the coupling efficiency is the best. Images captured through cameras are sent to the computer. When the plug lens and Re-Lens have off-axis or tilt, the system will calculate the coupling efficiency and estimate the axis offset or tilt angle.

The optical fiber used in this study is multimode optical fiber, where the diameter of its coating layer is 125 μm, and diameter of its core is 9 μm. The light signal transmission depends on the optical fiber core. The traditional optical fiber is aligned by welding, thus, when the traditional optical fiber is aligned, the biggest offset from X and Y axis is about 4.5 μm. Light Peak is additionally provided with a plug lens and Re-Lens microlens module, where the light signal is transmitted after amplification in order to expand the maximum offset scope of light transmission. After signal amplification through the microlens module, the maximum acceptable offset from X and Y axis is 20 μm, which is about five times that of the traditional welding method. However, in terms of the optical transmission quality, generally enterprises can accept the lowest coupling efficiency of more than 60~70%. As can be seen from the experiment, when the Light Peak microlens module is 10 μm from the axis or tilted by 0.0078°, the coupling efficiency remains at about 60%. Thus, the allowable offset advantages of FSOIs can be seen.

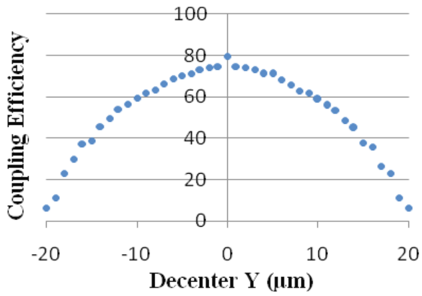
The detection method in this study is active optical fiber coupling detection, with a red laser as the light source. The laser light device is provided in the input terminal of the optical fiber connector, and laser light is transmitted through the optical fiber. The plug lens diffuses and transmits a parallel laser, while the Re-Lens focuses and couples the laser into an optical fiber, isolates the coupled light points in the images from the background using the image processing method[27] and calculates the average grey scale value of the coupling light points, which is defined as the optical power value. The brightness value of the images is recorded under the conditions that the laser is not coupled with optical fiber, and is taken as the basic optical power value. According to this basic value, the coupling efficiency is calculated after the axis of the plug lens is aligned with that of the Re-Lens. The coupling efficiency is calculated based on the unit amount of movement towards each axial direction, and then a database is established. The optical fiber alignment offset is obtained through comparison with the data in the database. A single axial direction is guided through the program, and is pre-established as a positive axial rotation. The coupling efficiency trend of positive and negative offset from each axis is symmetrical, thus, the axial direction can be obtained by the coupling efficiency changes and then the axis position is searched. First, the axis position of the optimal coupling efficiency is searched on the XY plane, the angle of the tilted axis is corrected, finally, the Z axis database is compared, and the offset from the Z axis is calculated, in order that the best coupling efficiency position of the plug lens and Re-Lens can be determined (method #1).

Theoretically, according to measured coupling efficiency data, regardless of positive or negative directions on the same axis, an equal distance from the axis means equal efficiency; however, due to experimental error, equal distance (within 2 µm) does not correspond to equal efficiency, thus, after many experiments, the symmetrical positive and negative axial data are averaged, and established as a database (method #2). For example, Fig. 8(a-d) shows the coupling efficiency database of offset from X, Y, and Z axis; Fig. 8(e-f) shows the coupling efficiency database of tilt angles θ_x and θ_y.

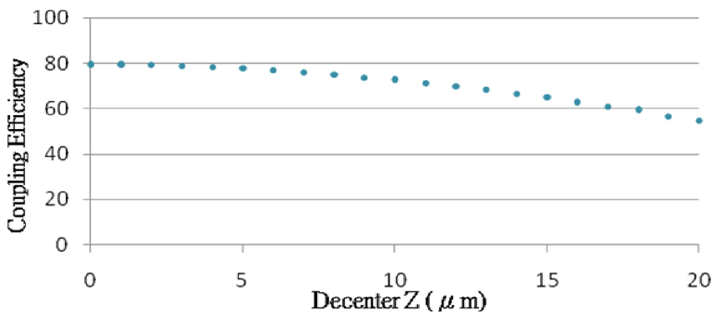
Figure 9 shows the comparison of the method #1 and method #2 in coupling efficiency, as measured by images: The average efficiency difference of offset from the X axis is 1.95%, the average efficiency difference of offset from the Y axis is 1.92%, the average efficiency difference of offset from the Z axis is 1.9%, the average efficiency difference of tilt angle θ_x is 2.2%, and the average efficiency difference of tilt angle θ_y is 2.6%. The experimental results showed



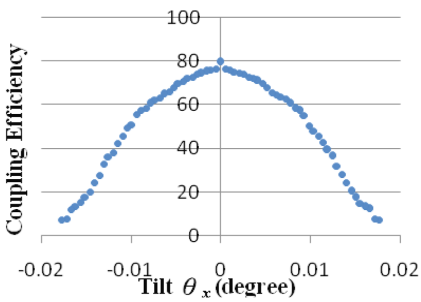
(a) X offset



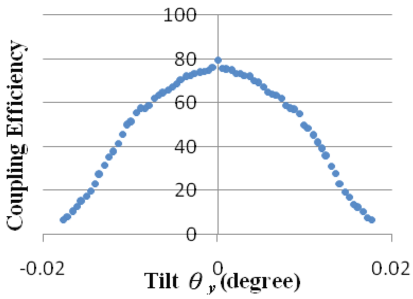
(b) Y pffset



(c) Z offset



(d) θ_x offset



(e) θ_y offset

Fig. 8 — Coupling efficiency database of offset from (a) X, (b)Y, and (c) Z axis; the coupling efficiency database of tilt angles (e) θ_x and (f) θ_y.

