Stability effects on optical component assembly and measurement using an automation system

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ABSTRACT

Alignment stability, maintaining a minimum loss state in optical power during product fabrication, is one factor in evaluating processes and equipment for assembly and testing of fiber-optic/optical components. Cost reduction through yield improvement will require some level of alignment automation. To illustrate the changes in optical power over time and dimensional change, a 6-axis commercially available alignment robot has been characterized by aligning a single mode fiber to a single mode fiber and to a planar lightguide circuit. Optical and mechanical performance (resolution, repeatability, and stability) is presented and correlated. External factors affecting the automation system's optical performance are discussed.

Keywords: stability, repeatability, resolution, sensitivity, optical power, fiber alignment, alignment robot

1. INTRODUCTION

The telecommunication market is evolving under many different pressures from business and capacity issues to technology issues. A major element of the evolution is conversion to optical networks for certain markets. With respect to those optical networks and regardless of what the drivers are, it seems clear that some level of automation will be needed in the optical network components fabrication processes. Costs need to be reduced. Yields and reliability need improvement. Eventually throughput to meet future demand will become a major factor. The technology of connecting photon-transmitting devices requires a level of alignment far more critical than connecting wires for current flow and at dimensions associated with integrated chip manufacture.

This paper will discuss one small but critical aspect of automating the technology, alignment stability. Two critical steps in the manufacturing processes require some level of alignment and stability. Emulating the semiconductor process form, the process itself is measured by evaluating components at the chip level. This allows early process changes to improve yield and eliminates defective product before more costs can be incurred. The second step is the actual connection of the optical element to a larger system. In both steps, signal losses and signal change over time from the alignment mechanism are important parameters to the system designers and fabricators.

Signal change or optical signal loss, expressed as relative dB loss over time under varying conditions, will be reviewed[1] and related to alignment issues. Dimensional data will be presented that are important to the design of alignment systems and reinforces the optical performance data presented. Ultimately the system designer must choose the levels of loss that can be tolerated. This is influenced by factors ranging from the number of connections to cost limits in achieving those final few percent improvements. This in turn allows the process designer to make choices in the process and equipment from a tool assisted manual station to an automated work cell.

Underlying the alignment stability are other factors influencing the optical signal loss. The alignment challenge is to mate parts with micrometer dimensions, dissimilar cross-sections, different numerical apertures, multiple refractive index changes, and hold optical power losses to a minimum. For example, the most commonly used component is a single mode fiber (SMF) with a round active area of 5 to 9 micrometers in diameter. Another typical component is a planar lightguide circuit (PLC), which may have square or rectangular cross-sectional active area with typical size of 3 to 8 micrometers on each side. A simple connection among SMFs and PLCs will result in four different matching combinations: round to round, square to square, round to square, and square to round.

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The stability challenge is to hold the alignment or at least not to contribute drift over a period of time. A typical process node can include alignment to optimize power, displacement for a process step, and then return to the optimized power location. Another process requirement can be holding position for minutes during a bonding process. A typical quality process can include optimizing for power and then holding position while 20 minutes of measurements are performed.

The device under characterization is an alignment robot capable of six degrees of movement. It is one element in a set-up whose performance can be influenced by positioning fixtures, mounting hardware, baseplates, vibration, temperature changes, and operator techniques, to identify a few variables. Experimental optical performance data will be used to explain the robot's contribution to the overall alignment stability and where possible the contributions of other external parameters and variables. The robot's mechanical performance will be correlated with the system's optical performance.

As noted by Ragona, yield is the main contributor to cost reduction and outweighs equipment costs, throughput, and maintenance at high utilization rates.[2] Yield is greatly influenced by maintaining an optimum optical connection during processing. What should be considered to maintain that optimum setting? *Stability* in the short term of less than a second is important for reproducible measurement of power. *Stability* in the long term of 10 to 20 minutes is critical for adhesive bonding and/or device characterization. *Bi-directional repeatability* allows movements off the initial alignment position for verification of optimal point, intermediate assembly task, or change of part and return to the initial alignment position. *Resolution* is an indication of the sensitivity of the system to controlled changes. The resolution, repeatability, and stability are important in both the optical and mechanical domains.

Some of the fundamental process design factors to consider and evaluate in improving yield relative to alignment and stability over time are effects of:

- Geometrical convolution of the active areas being aligned
- Index matching media in eliminating interferometric power level changes
- Materials used in the entire alignment system and the collective changes in response to environmental changes
- Repeatability from a displacement back to the optimum power level
- Resolution or how sensitive does the system need to be to hold peak power.

2. SETUP

A commercially available 6-axis alignment robot (FR-3000 NanoRobot™ system by EXFO) is used for the study. Two different setups are constructed in characterizing the alignment robot's mechanical performance and the optical performance of the automation/alignment system, respectively. The block diagram of the setups and their descriptions are shown in the following.

2.1 Interferometer setup

To measure the mechanical resolution, repeatability, and stability of an alignment robot, a typical interferometer measurement setup on a vibration isolation table is used, as shown in Fig. 1. The laser head and detector is the Hewlett Packard 5518A. The incoming laser travels through the interferometer (Hewlett Packard 10766A Linear Interferometer) and splits into two paths. One beam is reflected by the retro-reflector (Hewlett Packard 10767A Linear Retro-reflector) mounted on the alignment robot, and the other is reflected by a similar retro-reflector attached on the interferometer as a reference. The interference fringes between the reflected target beam and the reflected reference beam are sensed by the detector and the linear displacement of the alignment robot is obtained.

2.2 Setup for measuring optical power transmission

To characterize the alignment system's optical resolution, repeatability, and stability, the configuration shown in Fig. 2 is employed.[1] The optical power transmission is measured between two fiber arrays on a vibration isolation table. (Similarly, this setup is used for measuring the optical power transmission from a PLC to a fiber array.) The fixed fiber array (or PLC), used as a sender, is mounted on a fixture and breadboard, which is made of either aluminum or steel. Another fiber array, used as a receiver, is mounted on the alignment robot facing the first one. Each fiber array contains several ~ 9 µm diameter SMFs. During the experiment, only one SMF on each fiber array is lighted. An EXFO FLS-2100 Optical Light Source with 1550 nm wavelength selected is connected to the fixed or sender element.

