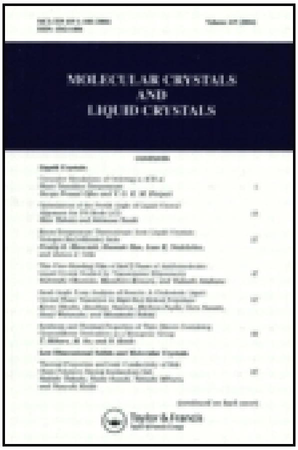

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Accurate Measurement of the Pretilt Angle in a Liquid Crystal Cell by an Improved Crystal Rotation Method

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To measure the pretilt angle in a liquid crystal cell, the crystal rotation method is commonly used because it is very precise and the measurement time is short. However, if the cell gap is not uniform, a significant error occurs due to a shift of the measurement point. This shift is caused by refraction at the glass plate when rotating the cell. In this paper, we estimate the magnitude of this error theoretically and experimentally and propose an improvement of the crystal rotation method by which an accurate value of the pretilt can be obtained even when the cell gap is not uniform.

Keywords: liquid crystal, pretilt angle, crystal rotation method, measurement error

1. INTRODUCTION

The orientation of liquid crystal molecules in a cell is determined by the alignment conditions at the boundaries. Therefore, the alignment of liquid crystals on surfaces is very important for a proper control of the characteristics of liquid crystal devices. The orientation of a liquid crystal (LC) at an interface can be described by an azimuthal angle in the plane of the surface and by a polar angle away from the surface. The azimuthal angle can be easily measured,[1] but the measurement of the polar angle or so-called pretilt is more complicated. At present, the following four methods have been reported: the crystal rotation method,[2] the capacitance measurement method,[2] the magnetic null method[3] and the ATR (Attenuated Total Reflection) method.[4] Among them, the crystal rotation method suggested by Scheffer *et al.*[2] is commonly used because precise measurements are obtained rapidly. However with this method, the measured pretilt angle can contain a significant error when the cell gap of the sample is not uniform. This is due to the fact that glass refraction causes a shift of the measurement point when rotating the cell. In this paper, we estimate the influence of the uniformity of the cell gap on the measurement error theoretically and experimentally. We propose an improved method to reduce this error in a simple way. Eventually, we verify the validity of our new method.

2. MEASUREMENT ERROR OF THE PRETILT ANGLE IN THE CONVENTIONAL METHOD

2.1 Measurement Principle of the Pretilt Angle

The experimental set-up for the crystal rotation method is shown in Figure 1. We use a sample cell that consists of two glass substrates rubbed in antiparallel directions. The sample cell can be rotated about the center axis that is parallel to the surface and perpendicular to the rubbing direction. The polarizer and analyzer are perpendicular to each other and oriented at an angle of 45 with the rubbing directions. The retardation of a light beam, passing through the cell at an angle of incidence ψ as shown in Figure 2, can be expressed by[5]

$$\delta(\alpha, \psi) = \frac{2\pi}{\lambda} \cdot d \cdot f(\alpha, \psi) \tag{1}$$

where d is the cell gap of the liquid crystal sample and λ is the wavelength of the incident angle. $f(\alpha, \psi)$ is a function of the pretilt angle α of the liquid crystal and the rotation angle ψ which is defined as the angle between the incident light beam and the direction normal to the cell. $f(\alpha, \psi)$ is expressed as follows[6,7]

$$f(\alpha, \psi) = \frac{1}{c^2}(a^2 - b^2) \cdot \sin\alpha \cdot \cos\alpha \cdot \sin\psi + \frac{1}{c}\left(1 - \frac{a^2 b^2}{c^2} \cdot \sin^2\psi\right)^{1/2} - \frac{1}{b}(1 - b^2 \cdot \sin^2\psi)^{1/2} \tag{2}$$

$$a = \frac{1}{n_1}, \quad b = \frac{1}{n_2}, \quad c^2 = a^2\cos^2\alpha + b^2\sin^2\alpha$$

