High-Precision Characterization of Single-Mode Optical Fiber Arrays

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***Abstract*—A precise method of measuring core center dispersion in single-mode fiber arrays is presented. This approach dispenses with the use of high-precision linear translation stages and is based on a direct comparison of the fiber core center position to a simple lithographically patterned template. Combining image recognition and efficient processing algorithm, the fiber-core center positions of fiber arrays can be determined with precision of order of 0.1 μm, in both longitudinal and transversal directions. Complementary information about the position of fibers within v-grooves as well as bending of multifiber arrays can be also obtained.**

***Index Terms*—Characterization, fiber-arrays, optical fiber, optical waveguides, optoelectronic-packaging.**

I. Introduction

PASSIVE components for wavelength-division multiplexing (WDM) typically contain large numbers of input and output channels that require precisely aligned connections to optical fibers [1], [2]. The common solution used for the attachment of optical fibers to multichannel devices is the use of single-mode fiber arrays [3]–[5]. However, in order minimize the coupling losses between optical ports of the device being packaged and the fiber array it is necessary to have individual fibers of the array placed accurately, with submicron precision, with preset separation. Accurate inspection of the fiber array before packaging, to determine the center core dispersion of individual optical fibers, would be desirable in order to minimize overall coupling losses and loss inhomogeneity. The need for inspection of optical components capable of submicron accuracy arises often in packaging and fabrication situations.

Most of the characterization and packaging systems used to evaluate multiport devices with submicron accuracy use expensive high-precision translation stages. In this work we demonstrate an alternative method to characterize the core center dispersion of optical fiber arrays, without the need for very high precision translation stages. The method employs image recognition and processing and computer-vision comparison with a simple but very accurate template. We demonstrate possibilities of this technique by determining positions of fiber core centers in 48 channel v-groove arrays. With this approach we were able to measure optical fiber core center dispersion with the accuracy of order of 0.1 μm, in both longitudinal and transversal directions.

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II. Experimental

A simplified schematic diagram of the experimental arrangement used to inspect fiber arrays is shown in Fig. 1. A computer controlled commercial linear translation stage with precision of 2 μm was used. A commercial fiber-array and a precise template, encoder, were placed on the translation stage using two independent mechanical alignment fixtures with two angular axis movements. This enables independent focusing and angular misalignment corrections between the fiber-array and the template and the axis of motion of the translation stage [Fig. 1(a)]. Two CCD cameras with standard microscope lenses were used to image the template, the fiber cores, and the v-grooves of the fiber array. An image acquisition board with 10-bit digitalization was used to acquire the images from both cameras. In this configuration we were able to simultaneously image each feature of the template and the fiber cores (and v-groove edges) of the fiber array under investigation. Resolution of both imaging systems was calibrated using the known patterns on the template. We used values of $\sim 0.12\ \mu\text{m/pixel}$, controlled by the CCD-to-lens distance, for cameras imaging both the template and the fiber array. The entire experiment, control of the translation stage movement, acquisition and processing of captured images, and calculations of fiber-core position relative to the template pattern, was carried out under software control.

The template used as a reference in our experiment was fabricated using conventional silicon processing and optical lithography. The structure deposited on a 150-mm diameter wafer consisted of a layer of silicon dioxide, 0.1 μm thick, and a layer of sputtered aluminum (Al), approximately 1 μm thick. The Al layer was patterned and etched to form arrays of squares, 10 $\mu\text{m} \times 10\ \mu$m in size, spaced by 250 μm. After processing the wafer was cut into individual templates. High-resolution stepper lithography produced smooth and reflective aluminum squares with the size and placement accuracy of about 0.1 μm.

