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Content

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Abstract This report presents a cheap design and it's experimental results on the development of interferometry optical system and a further consideration to apply this optical system to a new refractometer. This newly developed optical system is based on the conceptual approach to design a high accuracy interferometer. The principles to design a high accuracy interferometer is summarized by introducing the concept of medimum interface. These design principles is revealled in the term of COMMEN PATH AND DOUBLE ATTACHMENTS. The cheap solution can be relized based on the concept 'commercially available '-- using all commerciallly available optical elements and easily to be used in any commercially available laser measuring system. The proposed optical system follows ideas to use the inside featuer existed in the optical system as much as possible. Except for the concepts mentioned above, the optical path is spatially arranged which is an relative cheaper solution to build a common path, double attachments interferometer. One more interesting feature in the system is that two frequency components and two polarized direction components pass through every optical elements in the same length, so in principal length changes are eliminated. Additionaly, the proposed refractometer configuration makes it possible to elimate the errors from the window bending and thickening, so that relative higher accuracy refractometer can be designed.

1. INTRODUCTION

With the progress of precision engineering, there is an increasing requirement on the accurate measurement. Laser interferometers play an important role in this field due to the characteristics of the laser and Michelson interferometer. The basic measuring unit of a laser interferometer is the optical change between the measuring beam and reference beam. As result the mechanical length is evaluated by the laser wave-length, refractive index, electronic counter and optical path factor. The accurracy of the interferometer mainly depends on the first three elements. In the real application conditions, the environment refractive index will present significant error with respect to calibration value due to the environmental condition change. Research [1] [2] and practical application [3] [4] have shown that the interference refractometer is a convenient means for the compensation of refractive index error or change.

The need for more accurate measurements requires a new class of interferometers that minimize the shortcomings of the typical interferometers presently used in laser measurement system. Normally an interferometer consists of a number of optical elements, such as beamspliter(s), mirror(s), retrorefletor(s) and waveplate(s), that are arranged so that the reference and measurement beams travel different optical paths. These interferometers are susceptible to path length errors due to thermal and mechanical effects. Those effects can be eliminated by using principles of common path and symmetrically double attachments. These two concepts have been already adopted by the modern design of interferometers, because these concepts make a design use the potentialities of the inferferometer system as much as possible. Based on these concepts a new type of interferometer - stable interferometer - was developed. in the early 1960 Dyson [7] proposed this type interferometer for traditiont interferometer, named " very stable interferometer. In the laser interferomery measuring system, both Hewllet-Packard [3] and Zygo [4] use this type interferometer. Basic characterestics of this type interferometer are the Double-attachment, Commen-path and Plane-mirror (DCP interfereometer).

This report conisistsof two main parts, first part is the conceptual approach to the design a high accuracy interference system. By introducing the interface concept, the principles of common path and symmetrically double attachment are clearfied. Second part is the design approach of a cheaply high accuracy interence system, which is realized by usage of penta prism.

2. Conceptual Approach to Design a High Accuracy Interference System

The optical length change is a measuring factor in the interfernce system. The optical length consists of two parts, mechanical length and relavent refractive index. In an interference system there may be several different combinations of different mechanical lengthes with their local refractive indexes and measuring beam may also pass through different these combinations. Therefore, a general expression of optical length change in an interference system can be written as follow:

$$OLC = \sum_{i=1}^{k} ML_{mi} * n_{i} - \sum_{j=1}^{l} ML_{rj} * n_{j} \qquad (1)$$

where

- OLC - Optical Length Change;
- ML - Mechanical Length;
- m - measurement;
- r - reference;
- k - number of parts passed by measuring beam;
- l - number of parts passed by reference beam;

In the case of interferometer this equation becomes as following:

$$OLC = MML * n_{me} + OLE \qquad (2)$$

and for the application of the refractometer equation reads

$$OLE = CL * (n_{e} - 1) + OLE \qquad (3)$$

where

- OLE - Optical Length Error;
- MML - Measuring Mechanical Length;
- CL - Chamber Length of refractometer;
- me - measuring environment;
- e - environment;

In general the optical error expression has a similar form with the optical length expression (1), except the measuring part in the optical length expression. In order to handle it easier, the expression of optical length error consists of two parts, interface error and non-common-path error, which is written as follow:

$$OLE = \sum_{i=1}^{a} OLE_{IOi} + \sum_{j=1}^{b} OLE_{NCj} \qquad (4)$$

where

a - number of intefaces;
b - number of uncommon pathes;

