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EQUAL OPTICAL PATH BEAM SPLITTERS BY USE OF AMPLITUDE-SPLITTING AND WAVEFRONT-SPLITTING METHODS FOR PENCIL BEAM INTERFEROMETER*

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Equal optical path beam splitters by use of amplitude-splitting and wavefront-splitting methods for pencil beam interferometer

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ABSTRACT

A beam splitter to create two separated parallel beams is a critical unit of a pencil beam interferometer, for example the long trace profiler (LTP). The operating principle of the beam splitter can be based upon either amplitude-splitting (AS) or wavefront-splitting (WS). For precision measurements with the LTP, an equal optical path system with two parallel beams is desired. Frequency drift of the light source in a non-equal optical path system will cause the interference fringes to drift. An equal optical path prism beam splitter with an amplitude-splitting (AS-EBS) beam splitter and a phase shift beam splitter with a wavefront-splitting (WS-PSBS) are introduced. These beam splitters are well suited to the stability requirement for a pencil beam interferometer due to the characteristics of monolithic structure and equal optical path. Several techniques to produce WS-PSBS by hand are presented. In addition, the WS-PSBS using double thin plates, made from microscope cover plates, has great advantages of economy, convenience, availability, and ease of adjustment over other beam splitting methods. Comparison of stability measurements made with the AS-EBS, WS-PSBS, and other beam splitters is presented.

Keywords: Beam splitter, pencil beam interferometer, equal optical path, Long trace profiler, phase shift, frequency drift

1. INTRODUCTION

The pencil beam interferometer developed by Von Bieren [1,2] in 1982-1983 is a very useful instrument for making precision surface profile and small angle measurements. The pencil beam interferometer is a precision angle measurement instrument. In order to test the small angle variation accurately, a pair of parallel pencil beams is sent out to a reflective surface under test. The pencil beams are scanned across the surface. The reflected beams are deviated according to the local slope at every scan point, and then they are focused to the focal plane of a Fourier transform (FT) lens, where an interference fringe is produced. The fringe displacements caused by angle variations are measured by a detector, from which a surface slope profile can be generated. The interference fringe pattern formed by the interference of the two pencil beams can be viewed as a Young's double slit pattern.

The pencil beam interferometer principle is used in the long trace profiler (LTP), developed by Takacs and Qian [3], which has been used to test aspheric mirror figure in the shape of conics, cylinders, toroids, hyperboloids, paraboloids, ellipsoid, as well as in the application of small angular monitoring [4]. Several versions of the LTP have been developed for solving specific measurement problems, such as the standard commercial version, the LTP II, a penta-prism LTP (PPLTP)[5], an in-situ LTP (ISLTP)[6,7], a vertical scan LTP (VSLTP)[8], and a portable LTP (PTLTP)[9].

2. EQUAL OPTICAL PATH BEAM SPLITTER AND BEAM SPOT PATTERN

The beam splitter for creating two parallel beams is the most important component in the pencil beam interferometer. Both amplitude-splitting beam splitters (AS-BS) and wavefront-splitting beam splitters (WS-BS) with the characteristic of equal optical path can be used in a pencil beam interferometer. Fig. 1(a) shows the beam splitter used by von Bieren[1,2]. It is a non-equal optical path beam splilter. The LTP II uses a "zero-path-difference" AS-BS, which is an equal path beam splitter (Fig. 1(b)). One pencil beam is divided into two perpendicular beams by a beam splitter. Each beam is reflected back by a right angle prism to the beam splitter again, and both beams are directed to exit in a parallel direction, but with a separation distance between them that is adjustable. The two exit beams are of an equal optical path with the ability to change the separation distance by moving one right angle prism perpendicular to beam. A new amplitude-splitting equal optical path beam splitter (AS-EBS) (Fig. 1(c)) comprised of two cemented prisms, and a new wavefront-splitting phase shift beam splitter (PSBS) (Fig. 1(d)), which uses a phase shift method are described below. The AS-EBS and PSBS have the unique characteristics of being both monolithic and equal optical path.