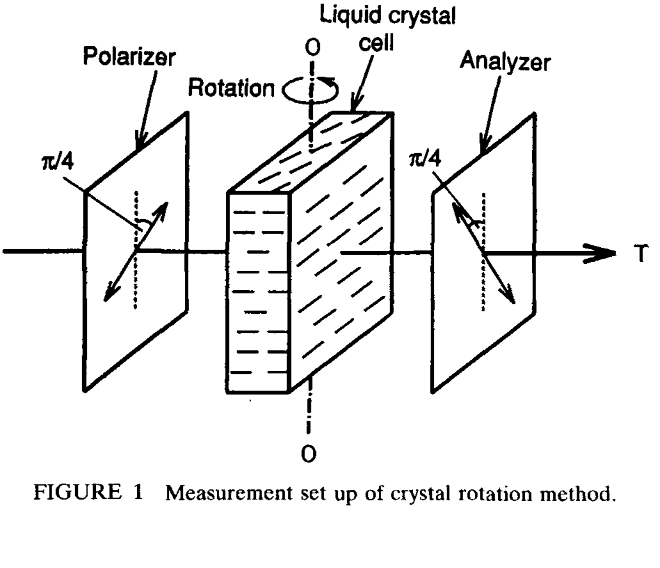

FIGURE 1 Measurement set up of crystal rotation method.

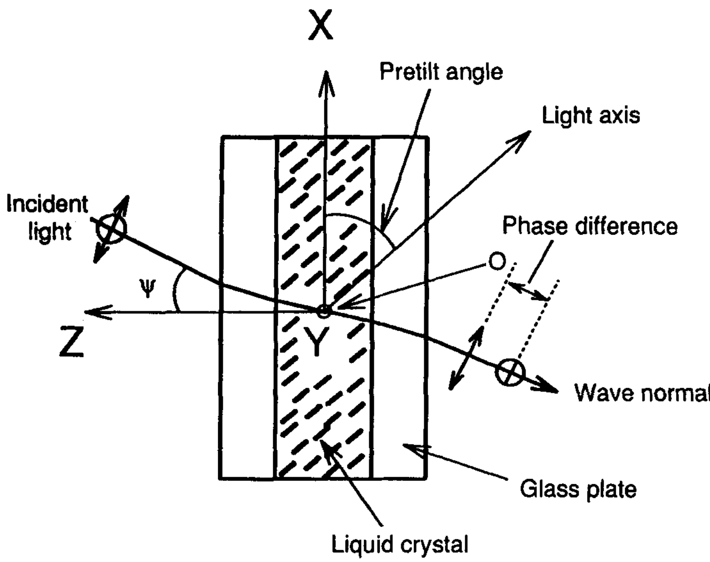

FIGURE 2 Cross section of liquid crystal cell geometry of molecular alignment and light path.

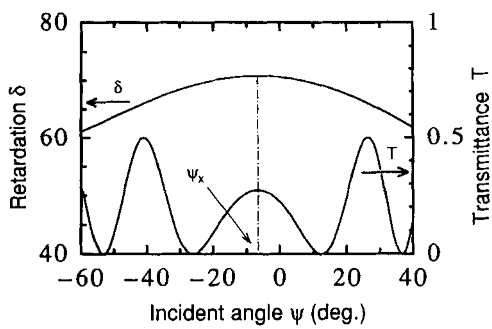

FIGURE 3 Calculated results of phase retardation δ and transmittance T as a function of incident angle ψ. Nematic liquid crystal layers with $n_1 = 1.76$, $n_2 = 1.52$ and thickness of $d = 30$ μm are assumed. λ and pretilt angle α are 640 nm and 2°, respectively.

where n_1 and n_2 are the extraordinary and ordinary refractive index of the liquid crystal, respectively. The polarizers enable us to detect a variation of the retardation by variation of transmission. With the configuration of Figure 1 the transmittance becomes

$$T(\psi) = \frac{1}{2} \sin^2 \left\{ \frac{1}{2}\, \delta(\psi) \right\} \tag{3}$$

We have calculated the transmittance T and the retardation δ as a function of the incident angle ψ in the case of a uniform cell with, for example, $d = 30$ μm and $\alpha = 2°$ as shown in Figure 3. The curve of the transmittance T is nearly symmetrical around a certain angle ψ_x. For this angle ψ_x, the retardation δ becomes a maximum.