The non-common-path error is defined as following (the detail is given in appendix): i.e.

$$OLE_{NC} = \sum_{i=1}^{k} ML_{Mi} * \Delta n_{Mi} - \sum_{j=1}^{l} ML_{Rj} * \Delta n_{Rj} \qquad (5)$$

$$OLE_{NC} = \pm \sum_{i=1}^{\pm(k-l)} ML_{M(R)} * \Delta n_{M(R)}$$

This expression means the local refractive indexes may be different in the different spatial elementary parts. If there are some parts in which two beams pass through with the same lengthes, OLE will be reduced. Especially if two beams passes through all the parts involved in the system the non-common-path error becomes zero. This comes to the approach to design an accurate interferometer, i.e. COMMEN PATH principle. This principle tells us that design of high accuracy interferometer must arrange the optical system so that the measuring beam and reference beam go through all the parts in the system with the exactly same mechanical length or as much as possible.

The interface-error is the error due to the unwanted mechanical length change in the interface of two media, such as laser beam goes from air into the optical element. Under the conditions of common path the error may express as following form:

$$OLE_{io} = \sum_{i=1}^{N} (\Delta ML_{ri} - \Delta ML_{mi}) * (n_1 - n_2) \qquad (6)$$

where

ΔML - Local mechanical length error in the attaching point;
1,2 - indication for medium;
N - number of the interface in the system.

This expression indicates that the beam, either measuring beam or reference beam, will generate an optical length error in an interface between two different media and there exists mechanical error in this interface. This error depends on the local error of attached optical elements and the difference between refractive indexes in the two side of interface. The concept of inteferace is illustrated in fig. 1. Suppose that two sides of interfaces

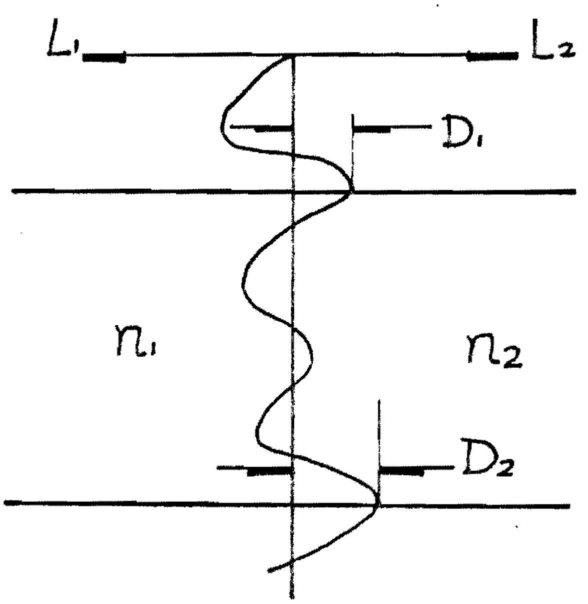


Fig. 1 Illustration of interface concept

separately have mechanical lengthes L1 and L2, the mechanical (error) change of attacthing points for two beams are the ΔML_m and ΔML_r. Hence, corresponding to this interface the optical length error is that:

$$OLE = [(L1-\Delta ML_r)-(L1-\Delta ML_m)] * n_1 + [(L2+\Delta ML_r)-(L2+\Delta ML_m)] * n_2$$
$$= (\Delta ML_m - \Delta ML_r) * (n_1-n_2) \qquad (7)$$

After expansion of the mechanical length change in the attaching point as "rigid-body-movement" error and "local-movement" error, it can be found that the "rigid-body-movement" error can be reduced, In order to show such result the mechanical length change in an interface is rewritten as following form:

$$\Delta ML = X * \alpha + Y * \beta + \Delta z_r + \Delta z_l \qquad (8)$$

where X, Y, : the local coordinates of attaching point;
α, β, : rigid angle movements around X or Y;
Δz_r : rigid plane movement in the z-direction;
Δz_l : Local-movement in the z-direction, including actural attacting point change due to the X-Y plane movement.