The transmitted light power is measured by an EXFO PM1600 High Speed Power Meter attached to the moving receiver element. During the measurements, the ambient temperature is monitored by a thermometer with resolution of 0.1 °C.

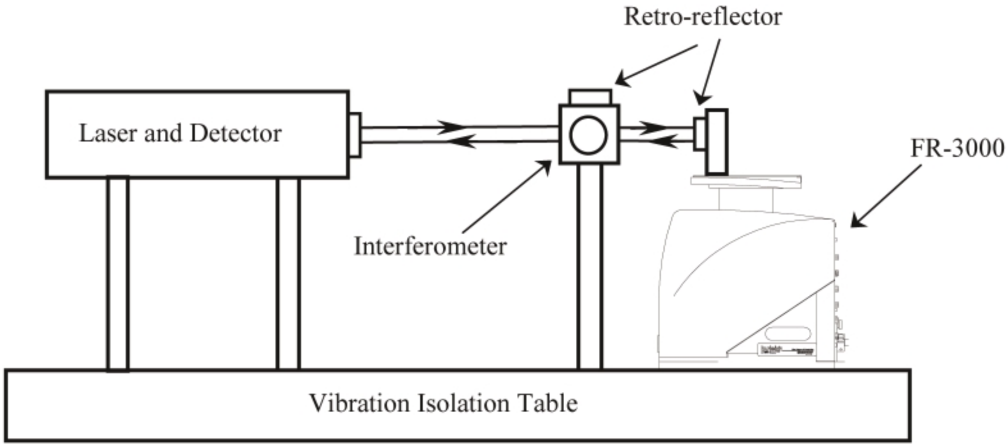

Figure 1: The setup for measuring mechanical performance of the alignment robot.

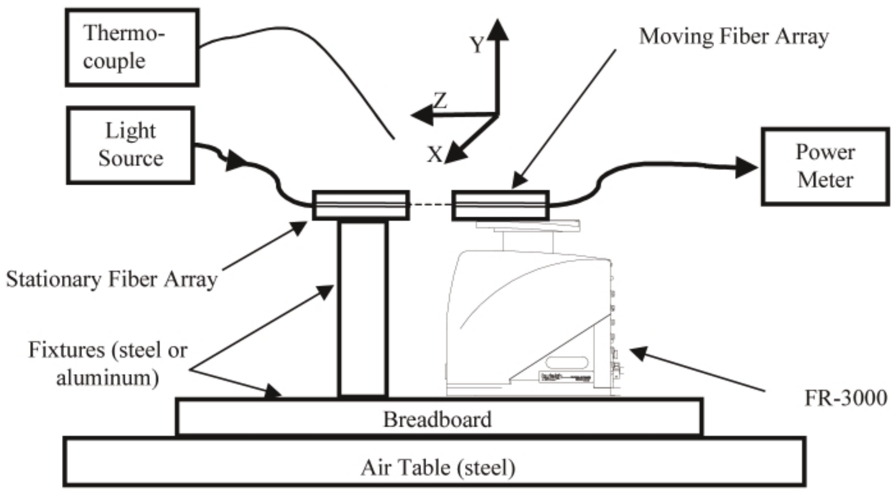

Figure 2: The setup for measuring optical power through fiber arrays.

3. RESULTS AND DISCUSSION

Optical performance is a key discriminator for fiber assembly process evaluation and analysis. Mechanical performance of the alignment robot is an underlying parameter contributing to the optical results. In this section, we discuss a typical alignment robot's mechanical performance, and how it relates to the whole systems' optical performance. The discussion will use experimental data to illustrate the points. For simplicity, the robot's performance is examined using the orthogonal linear axes (X, Y, and Z) only. A brief discussion on the effects of rotational axes[3] can be found in the Reference section.

3.1 Mechanical resolution, optical power distribution, and optical resolution/sensitivity

3.1.1 Resolution

Optical resolution is one component in assessing optical performance of an alignment system. Optical resolution is defined to be the minimum discernable optical power change. In theory, optical power resolution is directly related to the alignment robot's closed loop mechanical resolution, and this is especially true when the alignment system's mechanical closed loop resolution is not fine enough. However, when the alignment robot's closed loop resolution is fine, the optical resolution will be affected by many other external factors before mechanical resolution becomes critical. Several major external factors are the noise floor of the measurement system (e.g., the light source stability), geometrical convolution of the active areas being aligned, and the effect of index matching media.

Mechanical resolution is the smallest incremental movement that can be attained by each axis. There is a difference between resolution of each mechanical element (stage) and the robot's performance that is an amalgam of 6 elements. This minimum step size or resolution can vary significantly from 10 to 500 nm depending on the feedback methods used.[4] The feedback encoder resolution for each individual linear axis of this robot (FR-3000) is 20 nm. Ideally, the mechanical closed loop resolution at the platform top of FR-3000 should be 20 nm. However, the robot performance at each axis may not be the same as that of the corresponding single stage, due to Abbe error and other factors. In order to quantitatively measure the mechanical resolution of the alignment robot, the interferometer setup shown in Sec. 2.1 is used to record the linear motion at the robot platform top, while the robot is commanded to move one encoder step at a time in the same linear axis. The sampling time in between neighboring steps is 1 second to allow ample time for the robot to settle down. A four-cycle / nominal range of 100 nm (5 steps for each direction) movement at the platform top is recorded by the interferometer, as shown in Fig. 3.

Statistical analysis of the data shows that each step at the platform top is 21 nm ± 3 nm, and therefore verifies that the alignment system's linear axis resolution is truly about 20 nm. The majority of the noise is due to the background vibration noise. It is directly measured to be 5 nm in 2 Sigma, when the alignment robot stands still with the closed loop feedback remaining active. This number is actually the short-term mechanical stability, which will be discussed later in Sec. 3.3. In addition, the noise floor of the interferometer measurement itself is determined to be quite small (< 1 or 2 nm); this is measured with 2 retro-reflectors attached to the interferometer to simulate (almost perfectly) a no physical displacement scenario. Since the time duration for the whole measurement is less than 50 seconds, the slow thermal expansion effects due to temperature changes are a negligible contributor to the measured 2 Sigma noise of 6 nm.