We can use this condition to deduce a relation between ψ_x and the pretilt angle α. The condition for a maximum δ is expressed by

$$\left.\frac{df(\alpha, \psi)}{d\psi}\right|_{\psi=\psi_x} = 0 \tag{4}$$

Using Equations (2) and (4), we obtain

$$\frac{1}{c^2}(a^2 - b^2)\cdot\sin\alpha\cdot\cos\alpha - \frac{a^2b^2}{c^3}\left(1 - \frac{a^2b^2}{c^2}\cdot\sin^2\psi_x\right)^{-1/2}\sin\psi_x + b(1 - b^2\sin^2\psi_x)^{-1/2}\sin\psi_x = 0 \tag{5}$$

We can measure the transmittance T as a function of ψ and determine ψ_x from the center of symmetry of this curve. Substituting ψ_x into Equation (5), we can calculate the pretilt angle α.

2.2 Analysis of the Measurement Error

In case of the conventional crystal rotation method, the rotation center is fixed in the middle of the cell gap as shown by the point O in Figure 4 and the measurement point P in the cell shifts according to the rotation ψ of the cell because the incident light refracts at the glass substrate. Therefore, in order to obtain the correct pretilt angle, the cell gap of the sample must be perfectly uniform. However, when the cell gap is not uniform, the shift of the measurement point P causes a change of the cell gap as shown in Figure 4, and hence it induces an error in the measurement of the retardation and hence of the pretilt angle (cf. Equation (1)).

In this section, we estimate the measurement error in detail in case of a non-uniform cell gap when using the conventional crystal rotation method. We consider a wedge type cell which has a uniform variation of the cell gap as shown in Figure

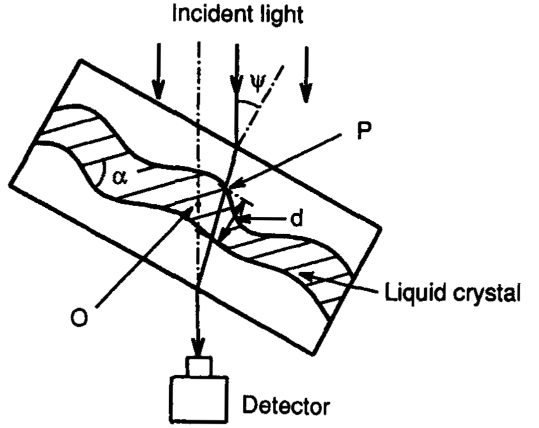

FIGURE 4 Light path through a cell with nonuniform gap.

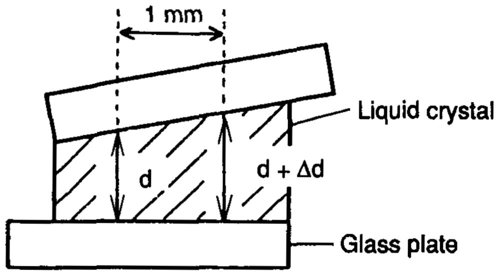

FIGURE 5 Definition of cell gap variation.