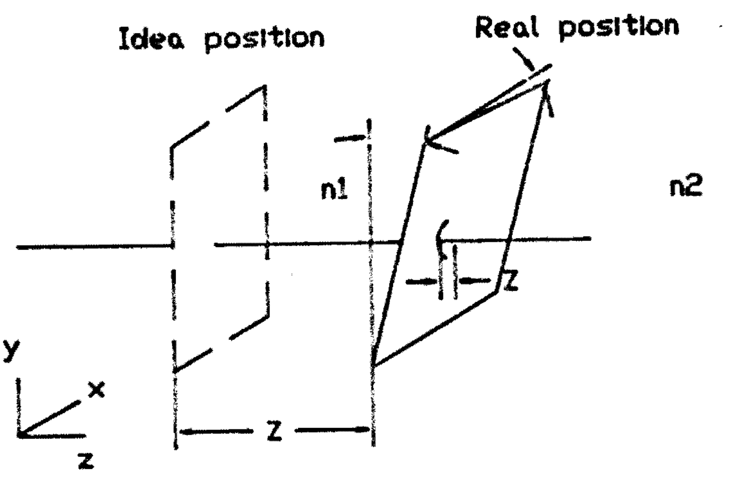


Fig. 2 illustration of errors in an interface

Introducing this expansion to the expression of interface the optical length change error yields

$$OLE = (Xm - Xr) \alpha + (Ym - Yr) \beta + \Delta z_l \qquad (9)$$

Because of common path arragement, the error Δz_r is cancelled which is further effect of COMMON PATH principle. From the equation (9), it can be seen that if one of the coordinates values is the same between the two beams this optical length change error is further reduced. More significant error reduction is to introduce another pair of beams to attach this interface with a special coordinate values, say, satisfy following condition.

$$(X_m' - X_r') = - (X_m - X_r) \text{ and}$$
$$(Y'_m - Y'_r) = - (Y_m - Y_r) \qquad (10)$$

The " angle-rigid-movements " also disappear, and OLE = Δz_l. This leads to the SYMMETRICALLY DOUBLE ATTACHMENTS principle, so that arrangement of (beam) symmetrically double attachments increase not only the resolution by factor two but also the accuracy. The symmetrically double attachments can be arranged in spatial way, in which the space is more efficiently used. The size of interferometer can be smaller. If two beams doubly attach every optical elements in the system, over-all accuracy of interferometer will sigificantly increase, because this arrangement is insensitive to all the "rigid-body-movement" errors. In the special case that second attachment can follow the same way as the first attachment in opposite manner the total errors, both "rigid-body movement" and "local-movement" errors disappear.(The discussion of interface error is under the common path assumption).

For an reflecting interface, beam attaching and back have same contribution to the optical length change errors. Therefore, the expression becomes

$$OLE = 2 * (\Delta ML_m - \Delta ML_r) * n \qquad (11)$$

This means that a reflection interface has greater errors than than a passing-through interface.

In order to easily apply OLE expressions to an abitrary interface the sign before the refractive index is defined as follow under the condition assumed in fig. 1. In an interface, if mechanical change error makes its mechanical length smaller the sign before the refactive index refering to this space takes positive, otherwise negative corresponding to the positive OLE under the condition of measuring beam minus reference beam.

In the real application, appearance of interfaces are always relative to each other, e.g. two interfaces in an optical plate. In this case error analysis in the first interface can be easily treated by adopting the interface concept introduced above. However, for the second interface the plate thickness must be considered. In this case equation (9) becomes

$$OLE = (Xm - Xr)\,\alpha + (Ym - Yr)\,\beta + \Delta z_l + A\,(1/(\cos\alpha\,\cos\beta)-1) \tag{12}$$

where

A - the thickness of optical plate.