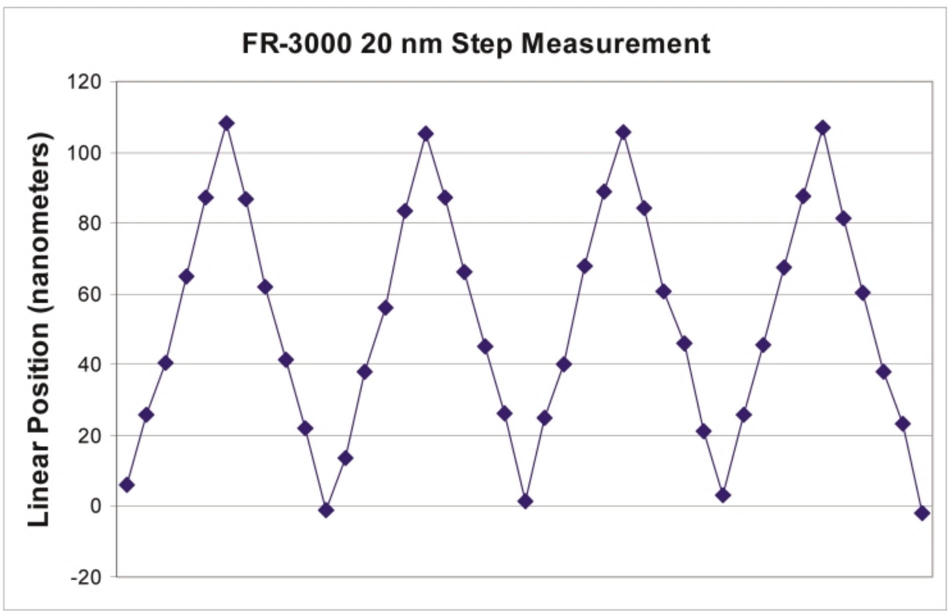

Figure 3: 20 nm step measurement.

3.1.2 Shape convolution and index matching fluid

The cross-sectional areas of the optical components and the gap media (air or index matching fluid) have an impact on the optical power sensitivities to positional displacement between mating components. In this study, the SMFs (in fiber arrays) are ~ 9 µm in diameter and the PLCs are ~ 4 µm× 4 µm in cross-sectional area. The index matching fluid used is made by Norland (Part Number: 9006 IML 150 and index of refraction: 1.52). In the experiment, the SMF target element, mounted on the alignment robot, is commanded to move 100 nm per step radial direction (either X or Y) across the peak optical power position, which was previously located. The transmitted optical power is measured from a SMF to a SMF and from a PLC to a SMF as a function of radial displacement between the source and target elements, for both air gap and with index matching fluid.1 The relative optical power in dB (normalized for each case) is plotted in Fig. 4.

The optical sensitivity to positional changes is high a couple micrometers or more away from the peak position, while it is very low at near the optical power peak position for all 4 cases. This low optical sensitivity is similar to a dead-band where change of displacement has little effect on the parameter of concern (optical power). By comparing the cases for SMF to SMF with cases for PLC to SMF and by comparing the index match cases with air gap cases, it is evident that both the use of a PLC and the use of index matching fluid increase the optical power sensitivity to positional changes at the optical peak position. The index matching fluid prevents the light from spreading,5 and therefore provides an equivalently sharper light beam than the cases without index matching fluid. The PLC has a smaller cross-sectional area than a SMF. In both cases, the final transmitted optical power is (in a complex form) a convolution between the source and target. The combined effects lead to narrower optical power peaks and higher sensitivities to positional changes.

Figure 5 shows the data in finer detail to better illustrate the sensitivity at the optical power peak position from Fig. 4. For simplicity, only the optical power for SMF to SMF vs. radial displacement (measured at 20 nm per step) is shown. The optical power sensitivity is not a constant. Here, we specify the sensitivity as the optical power change for a displacement of 100 nm from the peak position. The optical power sensitivity is ~ 0.01 dB/100 nm for SMF to SMF with index matching fluid used. For the air gap case, the sensitivity is somewhat lower, but difficult to be exactly quantified due to the noisier signal (about 0.03 dB in 2 Sigma noise). The optical power vs. radial displacement for PLC to SMF was also measured. The optical power sensitivity for PLC to SMF with index matching is ~ 0.02 dB/100 nm. Similarly as shown in Fig. 5, for the air gap case, the sensitivity is somewhat lower than that of the index matched case (< 0.02 dB/100 nm), but the signal is noisier. The noisy optical power for the air gap cases has a fundamental physical reason, as will be explained in Sec. 3.1.3.

The optical power sensitivity (0.01 or 0.02 dB/100 nm) will determine the optical resolution, only if a minimum mechanical step change can cause significant optical signal changes, compared with the noise floor of the system. Since the alignment robot has 20 nm positional closed loop resolution, and the light source stability is ~ 0.006 dB, the mechanical resolution in the radial axis (X and Y) is not a determinant factor[6] for the optical resolution at the peak optical power location. As the receiver element deviates from the peak location (or dead-band), the sensitivity of optical power change to position change increases dramatically (e.g., 0.03 dB/100 nm at 1 µm away from the peak power location for the index matched case in Fig. 5). A 20 nm positional step can cause detectable optical power changes.