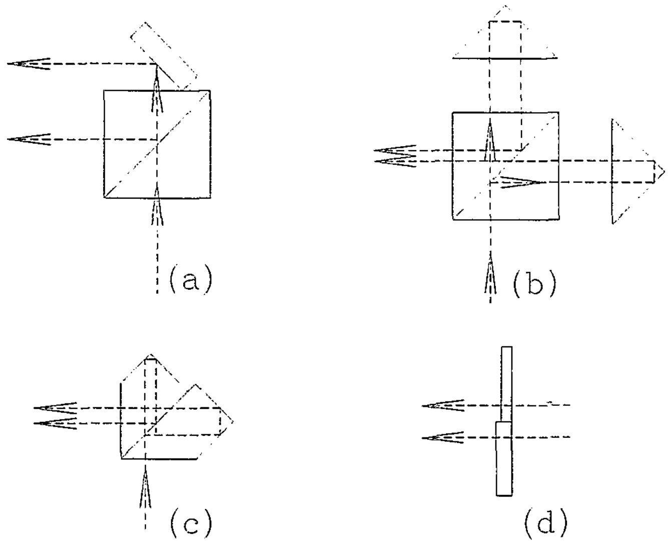

Fig. 1: Different beam splitters for pencil beam interferometer:
(a) Von Bieren's beam splitter
(b) Beam splitter used in LTP II
(c) Equal optical path beam splitter (AS-EBS)
(d) Phase shift beam splitter (PSBS)

If the two parallel beam components (Fig.2(a)) in pencil beam interferometer have the same optical phase, the beam spot in the image plane will have its maximum at the center of the beam spot (Fig. 2(b)). In general, a pencil beam profiler uses two parallel beams with a π phase shift between them as a probe in order to produce a minimum at the center of the beam spot (Fig. 2(c)). In the case of the LTP II, the π phase shift is set by displacing one right angle prism a distance of $\lambda/4$ in the incident beam direction.

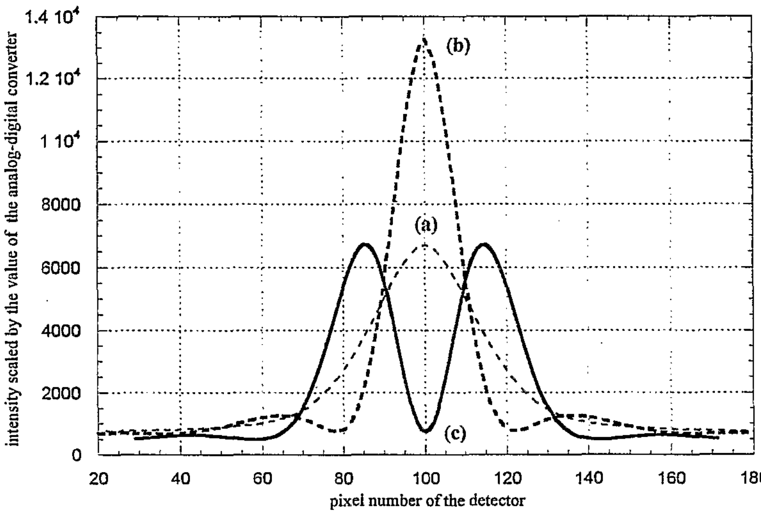

Fig. 2: Beam spot pattern at the focal plane of the FT lens:
(a) A single pencil beam
(b) Double beams combined without optical path difference between two beams
(c) Double beams combined with a π phase shift between two beams

The fringe spot size is determined by Airy diffraction disk, its diameter $a = 1.22 * \lambda * f / d$, where d is the diameter of two pencil beams, f is the focal length of the FT lens. Inside the spot, the interference fringe period, H, is determined by the separation distance, D, between the two parallel pencil beam components and the FT lens focal length according to Fraunhofer diffraction in a Young's double slit experiment: $H = f * \lambda / D$.

Please note that the term "equal optical path" is used to denote two parallel pencil beams that have an optical path difference of less than about $\lambda/2$.

3. EQUAL OPTICAL PATH REQUIREMENT

The major reason for the success of the Long Trace Profiler is the use of a "zero-path-difference beam splitter" in the pencil beam interferometer[3]. A non-equal optical path system will produce an error if the frequency or wavelength of the light source drifts during the measurement.