Representative images of an Al square from a template and from a single-mode back-illuminated fiber placed in a v-groove of a 0° polished array are shown in Fig. 1(b) and (c), respectively. Images of the fiber core and the v-groove can provide complementary information about their respective placement and thus allow for tracking of possible sources of problems. The position of the fiber core is determined by first acquiring an image containing the entire v-groove and the fiber placed in it. Edge detection algorithm is then used to capture edge lines of the v-groove. The intersection of these lines provides the coordinate of the v-groove vertex and the v-angle value. Since the nominal diameter of the fiber is known, the expected position of the core can be approximated at this point. Another

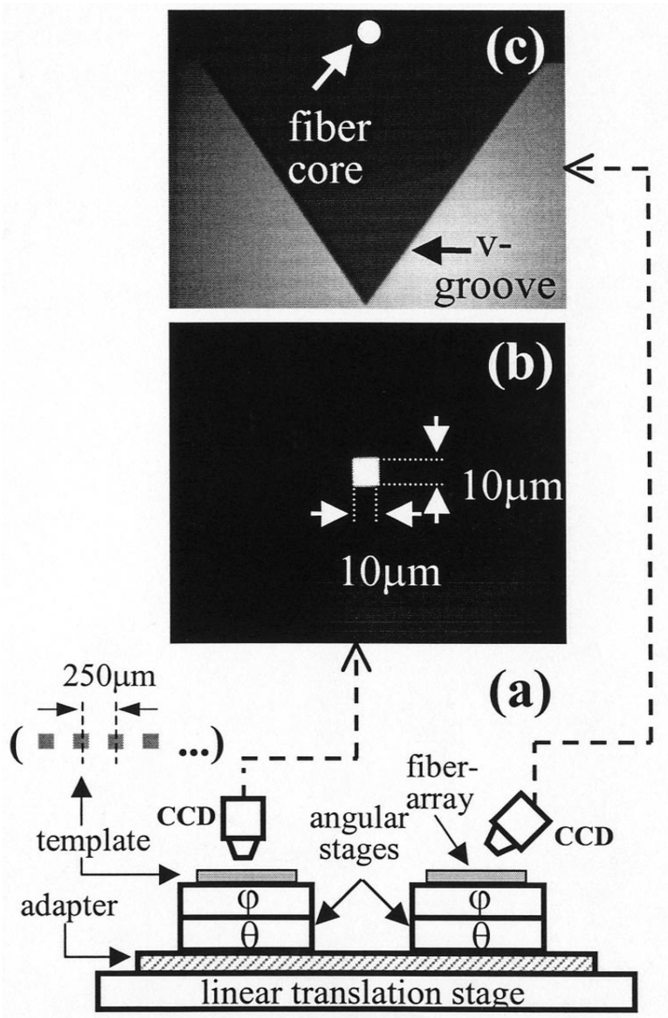

Fig. 1. (a) Schematic diagram of the experimental setup used to characterize the fiber core center dispersion in fiber-arrays, (b) image from an Al deposited square pattern on a silicon substrate of a template, and (c) image from a single-mode optical-fiber on a v-groove of a fiber-array.

area of interest is then defined around the expected core position and edge detection algorithm is applied to it to extract the core center. Image recognition is used to determine the location of the Al squares on the image of the second charged couple device (CCD) camera. A *centroid* routine is used to extract the center of energy of the image intensity to determine the square's center position. The assumption made here is that the translation stage is good enough to bring these images into fields of view of CCD cameras with every step.

III. Model and Computer Simulation

Extraction of precise center core coordinates by comparing the known template period to the fiber center positions is made complicated by the complex motion of the stage. A direct comparison of the core position and the template is practical only for a very high quality translation stage. Most translation stages exhibit fairly complex motion, with transverse excursions and twists on submicron scale, in addition to the lack of precision in longitudinal translation. Furthermore, errors of the stage motion accumulate and correction becomes more difficult as the number of steps increases. The model described below deals with this problem in a systematic fashion.

Let us assume a pure linear movement of the translation stage (TS) in the x-direction by a step ${}^{TS}T$ and consider a small angle ${}^{T}\theta$ between the template (T) and the direction of the translation stage movement. The calculated (c) position of template square centers, in the image (I) coordinates given by ${}^{T}_{c}x^{I}_{k}$, ${}^{T}_{c}y^{I}_{k}$, where $\mathrm{k} = 1, 2, \ldots, \mathrm{N}$, where N is the number of pitches, are referenced to the measured (m) position of the first square center ${}^{T}_{m}x^{I}_{1}$, ${}^{T}_{m}y^{I}_{1}$. Since the magnifications of the two image acquisition systems are slightly different, it is necessary to convert pixels to microns. The calculated image coordinates for all square centers of the template are given by the following expressions:

$$\begin{aligned} {}^{T}_{c}x^{I}_{k} &= {}^{T}_{m}x^{I}_{1} + \left[{}^{T}T(k-1)\cos({}^{T}\theta) - {}^{TS}T(k-1)\right] \\ {}^{T}_{c}y^{I}_{k} &= {}^{T}_{m}y^{I}_{1} + {}^{T}T(k-1)\sin({}^{T}\theta) \end{aligned} \tag{1}$$

where ${}^{T}T$ is the nominal template period. The angle ${}^{T}\theta$ can be obtained directly from the measured y-values in the image coordinate system ${}^{T}_{m}y^{I}_{k}$ using the expression

$${}^{T}\theta = \left\langle {}^{T}\theta_{k} \right\rangle, \quad {}^{T}\theta_{k} = \arcsin\left[\frac{{}^{T}_{m}y^{I}_{k+1} - {}^{T}_{m}y^{I}_{k}}{{}^{T}T}\right] \tag{2}$$

where $\langle {}^{T}\theta_{k} \rangle$ is the average misalignment angle. The translation stage does not move with each step by exactly the period ${}^{T}T$ of the template, and the errors introduced in x- and y-directions, ${}^{x}\xi_{k}$ and ${}^{y}\xi_{k}$, can be calculated from:

$${}^{x}\xi_{k} = {}^{T}_{m}x^{I}_{k} - {}^{T}_{c}x^{I}_{k} \quad \text{and} \quad {}^{y}\xi_{k} = {}^{T}_{m}y^{I}_{k} - {}^{T}_{c}y^{I}_{k} \tag{3}$$

We now turn to the problem of finding the positional errors of the fiber array. Using (3) we correct the measured core centers of the fiber array (A), in the image coordinate system ${}^{A}_{m}x^{I}_{k}$, ${}^{A}_{m}y^{I}_{k}$, as follows:

$${}^{A}_{\mathrm{corr}}x^{I}_{k} = {}^{A}_{m}x^{I}_{k} - {}^{x}\xi_{k} \quad \text{and} \quad {}^{A}_{\mathrm{corr}}y^{I}_{k} = {}^{A}_{m}y^{I}_{k} - {}^{y}\xi_{k}. \tag{4}$$

The distance between consecutive fiber-center positions in the array may vary due to small variations in the fiber positioning within the v-groove and possible eccentricity of the fiber. An expression similar to (1) can be written for the x-coordinates of the cores, in the image coordinate system. Since the distances between consecutive x-coordinates of core centers $({}^{A}T_{j})$ are not known, the following transcendental equation should be solved numerically in order to obtain the values of ${}^{A}T_{j}$:

$$\begin{aligned} {}^{A}_{\mathrm{corr}}x^{I}_{k} &= {}^{A}_{\mathrm{corr}}x^{I}_{1} - {}^{TS}T(k-1) + \sum_{j=1}^{k-1} {}^{A}T_{j}\cos\left({}^{A}\theta_{j}\right), \\ {}^{A}\theta_{j} &= \arcsin\left(\frac{{}^{A}_{\mathrm{corr}}y^{I}_{j} - {}^{A}_{\mathrm{corr}}y^{I}_{j-1}}{{}^{A}T_{j}}\right). \end{aligned} \tag{5}$$

Once ${}^{A}T_{j}$'s are determined, the average angle ${}^{A}\theta(= \langle {}^{A}\theta_{j} \rangle)$ between the fiber array and the x-axis and the average distance ${}^{A}T(= \langle {}^{A}T_{j} \rangle)$ between consecutive fiber centers in the array can be determined. After calculating ${}^{A}T_{j}$ and ${}^{A}\theta_{j}$ the position