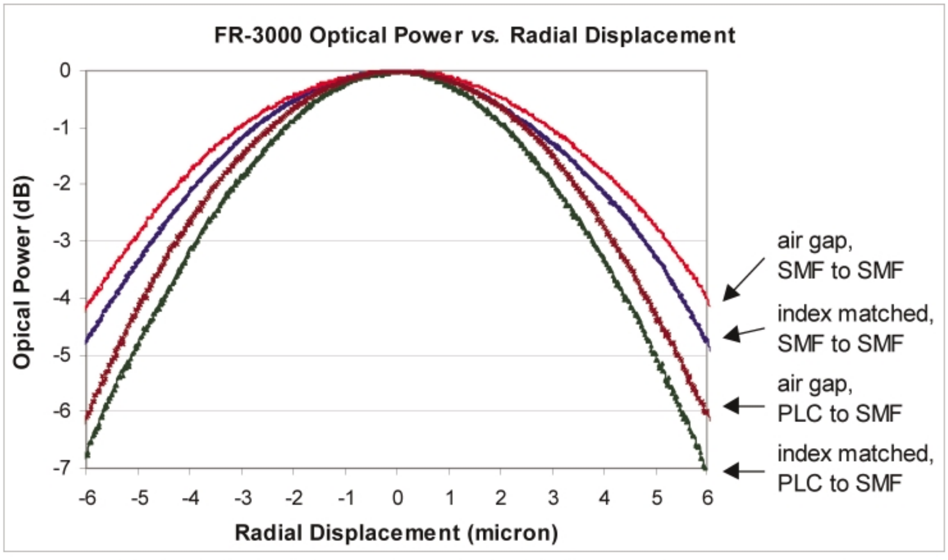

Figure 4: Effects of SMF to SMF vs. PLC to SMF and index matching fluid on optical power vs. radial displacement (100 nm step).

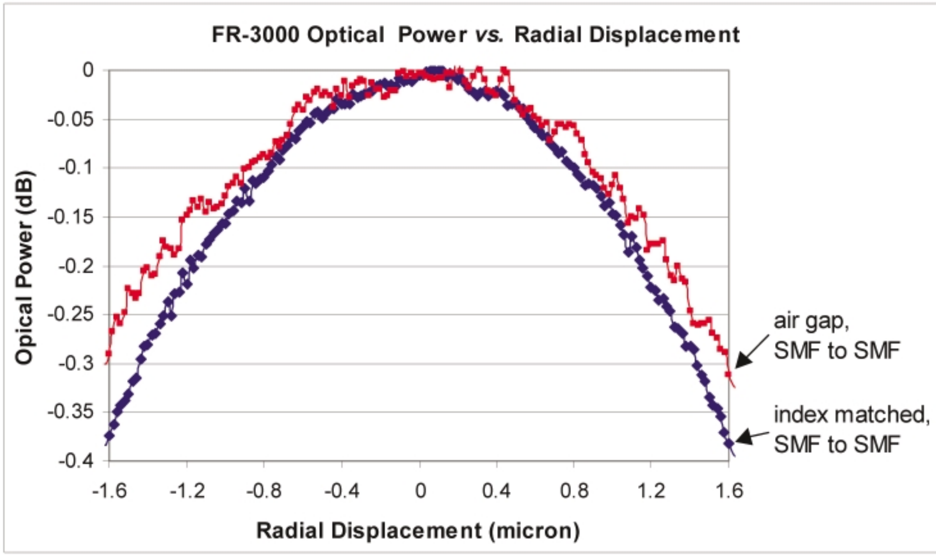

Figure 5: A close look at the optical power vs. radial displacement for SMF to SMF (20 nm step).

3.1.3 Interference in Z axis

The sensitivity of the optical power to displacement along the optical axis (Z) is strongly affected by use of an index matching fluid. Figure 6 shows the optical power vs. Z for two SMFs with (the almost linear curve) and without (the curve with multiple oscillations) index matching fluid.[1] Z = 0 is where the two fiber arrays (containing the two SMFs under study) touch at the front surfaces.[7] Both curves exhibit a slight fall off in power due to lower light collection efficiency from the acceptance cone as the Z separation increases. For the curve without index matching fluid, the oscillation patterns have peak to peak amplitude of about 0.35 to 0.4 dB. The air gap between the two fibers creates a cavity that contributes a phenomenon similar to Fabry-Perot interference, which in turn produces a strong Z axis displacement sensitivity. One period of the oscillation is about 775 nm, which is the half wavelength of the light. The highest sensitivity happens at the location of the highest optical power changes, which is estimated to be 0.15 dB/100 nm! Thus without index matching, the Z axis becomes the dominant factor for optical power sensitivity. For a robot with 20 nm mechanical resolution, one step corresponds to 0.03 dB. Without index matching fluid, the optical resolution is limited to 0.03 dB by the mechanical resolution in the Z axis. With index matching fluid (the top curve in Fig. 6), the interference pattern disappears. The sensitivity is only 0.0015 dB/100 nm. Therefore, with index matching fluid, Z axis displacement is not a key factor for optical power sensitivity; the optical resolution is determined by the stability of the light source.

A close-up of the last 2 µm of the Z motion before the two SMFs touch is shown in Fig. 7. The data is taken with 20 nm steps in the Z axis. For the index-matched case, the 2 Sigma noise is 0.006 dB in addition to the slight increase with Z as explained above. For the air gap case, the peak or valley region is much less noisy (0.006 dB in 2 Sigma) than at the transition region. This 0.006 dB is mainly the light source noise. Over the transition region between the peak and valley, the 2 Sigma noise is calculated to be about 0.04 dB. This high level of noise reflects the high optical power sensitivity to positional step changes (vibration noise randomly induced).

The implication to a process is clear. Since the Z position is not intentionally chosen, it is highly probable that Z is at a transition region with high optical power sensitivity to positional changes. Although the Z position of the alignment robot is fixed by the encoder feedback, slight Z axis vibration noise or the induced step changes in Z axis of the alignment robot due to the vibration noise can cause large optical signal noise, especially if it is on the high sensitivity transition region. This also explains the noisy optical signal (2 Sigma 0.03 dB) for the air gap cases in Sec. 3.1.2.

Compensating for this effect can be accomplished by minimizing the index differences at the transition planes. The refractive index of SMFs is about 1.47. Even with the refractive index of 1.52, the index matching fluid used reduces the

Z interference undulation amplitude to below 0.005 dB by estimate, almost undetectable 0.006 dB noise floor. Index matching fluid greatly reduces the Z axis interference effect and lessens optical sensitivity vs. axial position. In addition, index matching fluid prevents the light beam from spreading and increases the overall transmitted power. This phenomenon tends to increase the optical sensitivity to radial position (X and Y) and to worsen optical resolution to a small degree, as shown in Sec. 3.1.2. However, the Z axis is the dominant axis for the optical sensitivity and resolution. Thus, using index matching fluid is still an efficient way to significantly improve optical resolution overall. Another way to reduce the interference effect is to use components with angle polished front surfaces, e.g., 8°. This can reduce the interference somewhat but can not largely remove the interference due to the residual interference of the multiple reflected light beams especially when the two front surfaces of concern are very close (e.g., compared with the diameter of the fiber core).