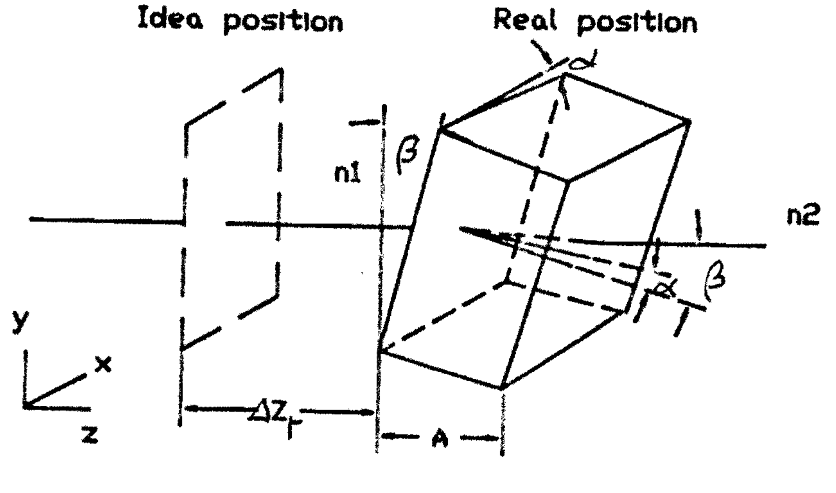


Fig. 3. Illustration of relavent interface

Summarization of this section what have been disscussed yields the following basic principles to design a high accuracy interferometer.

1. COMMON PATH principle: In this category, there exsit two classes of eliminations, 1).product of mechanical length and refractive index change, 2). product of mechanical length change and real refractive index. The Common Path means that two beams pass through exactly same number of elementary parts with same mechanical length on each elementary part. The error effects can be reduced to to a minimum by designing the interferometer so that the reference and measurement beams travel equal optical path lengths through each optical elemnet in the main interferometer body. The optical path length only differs between a single reference and measurement surfaces so that space can be optimally used, particularly when the measurement is being made in a vaccum chamber. Only the reference and measurement surfaces enter critically in the measuremenat.

2. DOUBLE ATTACHMENT principle: This principle tells that the rigid-body-movement error in an interface can be reduced by doubly attaching a element. If this double attachment is symmetrically arraged the rigid-body-movement error can be eliminated.On the other hand, double attachment incraeses resolution by a factor two, which is general case. In the special case that second attachment can follow the way same as first attachment in oppsite manner the total errors, both "rigid-body movement" and "local-mevement" errors disappear. Symmetrically double arragement will further come to concept of " Spatially symmetrical double attachment", which implies that the laser beams pass through all the element in the three dimensional way and each beam attach one surface twice. In this way the spaces of optical elements are more efficiently used and any non-local error is elimated. It should be noted that the manufacturing errors of optical elements are also doubled, due to the different attaching point for different beams. On the other hand energy loss wiil increase due to the longer optical length.

3. A Cheap Solution of High Accuracy Interferometer

3.1 Principle of PPPM Interferometer

Fig. 4 schematically illustrates the principle of PPPM interferometery. It can be seen that the two frequency components and two polarized direction elements (with signs " . " and " ↑ " goes through exactly same path length.)