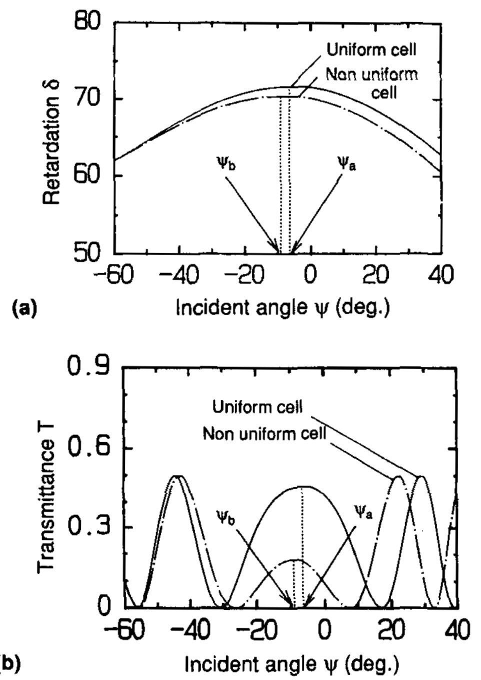

FIGURE 6 Retardation and transmittance of a cell with uniform gap (full line) and a cell with nonuniform gap (dash-point line) (n_1 = 1.76, n_2 = 1.52, d = 30 μm, λ = 632 nm, Δd = 0.2 μm/mm). (a) Relation between incident angle and retardation, and (b) relation between incident angle and transmittance.

5. We define the cell gap variation Δd (μm/mm) as the change of the cell gap when we move 1 mm sideways along the surface of the cell. In Figure 6, we plotted the calculated transmission for the case Δd = 0.2 μm/m (point dash line), as well as for the case of a uniform cell gap (solid line). The transmittance of the uniform cell is symmetrical about ψ_a, that of the wedge cell is symmetrical about ψ_b. From ψ_a we can deduce the correct pretilt angle of the cell, but from ψ_b we deduce an incorrect pretilt angle. The error $\Delta\alpha$ for the conventional crystal rotation method is plotted as a function of the cell gap variation Δd (μm/mm) in Figure 7(a) where the pretilt angle α is a parameter. The error $\Delta\alpha$ linearly increases with the cell gap

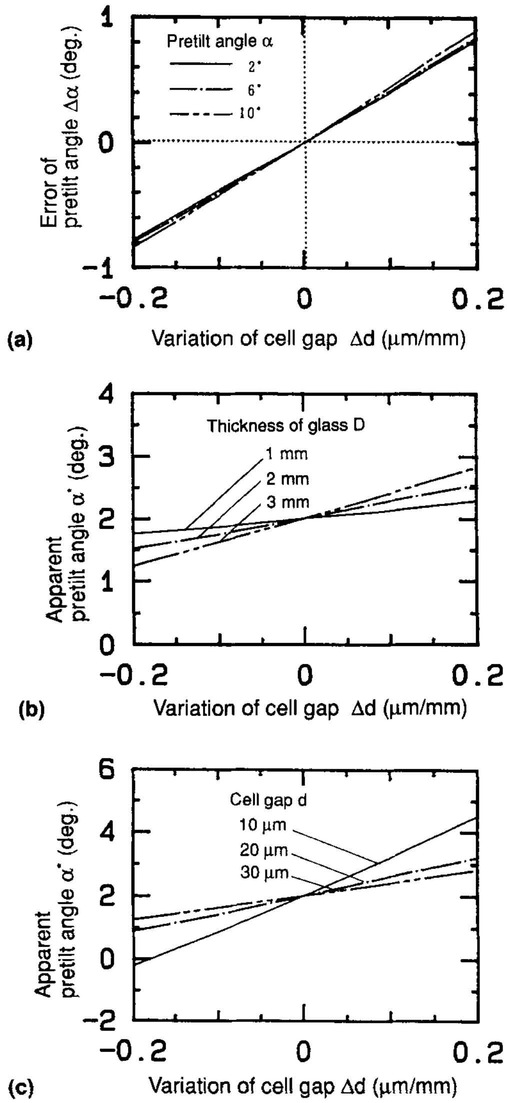

FIGURE 7 Apparent pretilt measured with conventional method as a function of cell gap variation (default values: $D = 3$ mm, $d = 30$ μm). (a) Dependence on value of pretilt, (b) dependence on glass thickness, and (c) dependence on cell gap.

variation Δd. Figures 10(b) and (c) show the effect of the thickness of glass plate and the cell gap on the error.