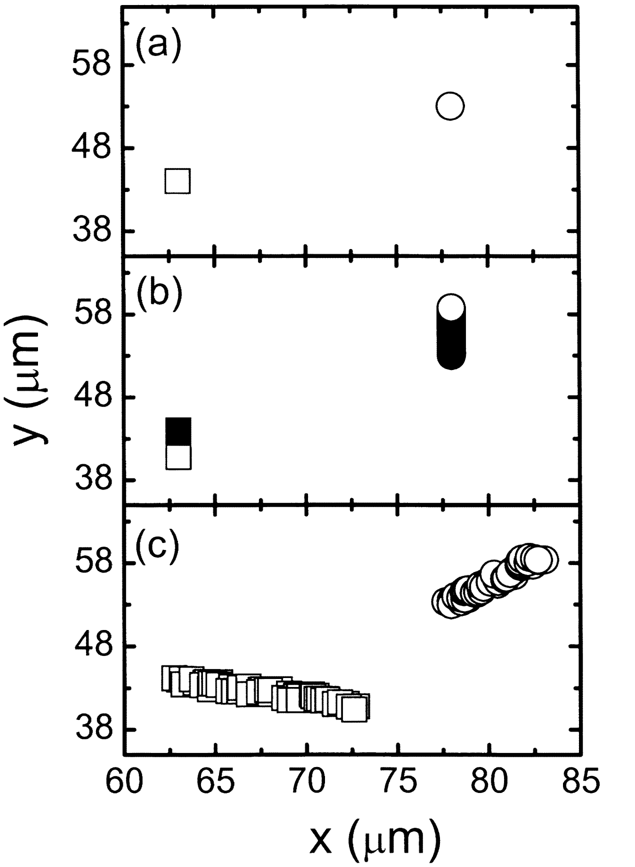

Fig. 2. Plots of simulated x-y position of fiber core and square centers for different sets of parameters: (a) $^{\rm TS}{\rm T} = {}^{\rm T}{\rm T} = {}^{\rm A}{\rm T} = 250.0\ \mu{\rm m}$, $^{\rm T}\theta = {}^{\rm A}\theta = 0$, (b) $^{\rm TS}{\rm T} = {}^{\rm T}{\rm T} = {}^{\rm A}{\rm T} = 250.0\ \mu{\rm m}$, $^{\rm T}\theta = +0.027^\circ$ and $^{\rm A}\theta = -0.015^\circ$, (c) $^{\rm TS}{\rm T} = 250.1\ \mu{\rm m}$, $^{\rm T}{\rm T} = 250.0\ \mu{\rm m}$, $^{\rm A}{\rm T} = 249.9\ \mu{\rm m}$, $^{\rm T}\theta = +0.027^\circ$ and $^{\rm A}\theta = -0.015^\circ$ and random error of $\pm 0.5\ \mu{\rm m}$ in both x and y centers.

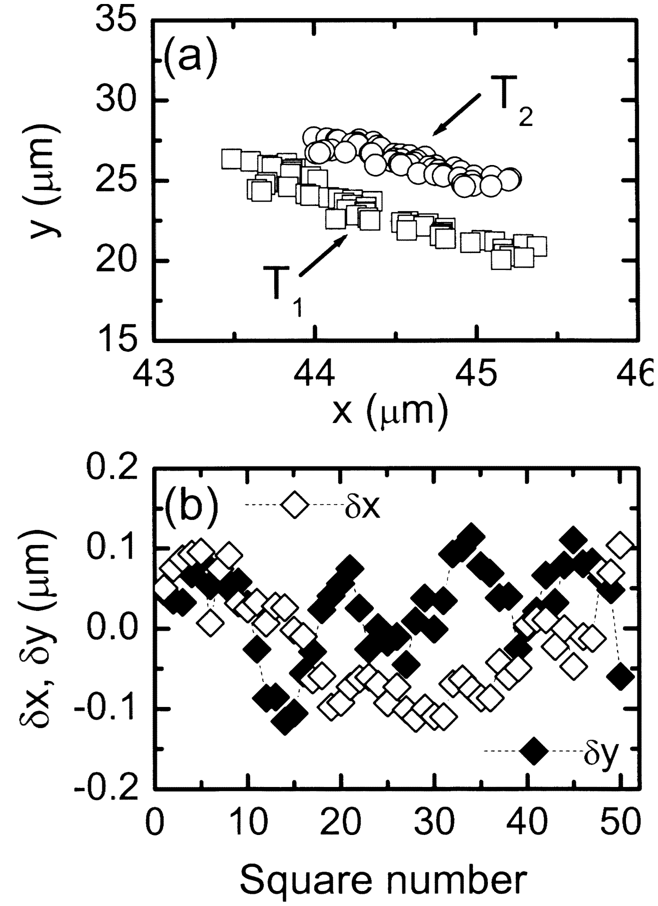

Fig. 3. (a) Measured y and x square center positions for two templates ($\rm T_1$ and $\rm T_2$) and (b) center dispersion (δx, δy) as a function of pitch number of template $\rm T_2$ relative to template $\rm T_1$.