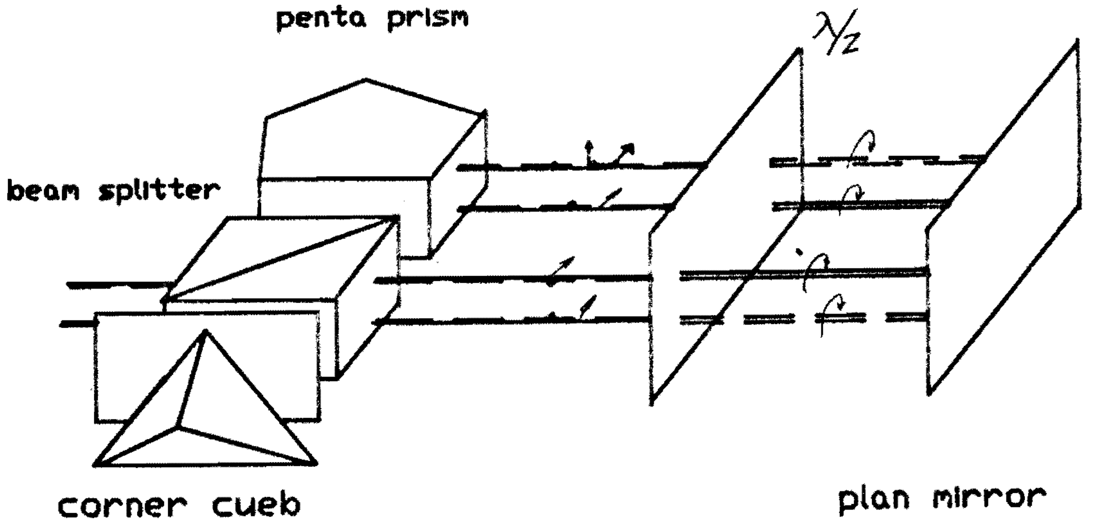


Fig. 4. The principle of PPPM inteferometer

The PPPM (Penta Prism Plane Mirror) interferometer consists of the main interferometer body and the remote reference mirror mounted as close to the movable mirror as expected. Two of orthogonally polarized components of the incident beam are spatially separated by the commecially available common polerized beam splitter. A penta prism is used as beam bender to make right angle reflection component of laser beam attaching to the reference mirror. Another component goes through the beamsplitter to attach the object mirror. The quater-waveplate make these two compenonts change the " through or reflecting" properties when component beams attach the beam spliter. Hence, the reference component beam will go through the beamspliter after backing from the reference mirror, and the measuring component beam will reflect after backing from object mirror. Thereafter, these two components beams pass through the half-waveplate once or quater-wave plate twice in order to alternate the path to make sure that both components travel same length and pass same optical elements. The corner-cube retroreflector or right-angle prism can be used to fold two component beams back through the same beamspliter and same penta prism after rotation by the waveplate. The arrangement of optical elements in this interferometer is satisfied the rules of thumbs -- concepts of "common path ", " double attachments" and " commecially availible optical elements ". Comparison the optical element arrangement with HP [3] and Zygo [4] DCP inteferometers PPPM arrangement is relative cheap solution to remain same DCP features, i.e double attachments, common path and plane mirror. The table 1. presents the comparison of those DCP interferometers. It can readily seen that the PPPM interferometer is an relative cheaper solution to have the DCP features in an interferometer.

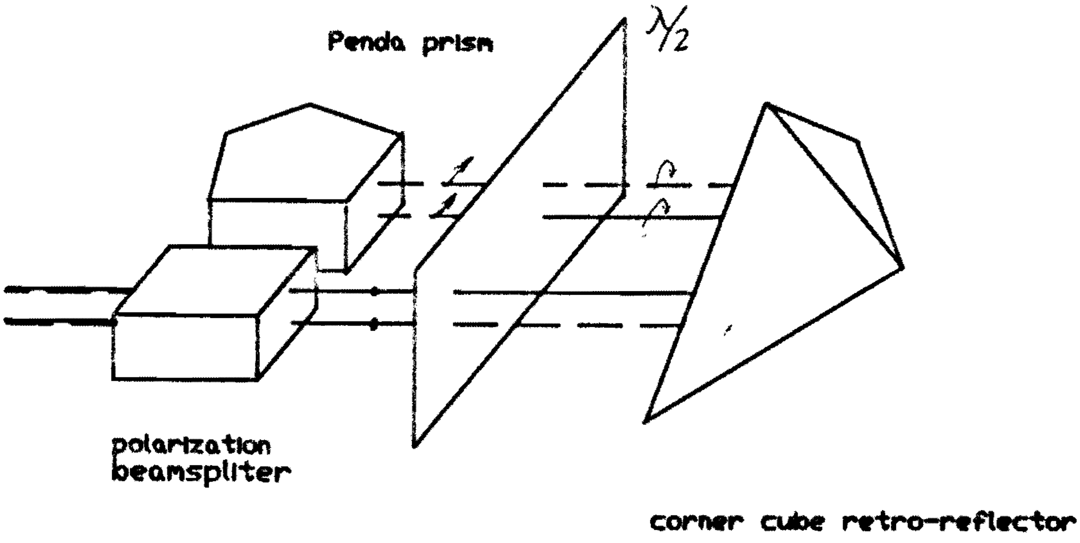


Fig. 5 The priciple of PPCR interferometer

3.2 Principle of PPCR interferometer

Fig. 5 gives a schem of optical arrangement of PPCR (Penta Prism Corner-Cube Retro-Reflector). This is an alternative form of PPPM arrangement.

In fact this system can be also considered as a modified form of the interferometery system in the TUE 2 referactometer [2]. The differnce is that the right-angle prism is replaced by the penta prism. One of the advantages doing so is that adjustment work of beam bending element is elimated. Secondly, because beams diagonoally pass through the measuring space which is built by both reference beam and measuring beam, it is possible to make an relative small separated hole for both champers in the referectometer application and use one relative big window for the all beams. This arrangement will reduce the thickening and bending effects because of symetrical load small area on a big window. (disscussion on thicking and bending effects see references [5] [6]).