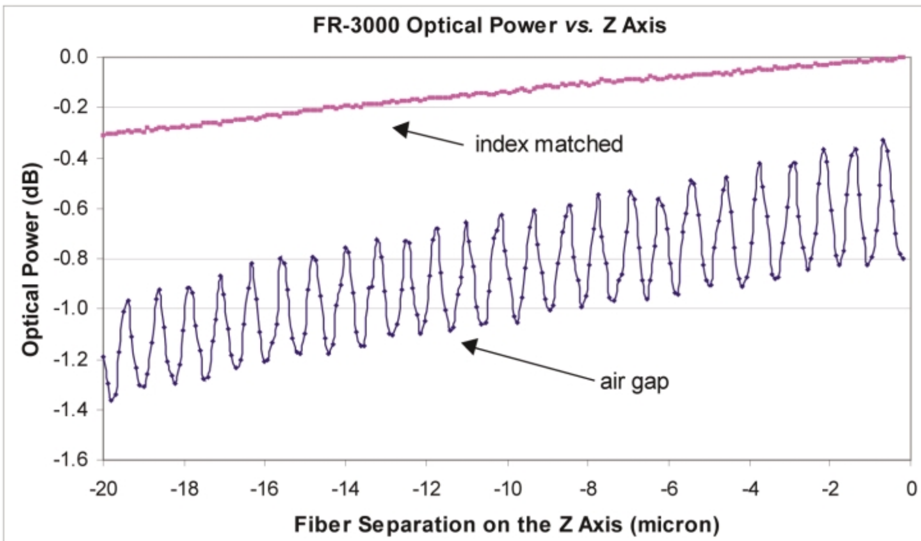

Figure 6: Optical power vs. Z (100 nm step) for two SMFs with (the top curve) and without (the bottom curve) index matching fluid.

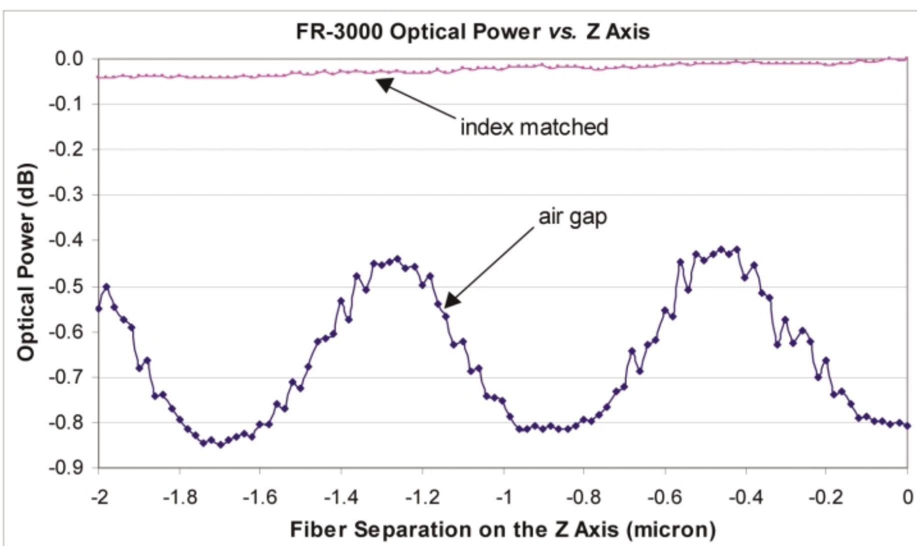

Figure 7: Optical power vs. Z (20 nm step) for two SMFs with (the top curve) and without (the bottom curve) index matching fluid.

3.2 Mechanical and optical bi-directional repeatability

The mechanical repeatability of the alignment robot is the ability of the robot to return to a target position from a displacement. The optical repeatability is the ability of a system to align to a certain optical criteria, move away and regain that optical criteria level again. The system optical repeatability could be by the alignment robot's mechanical repeatability, as well as external factors (e.g., the light source stability). The issue for this section is the sensitivity of the optical repeatability to the alignment robot's mechanical repeatability.

3.2.1 Mechanical repeatability

The following algorithm is used to measure the repeatability of one linear axis of the robot:

1. Move to the target position in the linear axis using encoder feedback; dwell 1 or 2 seconds.
2. Move forward a pre-selected step size in the linear axis; dwell 1 or 2 seconds; record position.
3. Move reverse the same distance in the linear axis back to the target position; dwell 1 or 2 seconds; record position.
4. Move reverse the same distance in the linear axis; dwell 1 or 2 seconds, record position.
5. Move forward the same distance in the linear axis back to the target position; dwell 1 or 2 seconds, record position.
6. Repeat steps 2 to 5 for 10 times.

The actual position at the target after each step (2 to 5) is recorded by the interferometer. The repeatability for bi-direction (each actual target position from both forward and reverse approach), the repeatability for uni-direction (each actual target position from either forward or reverse approach), and the offset between the average actual target position from forward approach and that from reverse approach can be derived. The repeatability is expressed in 2 Sigma values. Then the travel step size is varied to obtain repeatability and offset vs. travel step size relationship, which is shown in Fig. 8. In the figure, both the linear repeatability (or offset) and the step size is plotted in logarithmic scale. As the step size (travel distance) increases from 20 nm to 10 mm, the bi-direction repeatability (rhombus legend) increases from below 10 nm to a couple hundred nanometers, while the uni-direction repeatability (square legend) increases from below 10 nm to only 30 nm. The bi-directional repeatability is larger than uni-direction repeatability especially at longer travel step size because of the inevitable hysteresis of the bearings and structures in the alignment robot. Actually, when the travel step size is more than 0.1 mm (100 micrometers), the bi-direction repeatability is essentially the offset (triangular legend), indicating the hysteresis effect when the travel distance exceeds that level.