A beam splitter splits a pencil beam into two parallel beams I and II. The two beams propagate through the system and accumulate an optical path difference (OPD), denoted by δL (Fig.3). For a given wavelength $\lambda 1$, this OPD results in a particular phase difference N1 between two propagating wavefronts after they emerge from the beam splitter.

$$N1 = \delta L / \lambda 1$$

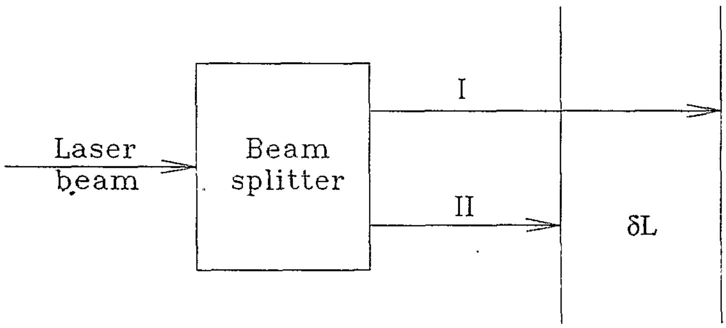

Fig. 3 Optical path difference of two parallel beams I and II

If the $\lambda 1$ is fixed, the interference fringe will not move because there is no phase change between two beams. However, for a different wavelength $\lambda 2$, the phase difference N2 will be different from N1

$$N2 = \delta L / \lambda 2$$

This means, over the same OPD, there are different phase differences between two beams for $\lambda 1$ to $\lambda 2$. The phase shift δN between the phases differences N1 and N2 will produce an interference fringe movement as an error in the measurement.

$$\delta N = N1 - N2 = \delta L * \delta\lambda / (\lambda * \lambda) \qquad (1)$$

where $\delta\lambda = \lambda 2 - \lambda 1$. The phase shift is dependent upon the values of the optical path difference, δL, and laser frequency drift $\delta\lambda$. The tolerance on the allowed difference between the optical paths in the beam splitter can be determined by the laser frequency drift and the desired measurement error δN for the pencil beam interferometer.

$$\delta L = \delta N * (\lambda * \lambda) / \delta\lambda \qquad (2)$$

For the purpose of estimation we can use one or two times of laser longitudinal mode space as the wavelength drift $\delta\lambda$ in the case of using a He-Ne laser, and we use the value of 5 Å as $\delta\lambda$ in the case of using a diode laser which corresponds to a frequency drift produced by temperature variation of 2 degrees (Table 1).

Table 1 Estimated off-equal optical path condition for allowed test error of 0.05 μrad

Light source	Longitudinal mode space (MHz)	wavelength variation $\delta\lambda$ ((Å)	Fringe movement δN (λ))	Allowed Max OPD δL (μm)
250 mm He-Ne (633nm)	687	0.0092	1/5600	77.7
450 mm He-Ne (633nm)	380	0.0051	1/5600	140.2
Diode laser (635 nm)		5.0	1/5600	0.14

For a sub-microradian measurement, an angle error E of less than 0.05 μrad produced by frequency drift is a necessary requirement. In an f = 750 mm pencil beam interferometer, a 0.05 μad angular error tolerance is related to an interference fringe movement $\delta h = 0.075$ μm on the detector

$$\delta h = E * 2 * f \tag{3}$$

As described above, δN is phase shift related to a fringe movement, which can also be calculated by

$$\delta N = \delta h / H \tag{4}$$

where H is the interference fringe period on detector. 0.075μm movement is 1 / 5600 fringe if two peaks distance of the interference fringe is set to 30 pixels on detector. Then the allowed maximum OPD, δL, can be obtained according to the equation (2) and is shown in Table 1.

Obviously an equal optical path system is absolutely necessary for a precise pencil beam interferometer. As described in previous papers, a non-stabilized He-Ne laser is sufficient for the precise measurement with an equal optical path system even with a larger tolerance. However, use of a diode laser requires an exactly equal optical path system if precise test results over a long period of test time is involved, because the diode laser has large frequency drift.