3.3 Applications as Displacement or Angle Inteferometers

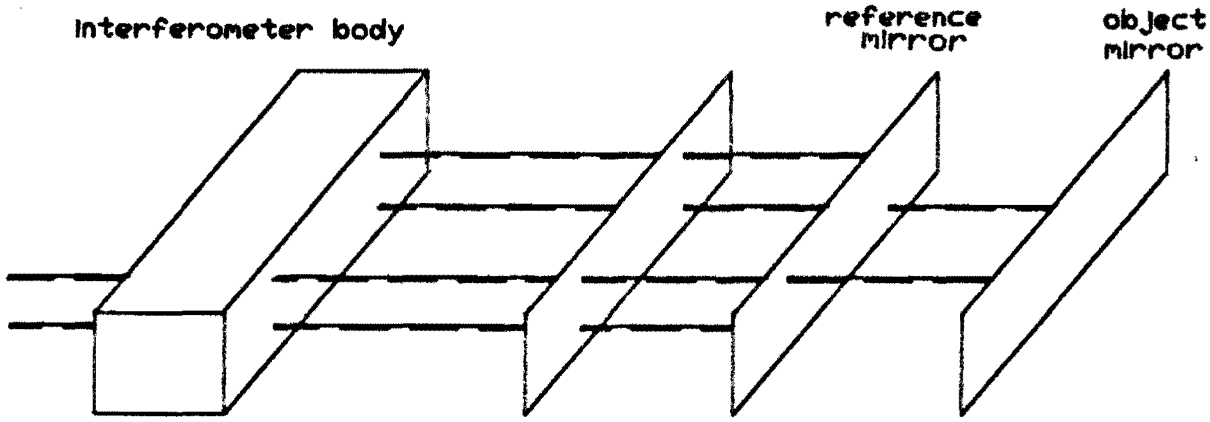
PPPM interferometer used as displacement or angle interferometer is separately shown in figs. 6a and 6b. The difference between these two applications is the two beam attachments in the reference mirror and object mirror. This can be easily realized by selecting the hole patten in the reference mirror. In the case of displacement interferometer the error from the non-parallel of two reflect mirrors can be eliminated by properly setting the interferometer system. If the centre point of the object mirro is a measuring point, the errors from non-paralle of two mirrors or angle motion of object mirror will be absent in the measurement result. In the case of angle interferometer the arrangement of hole patten only sensitive to the measuring angle motion. The angle value can be simplely defined through the optical length change divided by the beam distance of the beams attached to the moveable mirror. The operation of interferometer in both cases is under the small angle motion and small non-parallel error. The measuring range of system is limited by the angle torlerance of interferometer.

Table 1. Comparison of typical DCP interferometers

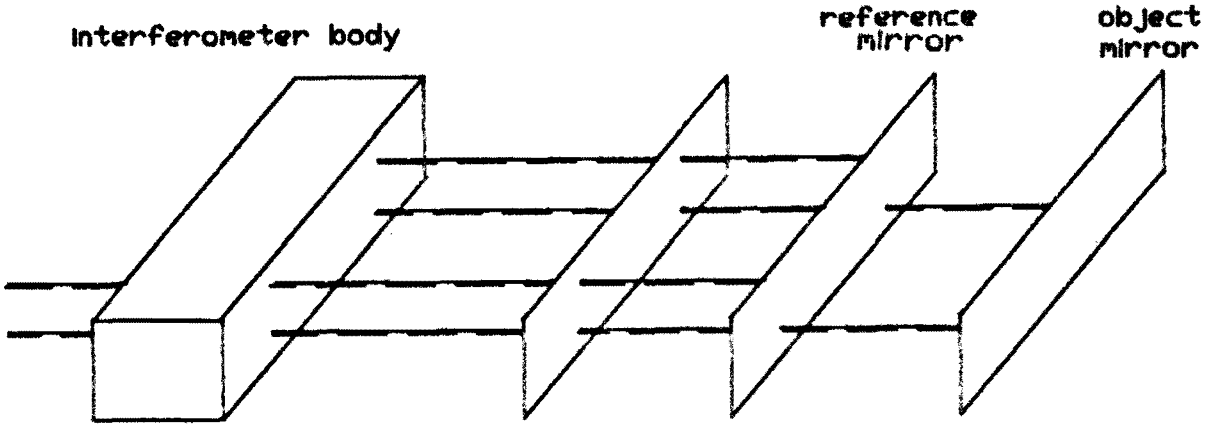
name	optical element	IOef	OLDf	characteristics
PPPM	BS(1),CC(1),PP(1),	44	4 * PP	double attachment common path plane mirror
Zygo	BS(1),CC(1),SP(1)	32	8 * SP	double attachment common path plane mirror
HP	BS(1),CC(1),CC(2)	56	4 * CC	double attachment common path plane mirror
CV	BS(1),CC(1),CC(1)			single attachment seprete path retroreflector