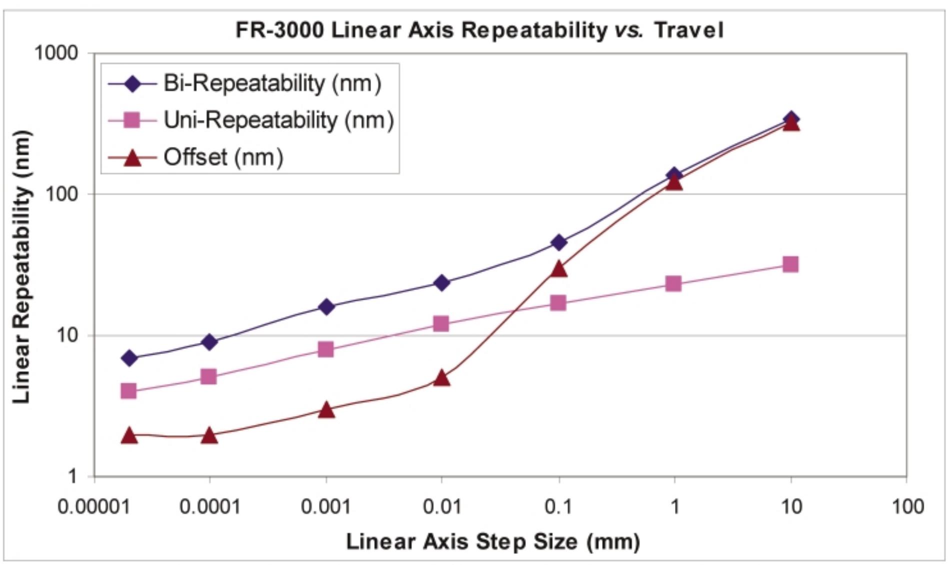

Figure 8: Linear axis repeatability as a function of travel step size.

3.2.2 Optical repeatability

There are two ways to specify the optical repeatability.[1] One is the repeatability due to the intrinsic mechanical bi-direction repeatability of the robot by moving away and back to the peak power location (optical mechanical repeatability). The other is the repeatability by repeating the same peak finding algorithm (optical algorithm repeatability). Two experiments using the same setup shown in Sec. 2.2 are performed to obtain these optical repeatability numbers.[1] The test condition is optimized with aluminum fixtures and with minimum environmental temperature variation for minimizing thermal expansion effects (see Sec. 3.3). Index matching fluid is used between the two SMFs and their spacing is set to be about 10 µm during the test.

An experiment with the following schedule was done to measure the optical mechanical repeatability:

1. Find the optical peak position in X-Y plane and record optical transmission power.
2. Move in X-Y plane to 80 random positions within ± 50 µm in both X and Y directions.
3. Move back to the original location (by positioning encoder feedback) and record optical transmission power.
4. Repeat 2 and 3 for 80 times (3 minutes to complete the data set; the thermal effect is not a contributor).

The optical repeatability (2 Sigma) for these 80 optical power readings is 0.007 dB for ~ 50 micron displacement, which is very close to the light source's short-term stability (2 Sigma) of 0.006 dB in the experiment during the same time frame. This demonstrates that the six-axis robot's intrinsic mechanical repeatability (typically 30 to 80 nm range, based on the mechanical repeatability data shown in Fig. 8 in Sec. 3.2.1) is not a major factor influencing optical repeatability. This makes sense, since the optical resolution (0.01 dB over 100 nm for SMF to SMF in Sec. 3.1.2) is too low to resolve these mechanical deviations at the peak power position. Only when the travel distance is larger than a few hundred µm, and correspondingly the bi-direction repeatability is more than 100 nm, will the mechanical repeatability have a somewhat noticeable effect on the optical repeatability.

To test the optical algorithm repeatability, an experiment with the following schedule was performed:

1. Find the optical peak position in X-Y plane; position and the optical power are recorded.
2. Move in X-Y plane to random position within ± 50 µm in both X and Y directions.
3. Find the optical peak position in X-Y plane, position and the optical power are recorded.
4. Repeat 2 and 3 for 80 times (45 minutes to complete the data set).

The optical algorithm repeatability (2 Sigma) from 80 optical power readings is 0.013 dB (2 Sigma), while the light source's stability within the same time frame is ~ 0.01 dB (2 Sigma). This shows that the system optical algorithm repeatability is mainly influenced by the light source stability, not by the alignment robot's mechanical repeatability and resolution.

The recorded X and Y positions by encoder for each run were analyzed. The average of the 80 excursions approaches 0 nm, which verifies no thermal drift. The standard deviations of X and Y were 90 nm and 94 nm, respectively. These are slightly below the limit of the optical resolution and verify that the optical resolution and repeatability are not determined by the mechanical closed loop resolution and repeatability, but rather by other external factors.

3.3 Mechanical and optical stability

3.3.1 Mechanical stability

The mechanical stability is the alignment robot's ability to hold a position for certain periods of time under certain environmental conditions. The mechanical stability in the short term (a minute or less) can be measured by the interferometer, since thermal drift in the short term is not a concern for the measurement. As already shown in Sec. 3.1.1, the noise floor measured when the alignment robot stands still is 5 nm at the 2 sigma value (closed loop feedback is still active to keep the position). Therefore it is appropriate to estimate that the mechanical stability (in X, Y, and Z axes) is 5 nm in 1 minute, and it is thermally independent.

It is not so easy to use the interferometer to measure the long term stability of the alignment system due to thermal drifting of the whole interferometer setup. However, in the long term, the main interest is the relative displacement between the two parts under alignment. In this case, the transmitted light itself can be used as a measure of the mechanical stability, which will be discussed later in Sec. 3.3.2.

3.3.2 Optical stability

The setup in Sec. 2.2 is used to measure the optical power stability of the whole system.[1] For the initial state, the spacing (Z) between the two fiber arrays is set to about 10 µm and the they are aligned (in one SMF channel) in the radial (X-Y) plane to achieve the maximum optical power transmission. Then, the transmitted light power is recorded every 30 seconds without averaging. Temperature is monitored every five minutes. Data are under four different conditions: with or without index matching fluid, and fixtures made of steel or of aluminum.[1] The conditions in Figs. 9(a) – 9(d) are very similar; the temperature drop is about 2 to 2.5 °C continuously over a 10-hour period. For index matched cases (Figs. 9(b) and 9(d)), the noise floor or short term stability (a few seconds) for the optical transmitted power is about 0.007 dB at 2 sigma, which is primarily the optical resolution or the instability of the light source. For the air gap cases (Figs. 9(a) and 9(c)), the short term stability is still the optical resolution, which is 0.03 dB, as discussed in Sec. 3.1.2 and Sec. 3.1.3.