of the fiber array core centers ${}^A_c x_k^{TS}$, ${}^A_c y_k^{TS}$, in the translation stage coordinate system can be calculated:

$$
\begin{aligned}
{}^A_c x_k^{TS} &= {}^A_m x_1^I + \sum_{j=1}^{k-1} {}^A T_j \cos\left({}^A\theta_j\right) \\
{}^A_c y_k^{TS} &= {}^A_m y_1^I + \sum_{j=1}^{k-1} {}^A T_j \sin\left({}^A\theta_j\right).
\end{aligned} \tag{6}
$$

Finally, deviations δx and δy of core center positions relative to a template with a well-defined pitch can be determined by taking the difference between core center coordinates ${}^A_c x_k^{TS}$, ${}^A_c y_k^{TS}$, obtained from Eq.(6), and the calculated template center positions ${}^T_c x_k^{TS}$, ${}^T_c y_k^{TS}$, in the translation stage coordinate system defined as

$$
\begin{aligned}
{}^T_c x_k^{TS} &= {}^T_m x_1^I + {}^T T(k-1)\cos({}^T\theta) \\
{}^T_c y_k^{TS} &= {}^T_m y_1^I + {}^T T(k-1)\sin({}^T\theta)
\end{aligned} \tag{7}
$$

To verify that the imprecision in the translation step is the predominant source of error two templates can be compared with each other. If errors ${}^x\xi_k$ and ${}^y\xi_k$, obtained independently from (3) for each template relative to the other are equal, the proposed algorithm indeed allows for the determination of fiber core separations, even with a low-precision translation stage.

The validity of the model can be tested by simulating positions of fiber cores and square centers [using (1)] and calculating the corresponding deviations from the template coordinates. Fig. 2(a) shows the simulated coordinate positions of an ideal template and a fiber-array, both with a period of 250 μm. The template and the fiber array were aligned to the movement direction of the translation stage. The translation stage moved exactly 250 μm at each step. In this case the position of the square and fiber core center coordinates in the images should be exactly the same for all the elements of the template and the array. Fig. 2(b) shows the result of introducing misalignment angles of $^{\rm T}\theta = +0.027^\circ$ and $^{\rm A}\theta = -0.015^\circ$ for the template and the fiber array, respectively. This results in a shift in the position of both fiber cores and template squares in y-direction as the translation stage moves. The projection of motion in the x-direction is very small, $< 0.002\ \mu$m, but not zero. This results in the motion of the y-x center coordinates along essentially vertical lines. In a more general case we consider: a) an average fiber array period of $^{\rm A}{\rm T} = 249.9\ \mu$m, b) template period of $^{\rm T}{\rm T} = 250.0\ \mu$m, c) average step of the translation stage travel of $^{\rm TS}{\rm T} = 250.1\ \mu$m, d) misalignment angle of $^{\rm T}\theta = +0.027^\circ$ and $^{\rm A}\theta = -0.015^\circ$ between the fiber array and the template with respect to the translation stage axis. In addition we introduce a random error of $\pm 0.5\ \mu$m in the x- and y-coordinates of the fiber core and square center. Random contributions in x and y