2.3 Experimental Results on the Measurement Error

In order to confirm the calculated error mentioned in the previous section, we actually measured the pretilt angle by using wedge cells with different cell gap variations. The alignment layer was a rubbed polyimide usually used for TN LCD(AL-

1051 from Japan Synthetic Rubber Co. Ltd.). For every wedge cell, we measured the pretilt at a point where the cell gap is 25 μm. The results are shown in Figure 8. We can see that the measured pretilt angle deviates more largely as the cell gap variation increases. For Δd as large as 0.3 μm/mm the apparent pretilt becomes 3.2°, which is significantly different from the correct value, 2.3°. Our calculated result is also drawn by point-dash line in the figure and is in good agreement with the experimental results.

3. NEW METHOD TO REDUCE THE MEASUREMENT ERROR

3.1 Principle

In the previous section we pointed out that a measurement error of the pretilt angle for a nonuniform cell gap is caused by the shift of the measurement point when the cell is rotated. Therefore, it is possible to reduce the measurement error if we can measure the retardation at a fixed point regardless of the incident angle. Scheffer *et al.*[2] proposed a method in which two cells are used to prevent the shift of the measurement point. One is the sample cell and the other is an empty cell. However, with this method, the empty cell must be made using substrates of the same material and the same thickness as the sample cell and a complex optical system is required to rotate both cells about the same angle and in opposite directions. Here, we propose a new method which compensates for the shift caused by light refraction using only one sample cell. In this method, the rotation center is fixed at a point O_1 as shown in Figure 9.

In Figure 9 we can see that the outgoing beam is shifted relative to the incident beam. In order to measure the transmission, the following setups can be used: (1) a broad light beam and a detector with a small area or (2) a narrow laser beam and a detector with a large area. In our case, we chose the former setup.

Now we determine the optimum position of O_1 to minimize the shift of the

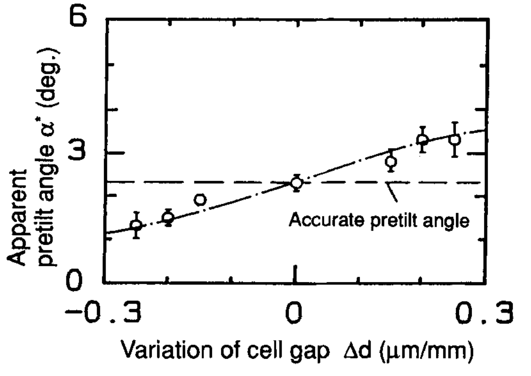

FIGURE 8 Measured value of pretilt angle as a function of the cell gap variation when using the conventional crystal rotation method.

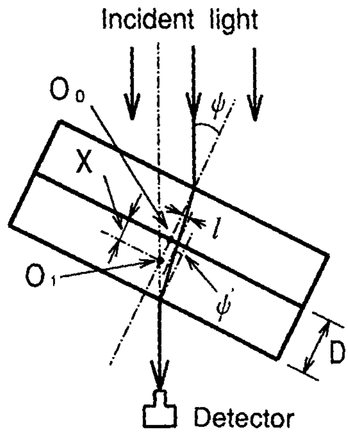

FIGURE 9 Light path when the rotational axis is set at O_1.

measurement point. The shift l in the measurement point caused by cell rotation is given by

$$l = (D - X)\tan\psi - D\tan\psi' \tag{6}$$

where D is the thickness of the glass, X is the distance between the rotation center and the middle of the cell gap and ψ' is the angle between the incident light beam in the glass and the normal of the glass substrate as shown in Figure 9. From Snell's law, we obtain the relationship between ψ and ψ' as

$$\sin\psi = n\sin\psi' \tag{7}$$

When we substitute Equation (7) into Equation (6) we obtain l as a function of ψ. A minimal shift l of the measurement point is required to reduce the measurement error, which means

$$\frac{dl}{d\psi} = 0 \tag{8}$$

From this condition we obtain[8,9]

$$\frac{X}{D} = 1 - \cos^3\psi\left\{\frac{1}{(n^2 - \sin^2\psi)^{1/2}} + \frac{\sin^2\psi}{(n^2 - \sin^2\psi)^{3/2}}\right\} \tag{9}$$