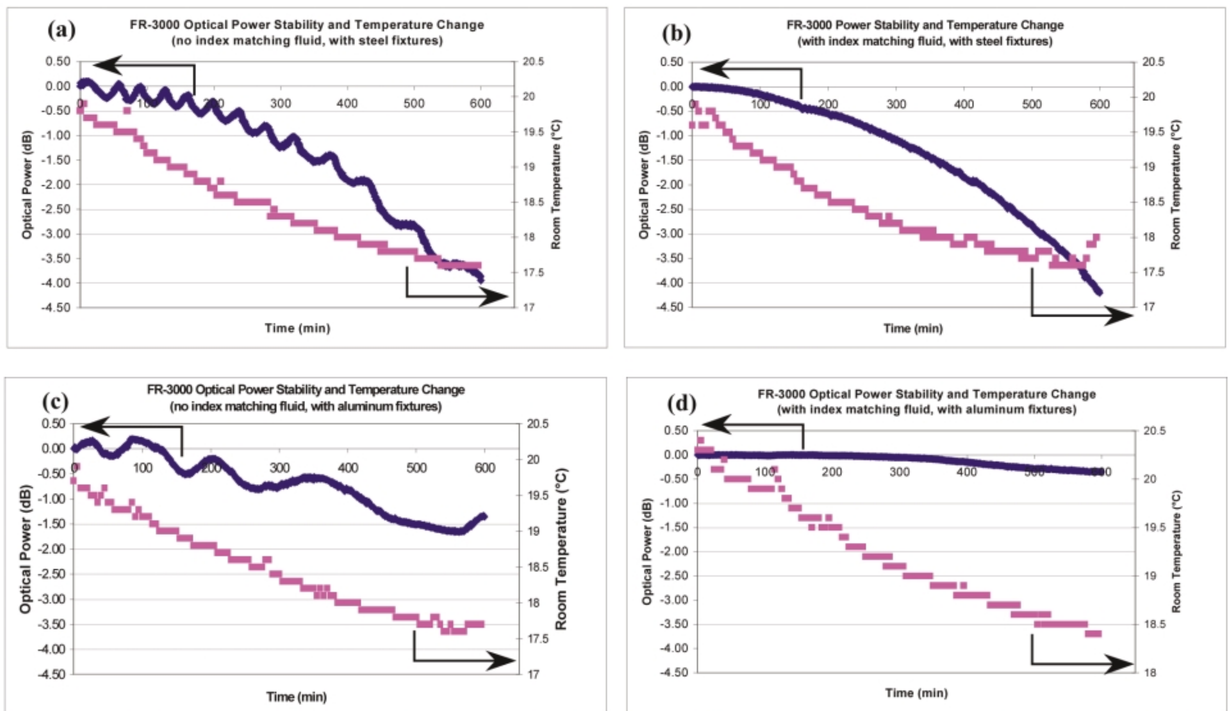

Figure 9: Optical power and temperature measured as a function of time. (a), with steel fixtures, with no index matching fluid, (b) with steel fixtures, with index matching fluid, (c) with aluminum fixtures, with no index matching fluid, and (d) with aluminum fixtures, with index matching fluid.

Compensating for coefficient of thermal expansion (CTE) in a system design can greatly enhance the optical stability performance. In this case, use of aluminum fixtures for a single material system (FR-3000 is mainly made of aluminum) that can accommodate thermal changes uniformly produces several times better performance in overall optical power stability. In Figs. 9(a) and 9(b) (steel fixtures), the overall drift is about 4 dB, while in Figs. 9(c) and 9(d) (aluminum fixtures), the overall drift is 1 dB or less over 10 hours and ~ 2.5 °C temperature change.

The interference effect on the optical power for the Z-axis (optical axis) is desensitized by use of an index matching fluid between the two fiber arrays (Figs. 9(b) and 9(d)). Therefore, the gradual decrease in the optical power over the long term is mainly due to the drift in the lateral or radial (X and Y) direction. Referring to Fig. 5, the power sensitivity to radial location is low when the two fibers are closely aligned. As one fiber displaces further away with respect to the other in the radial direction, the power drops more steeply and becomes more sensitive to the radial location. By matching the power stability curves with the power distribution vs. radial displacement curves, the radial direction drift can be determined. It is about 5 or 6 μm for the steel fixtures, while 1 or 2 μm for the aluminum fixtures over 10 hours and ~ 2.5 °C temperature change. The same numbers can be derived from Figs. 9(a) and 9(c).

Without index matching fluid, there are undulation patterns on the optical power. The undulation amplitude is about 0.35 dB. It is also noted that the optical power noise at peaks and valleys is much less than the noise in the transition

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region. These confirm the observations for the Z axis interference in Sec. 3.1.3. in Sec. 3.1.3, one period of the undulation corresponds to Z-axis drift of half the wavelength, which is 775 nm. Therefore, by counting peaks or cycles of the undulation, the Z axis relative movement can be determined. In Fig. 9(a) (steel fixture), the Z axis drift is about 10 µm during the 10 hours and ~ 2.5 °C drift. In Fig. 9(c) (aluminum fixture), the Z axis moves only about 3 µm during the 10 hours and ~ 2.5 °C drift.

The above mechanical thermal drift measurements can serve as a baseline for the long term mechanical stability, and they are temperature dependent. These numbers agree well with the thermal drift estimates. For example, the CTE of aluminum is 23×10^{-6} /°C; the CTE of steel is 16×10^{-6} /°C. For a length of 300 mm and a change of temperature of 2.5 °C, the net dimensional change is estimated to be $(23 - 16) \times 10^{-6}$ /°C × 2.5 °C × 300 mm = 5.25 µm, close to the measured numbers.