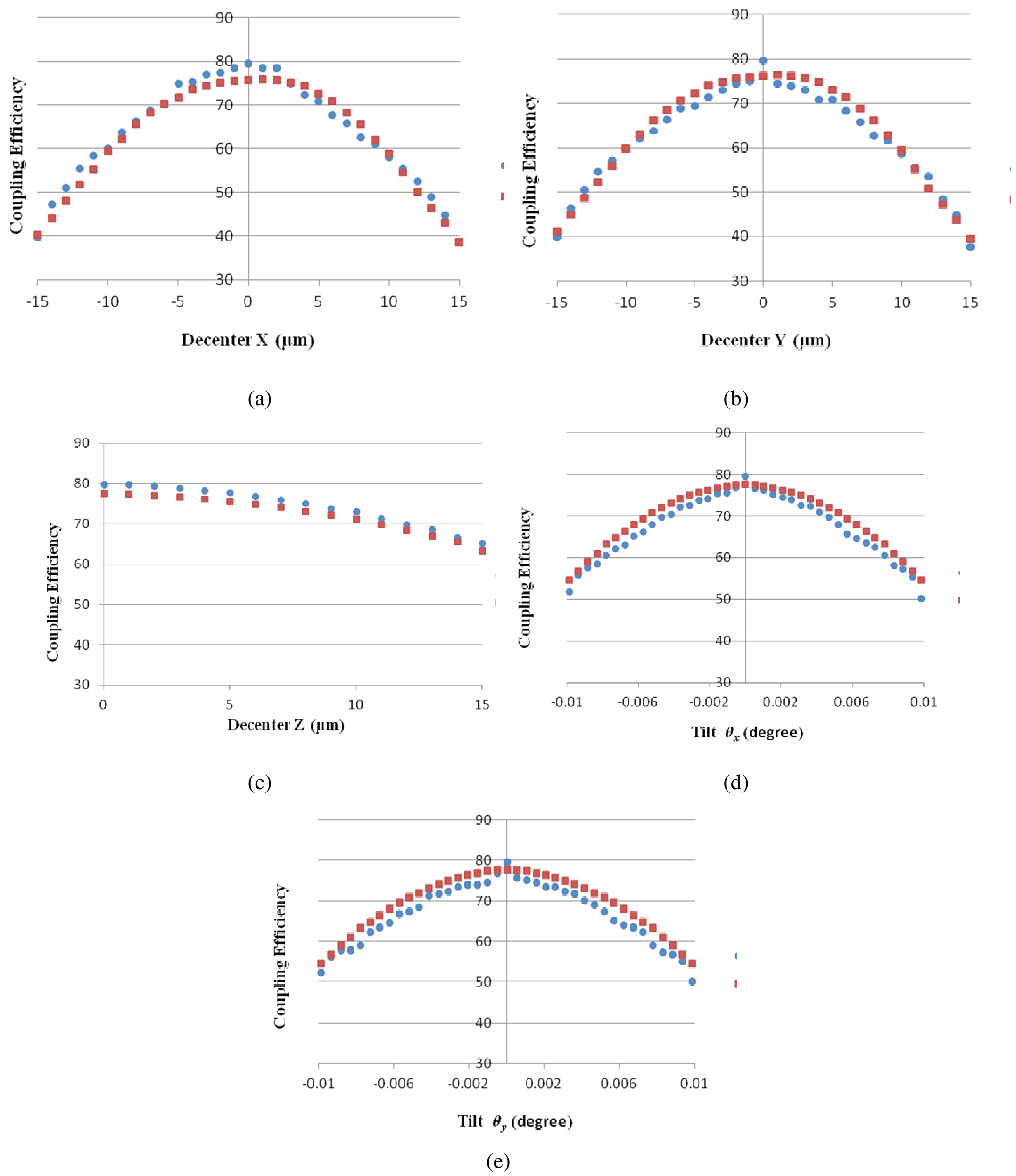


Fig. 9 — Comparison of the method #1 (blue mark) and method #2 (red mark) in coupling efficiency.

that the efficiency detected by the two detection methods is quite close, thus, the coupling light spot measurement by images has high feasibility.

5 Conclusions

This study integrates axial offset in various directions, thus, the system is fast, accurate, and continuous. As compared to the spiral-search routine with a 37-s average alignment time to attach single-mode optical fibers to laser diodes[28], this system guides the movement information through the program in order to avoid blind calibration during optical fiber alignment, and reduces the time consumption for alignment. Its precision can reach 1~2 μm, and its coupling efficiency precision can be within 2~3% error with a 30-s average alignment time.

Acknowledgement

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