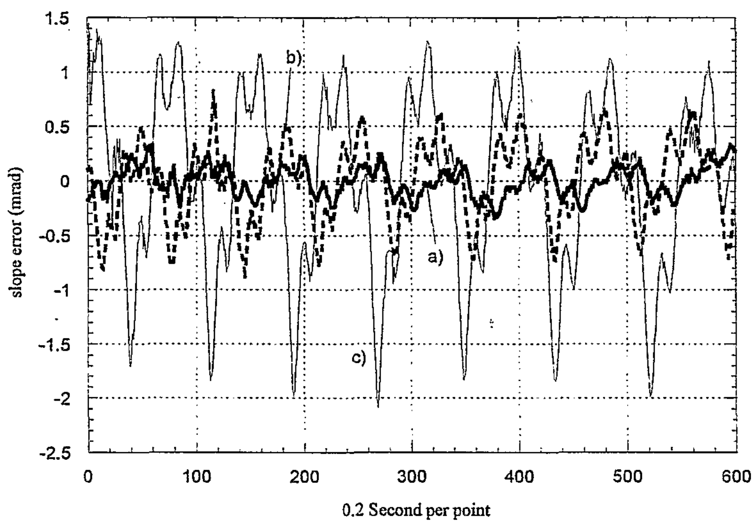

Fig. 4 Angle errors produced by frequency drift of a 250 mm He-Ne laser during warm-up from a cold start for different values of non-equal optical paths.
(a) Equal optical path without inserting glass plate
(b) Inserting a 1 mm glass plate into one path of LTP beam splitter
(c) Inserting a 2 mm glass plate into one path of LTP beam splitter

Fig. 4 shows recorded angle errors produced by frequency drift of a 250 mm long He-Ne laser during a warm-up from a cold start for different values of non-equal-optical-paths. It is done on a LTP II zero-path-difference beam splitter system[3]. In order to create large non-equal optical path conditions, glass plates of 1 mm and 2 mm were inserted into one arm of the beam splitter. Then we start a stability scan on the LTP II and simultaneously switch on He-Ne laser. Due to the increasing temperature, the He-Ne tube expands, resulting in a variation of laser cavity length. This causes the longitudinal mode frequency to continuously sweep within the Doppler broadened gain curve, which produces oscillating slope error curves. Thicker glass plates produce larger slope errors. The curve (a) is assumed to be an equal optical path condition. However, it still has a small oscillation due to the alignment error of equal optical path, and due to fringe intensity oscillation. The measured angle error roughly agrees with the calculated value.

4. EBS BY USE OF AMPLITUDE-SPLITTING METHOD

A new equal optical path beam splitter was developed for the PTLTP[10]. It is an amplitude-splitting beam splitter (AS-EBS) (Fig.5), which divides the amplitude of one wave front into two partial amplitude wave fronts. The AS-EBS consists of only two right angle trapezoidal prisms, A and B. The vertex opposite the right angle is a 45° angle. The longer bases, A2 and B2, are cemented together with a beam splitting film between them. The beam splitter is designed for equal reflectance and transmittance. The surfaces of the longer faces A4 and B4 (beam entrance and exit faces) are coated with anti-reflecting films.