Superb optical power stability can be achieved, under the optimum condition: index matching fluid, aluminum fixtures, and well-controlled temperature change rate (~ 0.1 °C/hour). It has been shown 1 that an optical power stability (or overall drift) of less than 0.05 dB over 10 hours and less than 0.02 dB over one hour with temperature change of only 0.4 °C can be achieved. Most applications require stability performance of less than 30 minutes. The first 30 minutes of Fig. 9(d) is shown in Fig. 10. It represents the optical stability performance that the six-axis alignment robot can provide for the system. The 30-minute optical power stability is ± 0.0075 dB (or 0.015 dB peak to peak).

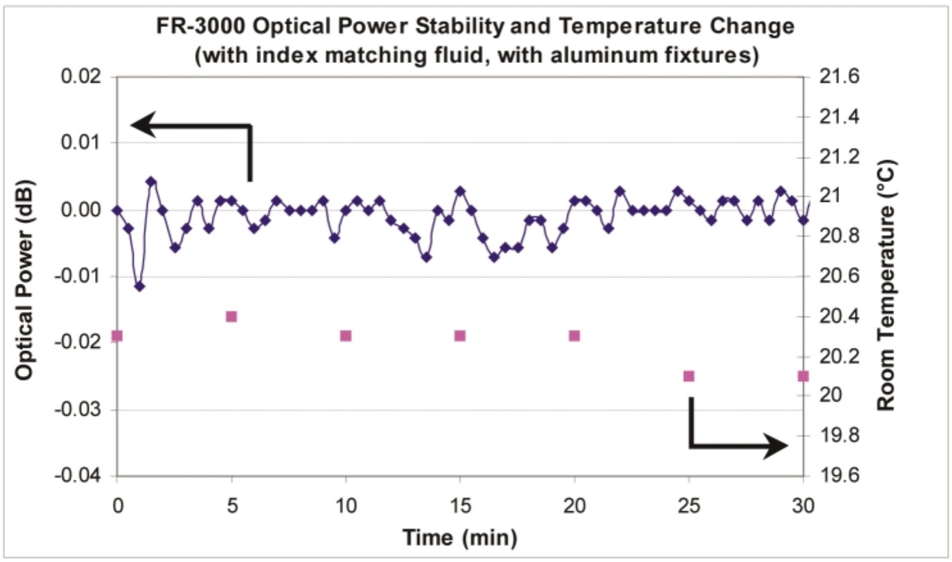

Figure 10: Zoomed-in optical power and temperature for the first 30 minutes of Fig. 9(d).

4. CONCLUSION

Alignment stability is one critical aspect in designing a process to assemble and measure optical components. Stability can be a function of time or of regaining a desired parameter after a displacement. This paper characterized a six-axis robot and some of the variables that affect process stability. The prime criterion was optical power. Mechanical parameters were correlated, where possible, to the optical power results.

The generic process requirements were assumed to be finding an optical peak, moving away and returning to that peak position without losing power, and maintaining that peak power during the process time (20 minutes or so). The components used to evaluate the system were SMFs of ~ 9 µm in diameter and PLCs with 4 µm× 4m in cross-section. For optical performance, resolution, repeatability, and stability are the three most important factors to be considered.

For mechanical performance, the alignment robot has been shown to have 20 nm mechanical resolution in the linear axis. Its mechanical repeatability increases slightly with travel distance. The mechanical stability in the short term is due to the vibration noise of the environment and in the long term is due to the thermal expansion effect.

Several conclusions can be made based on the optical performance data generated from the study.

- Active area and geometry of the aligned elements affects the optical sensitivity and resolution.
- Mechanical resolution of the radial axis (X and Y) cause optical signal changes below the noise floor of the system, and thus the noise floor limits the optical resolution.
- Index transitions in the optical train create significant power changes as a function of the interferometric fringe effect from Z axis displacements. The sensitivity can be reduced using index matching fluids.
- Optical repeatability depends mainly on external factors (e.g., input light source noise).
- Short term stability of the alignment process is the optical resolution.
- Long term stability of the alignment process is greatly affected by temperature and the resultant thermal expansion contributions.
- Thermal expansion effects can be reduced by careful design of the whole alignment system, primarily material matching.

The assumption that an alignment robot is needed to provide the consistency required for yield improvement (cost reduction) was reinforced by the determination of the optical power sensitivity to a fine level of movement. As the optical feature size decreases (very small apertures < 1 or 2 µm in diameter), the alignment robot's mechanical resolution, repeatability, and stability along with the process/testing environment will need to improve to achieve the optical performance targets.

REFERENCES

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3 The FR-3000 has an angular closed loop resolution of 0.2 arc-sec and this was verified with an autocollimator. In order to estimate the influence of this 0.2 arc-sec rotational resolution, we approximate the platform top (the point of interest) of the alignment robot to be 4 inches away from the rotation center or pivot point. An angular single step of 0.2 arc-sec rotation will create an Abbe error of 0.2 arc-sec $\times$ 4 inch $\approx$ 0.1 µm. This appears to overwhelm the linear axis resolution. However, experiment shows that this is not the case. In reality, the vibration noise is controlled such as shown in Sec. 2, the vibration noise can not induce large angular rotation motion (~ 0.2 arc-sec or more) and the angular closed loop can lock the angle very well. However, if the vibration noise is not controlled, large angular motion instability could be induced and the corresponding linear axis resolution and stability and system optical performance could be greatly affected.

4 Tolbert, M. A., "Expertise in nano-alignment aids photonics manufacturing," Laser Focus World, pp. 161-169, January 2002.

5 Hecht, J., Understanding Fiber Optics, Prentice Hall, Upper Saddle River, New Jersey, 1999.

6 With an optical sensitivity of 0.02 dB/100 nm and a step change of 20 nm, the estimated optical signal change is 0.004 dB, below the noise floor of 0.006 dB. This estimation is conservative, since at 20 nm away from the optical power peak, the sensitivity is lower than that at 100 nm away.

7 A few micrometers spacing between the two SMFs in the two fiber arrays could still exist when the two fiber arrays touch. This is because the front surfaces of the sender and receiver fiber arrays can not be accurately aligned (typical ~ 0.1 degree misalignment) and the front surface of the fiber array is not necessarily made perpendicular to the absolute axis of each fiber.

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