For any variation of ψ, the rotation center should satisfy this equation. However it is not convenient to shift the rotation center according to the angle of the cell. Therefore, we fix the rotation center at an optimum point O_1, for which the experimental error is smallest. In principle the error becomes zero when X/D satisfies Equation (9) for $\psi = \psi_x$. Figure 10 shows this optimum X/D as a function

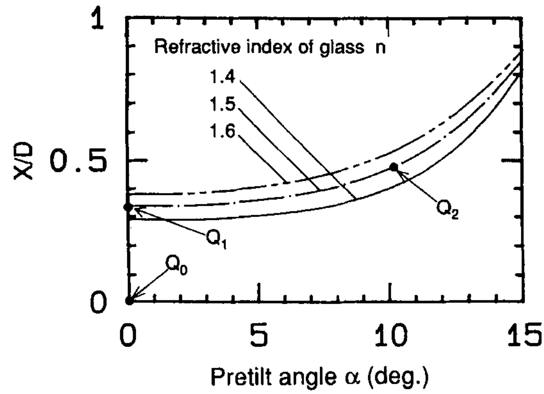

FIGURE 10 Relative between pretilt angle and optimum position of rotation axis X/D.

of the pretilt angle α. As shown in this figure the optimum value of X/D is a function of the refractive index n of the glass plate and of the pretilt angle α, so that we must adjust the rotation center according to the value of n and an approximated value for α. In the range of $\alpha = 0°-10°$ X/D is almost independent of α. Therefore, when the pretilt angle α is expected to be between 0° and 10°, we can set X/D according to $\alpha = 0$ rough approximation. When the pretilt angle is larger than 10° and no estimate is known, we set X/D by assuming $\alpha_0 = 0°$ and obtain a first result α_1. Then we can deduce a better X/D from α_1 Figure 10 and can measure a more accurate pretilt angle α_2.

In the case of measurement setup (2) with a narrow laser beam and a large detector, the method of calculation remains the same except that the rotation point O_1 is on the other side of the cell gap.

3.2 Analysis of the Measurement Error Using the New Method

We will estimate the error of the measured pretilt angle by a numerical example for the new method explained in the previous section. Let us investigate the case where we do not know a first estimate and we have to apply the iterative procedure. In order to help us understand this procedure, we have calculated the apparent pretilt angle as a function of the X/D value. The result and the procedure are shown in Figure 11. In the case of a wedge type cell with cell gap variation Δd = 0.1 μm/mm, refractive index of the glass $n = 1.5$, thickness of the substrate D = 3 mm and pretilt angle $\alpha = 10°$, we start by fixing the rotation center $(X/D)_0$ = 0.34, which we deduced from Figure 10 for a pretilt angle $\alpha = 0°$ and $n = 1.5$ (see Q_1). With this rotation center we measure a first approximation for the pretilt angle, $\alpha_1 = 10.15°$. From Figure 10 we deduce a better rotation center $(X/D)_1$ = 0.49 (see Q_2) and measure a more correct value of the pretilt angle. The result becomes $\alpha_2 = 10.04°$, which agrees well with the correct value of $\alpha = 10°$.