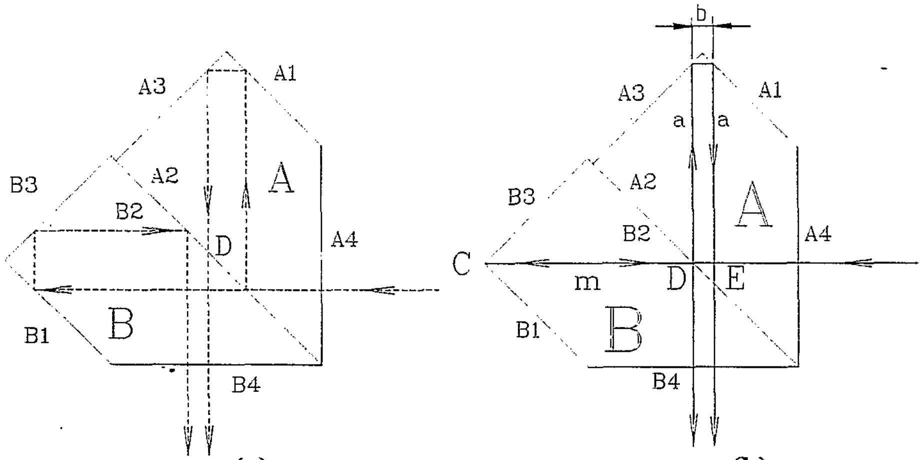

Fig. 5 (a) Equal optical path beam splitter (AS-EBS)
(b) Definition of equal optical path condition: $2m = 2a + b$

A single pencil beam from a laser or collimated fiber with a diameter of about 1 mm is incident on surface A4 at normal incidence. It is then divided into two mutually perpendicular pencil beams by the beam splitting film. The two beams are each reflected around their respective 90? vertexes and return to the beam splitting surface where they proceed to the exit face, B4. At the exit face B4, the desired beams are exactly parallel and are separated by a fixed distance that depends on the parameters that define the beam splitter construction. The AS-EBS has all the desirable characteristics of being equal optical path, monolithic, no moving parts and no air gap, which make it very stable.

In order to maintain equal optical path, the dimensions and relative positions of two prisms need to fulfill a certain condition of $2m = 2a + b$ [10]. As a result, the two prisms have slightly different thicknesses, and the two short faces A3 and B3 of the prisms are not exactly coplanar.

5. EBS BY USE OF WAVEFRONT-SPLITTING METHOD

Another way to produce two parallel beams with separation is by using a wavefront-splitting method[11,12]. The Young's experiment, Fresnel's double mirror, Fresnel's double prism and Lloyd's mirror are the most common examples of the wavefront-splitting method, but only Young's double slits can produce parallel beams.

A wavefront-splitting phase shift beam splitter (WS-PSBS) was introduced recently by Y. Zhao, et al.[13]. A phase shift step is a plate with a step on a surface. The step is made by etching in order to produce a fixed phase shift between two parts of a pencil beam, which spans over the step.

In Fig. 6 a collimated pencil beam A is incident on the center of a phase shift beam splitter, for example, a phase step plate B. The beam A has the same phase over its entire plane wave front. After passing through the phase step plate, the two half-beams C1 and C2 are phase shifted by a constant amount. The phase shift beam splitter produces a phase difference of π or any other phase that is required between the two half-beams (or partial beams). The plane wave front then becomes a step wavefront. It is a wavefront-splitting phase shift beam splitter (WS-PSBS), or simply a phase shift beam splitter (PSBS). A pencil beam combined with a PSBS can be considered as originating from double slits with a phase shift between the component beams.

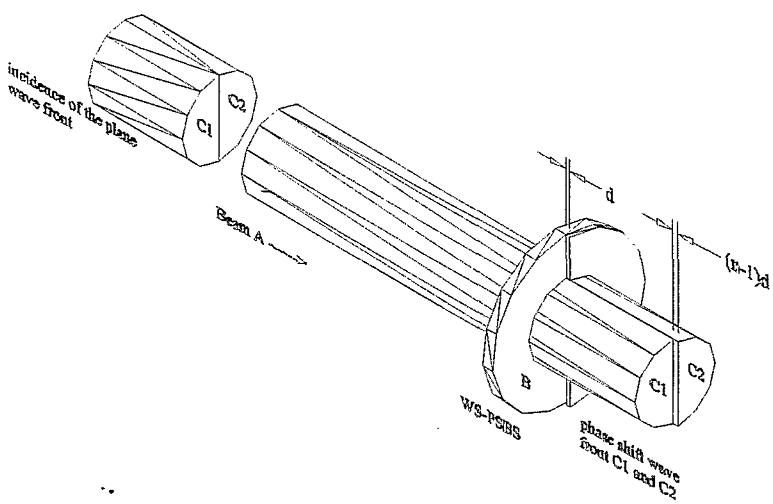

Fig. 6 Principle of Wavefront-Splitting Phase Shift Beam Splitter (WS-PSBS)