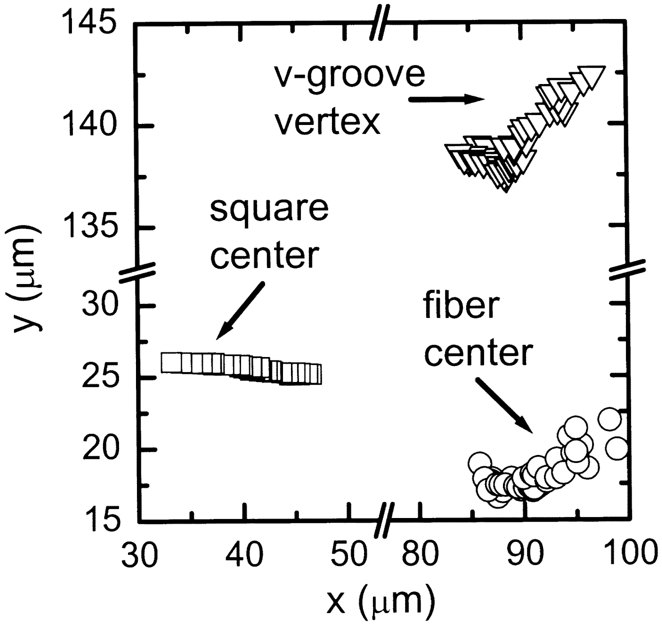

Fig. 4. Plots of x- and y center positions of fiber cores and v-groove vertexes of a fiber-array and square centers of a template.

directions are independent of each other. The result is shown in Fig. 2(c). Both x and y coordinates of center positions now change considerably as the number of steps increases. The change in the template and fiber array x-center values as the number of steps increases is due to the difference in periods of the template (fiber array) and the translation average step.

In all three cases discussed in Fig. 2(a)–(c) the calculated x- and y-core center positions of the fiber array are essentially identical to the originally simulated ones. This shows that the method is effective even in the general case where the period of the fiber array and the average step translation stage are different from that of the template. The method also corrects for the presence of random errors in both x and y directions. In other words, when the x (or y) center positions for each step of the template and fiber array are correlated, the deviation of the fiber core centers can be determined.

IV. Results and Discussion

In order to determine the resolution of the system, square center positions of two different templates (T_1 and T_2) were measured first and then the dispersion is calculated. The results are shown in Fig. 3. The results are similar to those of the simulation shown in Fig. 2(c). The variation in the x-center values for both templates as the number of steps increases, shown in Fig. 3(a), indicates a difference $({}^{\mathrm{TS}}\mathrm{T} > {}^{\mathrm{T}}\mathrm{T})$ between the average step of the translation stage (nominally 250 μm) and the template's period (also 250 μm). The slope differences shown in Fig. 3(a) reflect different misalignment angles (${}^{T_1}\theta = -0.028°$ and ${}^{T_2}\theta = -0.014°$) between the templates and the translation stage direction. The calculated mean deviation of the template T_2 relative to that of T_1 one, in both directions is shown in Fig. 3(b). The δx and δy mean values are close to zero but the maximum absolute deviation is better than 0.12 μm for both x- and y-coordinates. These values are representative of several consecutive measurements with the same set of template pairs. Same results were obtained on different template pairs. The nonzero deviation in the x and y-coordinates of template squares are attributed to two sources of errors. The first source (random) is the single-pixel resolution error of either camera. Since the measurements are carried out using two different cameras, this type of random error is not necessarily correlated, and consequently cannot be totally suppressed. Nonlongitudinal components of the translation stage motion are a second source of errors that affect mainly the x-center position values. This induces noncorrelated errors and contributes to x-square center deviation values [see Fig. 3(b)]. The results shown in Fig. 3 clearly demonstrates that is possible to apply the template reference approach to determine the optical fiber x- and y-core center positions in fiber arrays with a precision of order of 0.1 μm, even when using a low-precision translation stage. The resolution of our system $(\sim 0.1\ \mu\mathrm{m})$ allows us to estimate additional coupling losses in fiber arrays, as a result of lateral misalignments in both x- and y-directions, with a precision of ~0.0034 dB [6].