By similar calculations, we obtained the same accuracy for cells with other pretilt angles. Hence, we conclude that the error of our new procedure is less than 0.05°. By the way, a small but essential error is inevitable even if the incident point of the light beam at the liquid crystal interface does not shift, the point at the other

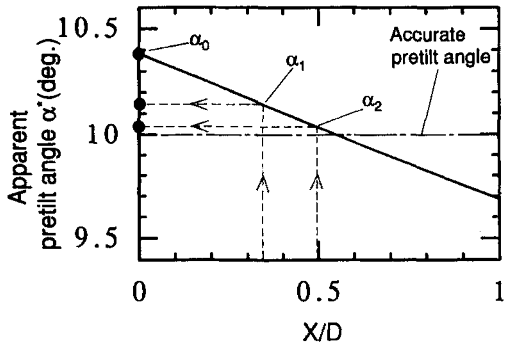

FIGURE 11 Relation between the position of the rotation center X/D and measured apparent pretilt angle α^* (Δd = 0.1 μm/mm).

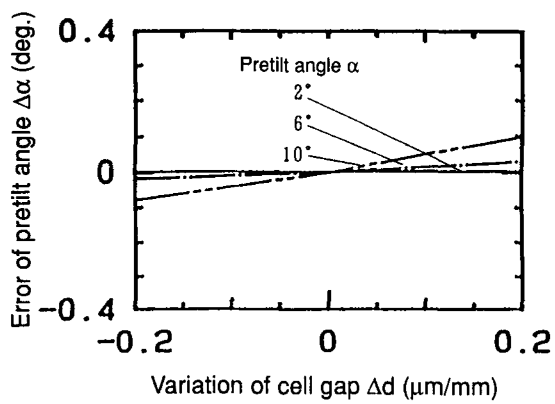

FIGURE 12 Relation between the cell gap variation and the error of the pretilt angle when using the improved crystal rotation method (n = 1.5, d = 30 μm, D = 3 mm).

interface where light beam comes out slightly shifts according to the incident direction and therefore, the thickness of the layer changes a little. Therefore, there is no need to measure more than two iterations to improve the accuracy.

By numerical calculation, we estimate the effect of the thickness of the glass substrate D, the cell gap d and the pretilt angle on the magnitude of the measurement error using the new method. We found that there is almost no influence of these parameters except for the pretilt angle α. There is a slight influence of the pretilt angle α as shown in Figure 12, but it is negligible small.

Finally we would like to remark that thanks to our method the relative error due to the nonuniform cell gap is reduced to 1–2%.

3.3 Experimental Verification of the New Method

In order to verify the theoretical result experimentally, we measured the pretilt angle by the new method. Figure 13 depicts the measured pretilt angle as a function of the relative variation of the cell gap Δd. In Figure 13 we also included the results of Figure 8 obtained by the conventional method. The comparison clearly dem-

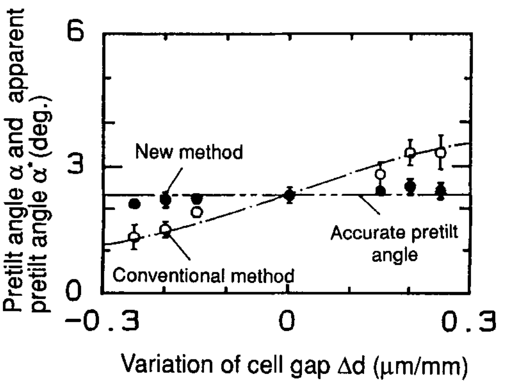

FIGURE 13 Measured value of pretilt angle as a function of the cell gap variation when using the conventional and improved crystal rotation method (α = 2.3°, d = 25 μm, D = 2.8 mm).

onstrates how our new method improved the accuracy of the pretilt angle measurement.

4. CONCLUSION

In this paper, we explained how a nonuniform cell gap causes a significant error in the measured pretilt angle when the conventional crystal rotation method is used. We showed that the error is nearly proportional to the thickness D of the glass substrates as well as to the cell gap variation Δd. The error also becomes larger when the cell gap decreases. We propose a new improved crystal rotation method to minimize the error. We showed that with this method the pretilt angle can be measured more accurately when the cell gap of the sample is not uniform.

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