1) Methods to create wavefront-splitting phase shift beam splitter

Any component with the ability to create different optical paths between two adjacent half (or less) wavefronts can be used as WS-PSBS. Following are some production methods, most of which we have experienced.

a) Etching a step with a height to produce π phase shift on a transparent material, for example, on a glass. The step height $d = \lambda/(2(n-1))$, where the n is the refraction index of the material, λ is the applied light wavelength (Fig.6 and Fig. 7(a)).

b) Coating a partial film on a transparent substrate to produce π phase shift. The film thickness should be $d = \lambda/(2(n-1))$, where n is the refraction index of the film (Fig. 7(b)).

c) Inserting very thin phase shift film, foil or plate into the half pupil, leaving the other part of the beam pupil blank. The thickness of the film or plate to produce a π phase shift (Fig. 7(c)) is $d =(2k+1)\lambda/(2(n-1))$, where k is an integer, which should be as small as possible determined by availability of a thin film or plate. Larger k means thicker film or plate, which will decrease the test accuracy due to the frequency drift of the light source. However, recent technology can provide for very thin films or plates. For example, a 0.03 mm thick microscope cover plate is available, which fulfills the requirement for the LTPs.

d) Using two thin plates with different thicknesses or optical path to create π phase shift (Fig. 7(d)). The thickness of two plate should be: d and $d_1 = d + 1 / (2(n_1))$.

e) Using two thin plates with equal thickness but with different setting angle to produce π phase shift (Fig. 7(e)).

f) Changing the refractive index in a half partial area of a plate in order to vary the phase shift, for example, by induced refraction index modification by strong laser.

The term "phase shift" described in this paper is used to indicate the phase difference between two output beams.

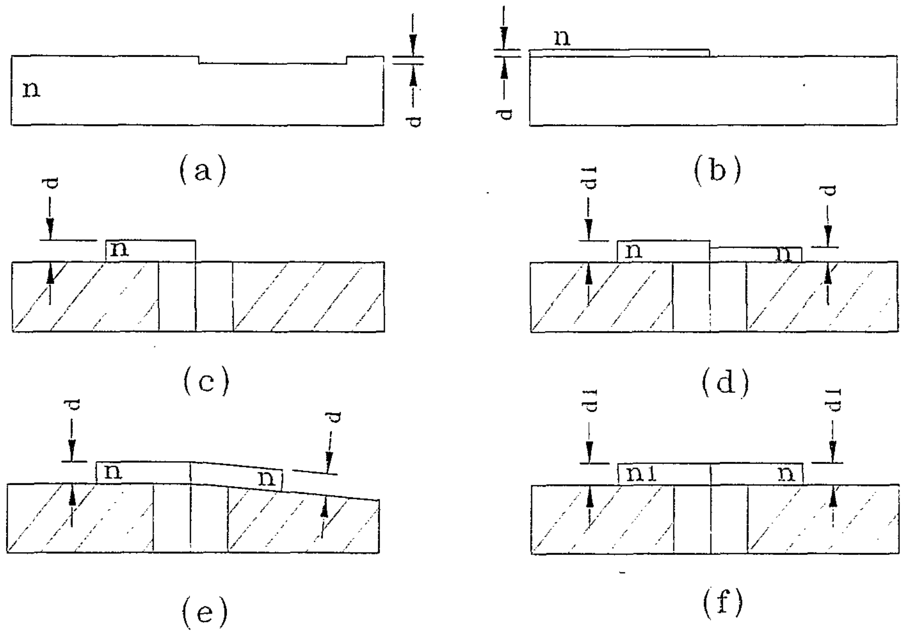

Fig. 7 Methods to producing wavefront-splitting phase shift beam splitters
(a) Etching a step on transparent plate
(b) Coating a film on transparent plate
(c) Placing a very thin transparent plate on the half aperture, leaving the another half aperture blank
(d) Placing two thin transparent plates to produce $\lambda/2$ optical path difference
(e) Placing two identical transparent plates with a different angle
(f) Placing one plate with two different refractive indices

Microscope cover plates are the preferred items for the methods of (c), (d), and (e). They are very convenient, inexpensive, and effective. Of course, a thicker plate is also suitable. Our reasons for recent development of the WS-PSBS are for improving stability as with the ESB-AS, further decreasing the size of the LTP, reducing the cost, and for simplifying the manufacturing.