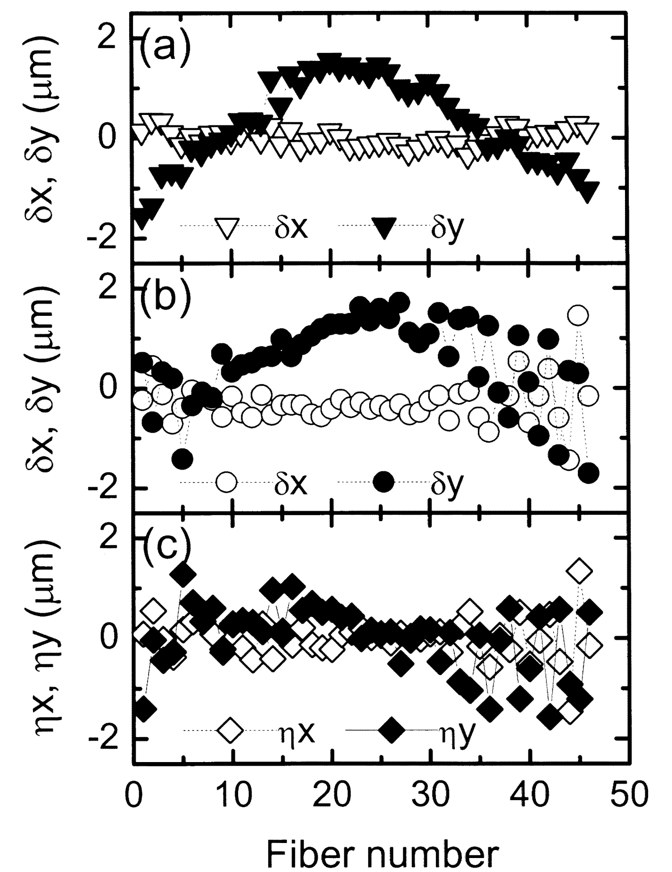

Fig. 5. Calculated center dispersion (δx, δy) as a function fiber number for (a) v-groove vertex and (b) fiber-core center, and (c) the x and y relative distances (ηx, ηy) between the fiber core and the v-groove vertex. For comparison purposes the original y-values were truncated by their mean value of $\sim$ 121 μm.

We apply the template reference method to characterize commercial single-mode arrays with 48 fibers. Fig. 4 shows an example of measured fiber-core and v-groove vertex x- and y-coordinates together with square center positions of the template. In analogy with results of Fig. 3(a), the change in the x- and y-center values of both template and fiber array with the number of steps is attributed to the period difference between the template and the fiber array and the average steps of the translation stage. The average calculated v-groove angle of $70.5 \pm 0.3^{\circ}$ is consistent with the expected tilt of (100) and (111) planes of Si. The period of the fiber array was calculated as ${}^{A}T = 250.027\ \mu$m. Fig. 4 also shows that the y-center values do not change linearly with x for both the fiber array core center and the v-groove vertex. This is attributed to bending of the fiber array in the transversal direction and becomes more evident in the calculated core and v-groove vertex coordinate dispersion shown in Fig. 5. The y-center coordinate deviation of the v-groove vertex shows a parabolic shape with the estimated radius of curvature of ~7 m. The maximum absolute deviation of x- and y-center values of v-groove vertex is 0.4 μm and 1.6 μm, respectively. The fiber-core y-center positions shown in Fig. 5(b) also exhibit a parabolic distribution and the estimated curvature radius for the fiber core centers is very similar to that obtained for the v-grooves. Larger values of the x- and y-core center deviations, Fig. 5(b), result from additional contributions of the core eccentricity and imprecision of fiber positioning within v-grooves. The placement of fibers within v-grooves can be evaluated by measuring the relative distance between the x- and y-centers of fiber cores centers relative to v-groove vertexes η_X, η_Y. In order to show the x and y-center dispersions in the same plot, Fig. 5(c), the original y-values were truncated by their mean value of $\sim 121\ \mu$m. It is clear that the majority of the fibers are placed within v-grooves with accuracy better than 0.5 μm.

The results of Fig. 5 clearly demonstrate the importance of fiber-array characterization before packaging. The x- and y-center dispersions shown in Fig. 5(b) would result in estimated coupling losses [6], due to lateral misalignment in both x- and y-directions, in excess of ~1.2 dB. The majority of fiber-arrays investigated in this work exhibited fiber core dispersions of less than 1 μm, resulting in estimated coupling losses lower than 0.5 dB.

V. Conclusion

We describe a method of measuring dispersion of fiber core centers in single-mode fiber arrays, without the need for high-precision linear translation stages. This method uses a precise template (encoder) as a reference. Image recognition and processing are used to determine the centers of fiber cores and v-groove vertexes with accuracy of order of 0.1 μm. A mathematical model used for data extraction is described in detail. Examples of fiber core and v-grove vertex distributions in fiber arrays are shown, illustrating the capability of our method.

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