Setting the required phase shift with the cover glass slides is quite easy. Inserting the adjacent pair of cover plates (only one cover plate in the case of (c)) into the optical path of the LTP and adjusting one relative to the other, one can see and adjust the phase shift by observing the fringe pattern on the detector. Because the thickness variation in a practical plate is much larger than the $\lambda/2$, it is easy to find a suitable thickness somewhere on the plate.

Because the WS-PSBS is monolithic and is used in the condition of equal optical path (only a slight deviation in the case of Fig. 7(c)), the instrument stability is perfect like the AS-EBS. The restriction of the WS-PSBS is that larger or smaller beam separations are difficult to set.

2) Double Thin Plates (DTP) as WS-PSBS

The methods (d) and (e) use double thin plates but in different ways. The two thin plates are in contact with each other. In the case of method (e) two plates are set at different angles relative to the incident beam. The two thin plates are nearly identical (in refractive index and thickness) as they can be cut from an adjacent area on a same cover plate.

The principle of the method (e) is based on the principle that if a parallel transparent plate is tilted away from the normal incidence position, the optical path in the plate will increase as a consequence, but the output beam is still parallel to the input beam. We can set the tilt angle to create a π phase shift between two partial wavefronts even if the two thin plates are absolutely identical.

Fig. 8 is the optical schematic of the portable LTP (PTLTP) with the cube beamsplitter replaced by the double thin plates.

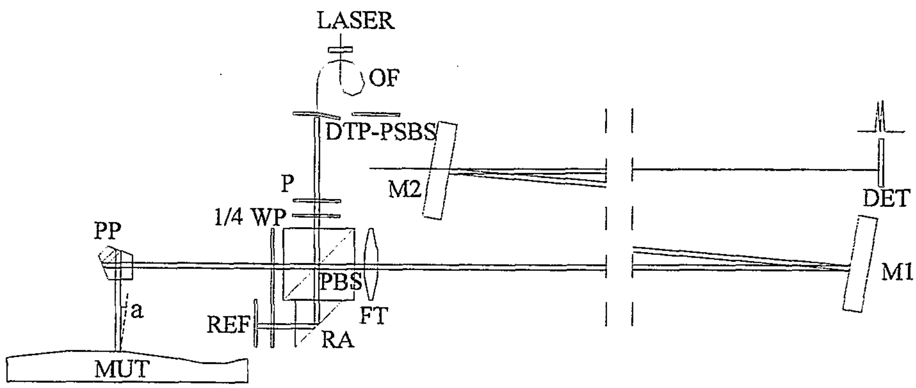

Fig. 8. Optical schematic of the portable LTP (PTLTP) by use of the double thin plates

3) Advantages of the Double Thin Plates (DTP) method

? **Stable monolithic structure:** The double thin plates are glued as one monolithic block without any relative moving parts, which makes the instrument very stable.

? **Stable characteristic of a zero OPD:** As the OPD of the DTP is only $\lambda/2$, it falls into the category of the equal optical path beam splitter, so the frequency shift of the light source will not produce significant fringe movement. It makes the instrument using the DTP highly stable and accurate.

? **Easy to produce:** The height of the phase shift step needs to be controlled well during fabrication or be selected to suit the OPD requirement of $\lambda/2$. It is costly to produce in terms of both time and money. In contrast, the double thin plates method is much easier to produce.

? **Good availability:** The cover plate is a common item used for microscope applications.

? **Near-zero cost:** The cover plates are very inexpensive, and can be cut in small pieces. So it is almost no cost for a WS-PSBS.

? **Easy to adjust:** If the height of an etched phase step is in error, it is not possible to change it to fulfill the π phase condition. On the other hand, in the case of the DTP, the thin plate is easy to replace or easy to adjust tilting angle to suit the $\lambda/2$ OPD condition accurately.

6. STABILITY MEASUREMENT COMPARISONS

Fig. 9 shows the stability test results for three different beamsplitters: (a) with a zero optical path beam splitter used by LTP II, (b) with an equal optical path beam splitter (AS-EBS) used by the PTLTP, and (c) with a double thin plates, WS-PSBS, used by the MINI-LTP. The oscillations of the stability scans with the double thin plates beam splitter WS-PSBS and with the equal optical path beam splitter AS-EBS are about 0.43 and 0.45 μrad rms over 24 hours and 15 hours respectively, even without the need of reference subtraction. Y. Zho reported their test result of 0.58 μrad rms over 10 hours by use of the etched step WS-PSBS. This stability is much better than the zero-optical-path beam splitter used by the LTP II due to the characteristics of the monolithic structure and equal optical path.

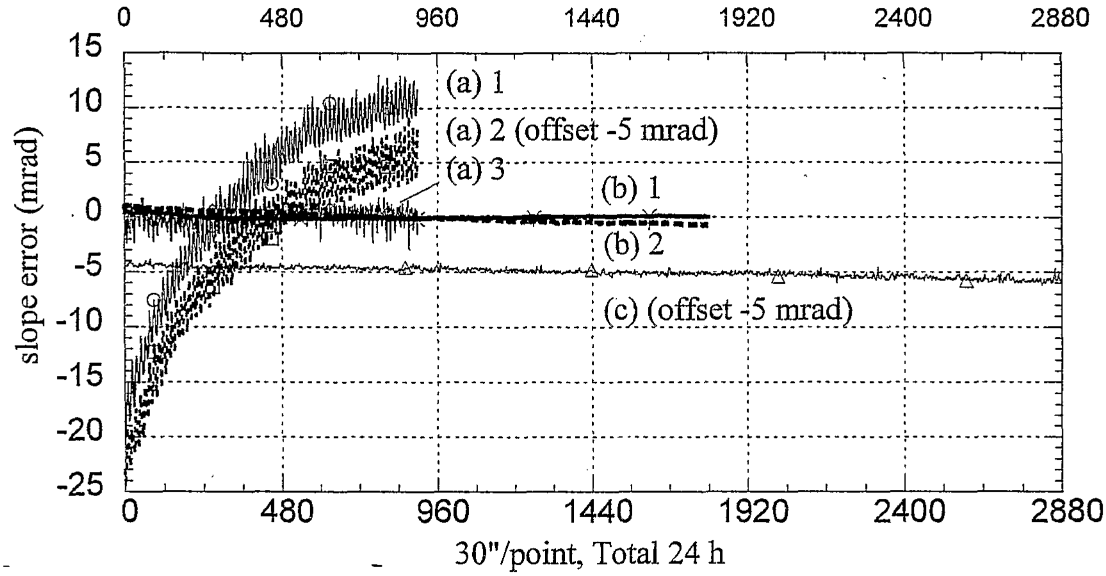

Fig. 9. Stability measurement results of different beam splitters
(a) Zero-optical-path beam splitter used by LTP II
1. Sample beam
2. Reference beam
3. Difference between sample and reference beams, 0.75 µrad rms, over 7.5 h
(b) Equal optical path beam splitter (AS-EBS) used by the PPLTP
1. EBS test 1, 0.15 µrad rms, over 15 h
2. EBS test 2, 0.45 µrad rms, over 15 h
(c) Double thin plates DTP PSBS used by the MINI-LTP, 0.43 mrad rms, over 24 h

7. CONCLUSION

The equal optical path beam splitter is absolutely necessary for the pencil beam interferometer. The Wavefront-Splitting phase shift beam splitter (WS-PSBS) and the equal optical path beam splitter (AS-EBS) are well-suited for use in a pencil beam interferometer. The characteristics of monolithic and equal optical path in the WS-PSBS and AS-EBS make the interferometers very stable. In addition to these excellent merits, the WS-PSBS by use of the double thin plates has the advantages of economy, convenience, availability, and easy adjustment. The stability of the LTP using them is about 0.43 µrad rms over 24 hours without the need for reference subtraction.

8. ACKNOWLEDGMENTS

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