<u>Notes for table 1.</u>

CV - Conventional interferometer,
HP - Hewlett-Packard, (ref. [3])
Zygo - Zygo corporation, Middlefield. (ref. [4])
CC - Corner Cube retroreflector
BS - polarizision Beam Spliter
SP - polariztion Share Plate
PP - Penta Prism
OLDf - Optical Length Difference factor
IOef - Interface error factor



a. displacement interferometer



b. angle interferometer

Fig. 6 Aplications of PPPM interferometer

4. Experiments on the PP type Interferomtery Optical System

4.1. Property checks of optical elements

The important optical element is the polarization beamsplitter. The polarization effect can be checked by the standard interferometer system provided by the producer of laser interferometer system. The optical arrangement can be like that shown in fig. 6. If system works the polarization beamspliter will work in any system. The polarization quality can be checked by the polarizer.Both experiments shows good results, which means that the polarization beamspliter has expected quality.

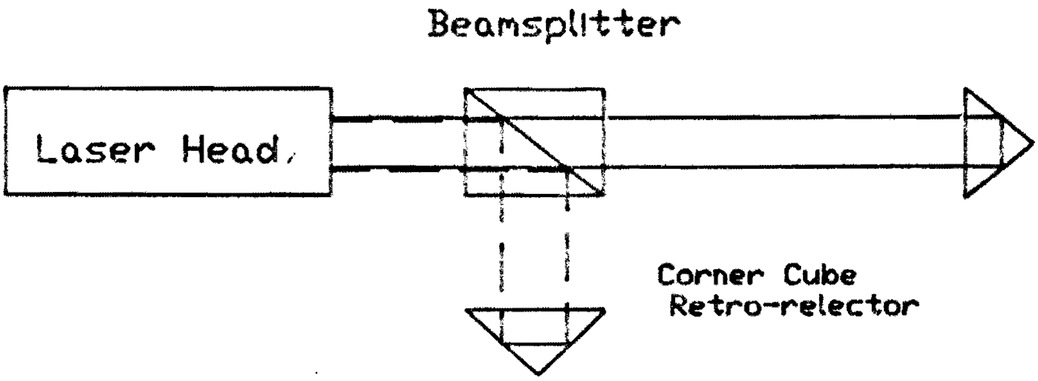


Fig. 7. The arrangement for polorization beamspliter checking

4.2 Experiments of PPCR system

The system arrangement is the same as the figure shown in the sesion 3.2. Using labortary available optical elements builds such system. Experiments show that beam alignment is very senstive to the adjustment of polarization beamspliter and relative sensitive to quater-wave plate. The senstive axis for the polarization beamspliter is the vertical direction (aroud Z-direction). This is true because it affects two components aligning position in the same degree and change the attaching angles to the end mirrors for both beams. The sensetive axes of the quater-wave plate are the Z-, Y-, and rotations around Z- and X- two axes.(the defination of coordinates are given in the principle schem.) X-direction is the transmission direction of the laser beam. The rotation around this axi determines the quater-wave plate working position. It is defined by the principle of quater-wave plate. Transmission effects from the Z- and Y- direction is probably due to the unequal thickness of the quater-wave plate. The rotation around the Z-direction presents an extra polarization effect. Perhaps this is the reason of observed effects. The operation of such system in a prelimanery experiments appears instability in the read-out. This instability may comes from following reasons. 1). the possible measurement of the refractive index in the laboratory environment, 2). possible instability from the test set-up. Last reason can be improved by checking beam alignment and first reason can be separated by using mask. The test set-up is put in the mask so that the refractive index change in the measuring condition will much decrease. The final test results are given in fig. 7, which shows that it satisfies the the applications. Author belives that the results will be better if other optical elements are also carefully selected and set-up is more carefully designed.

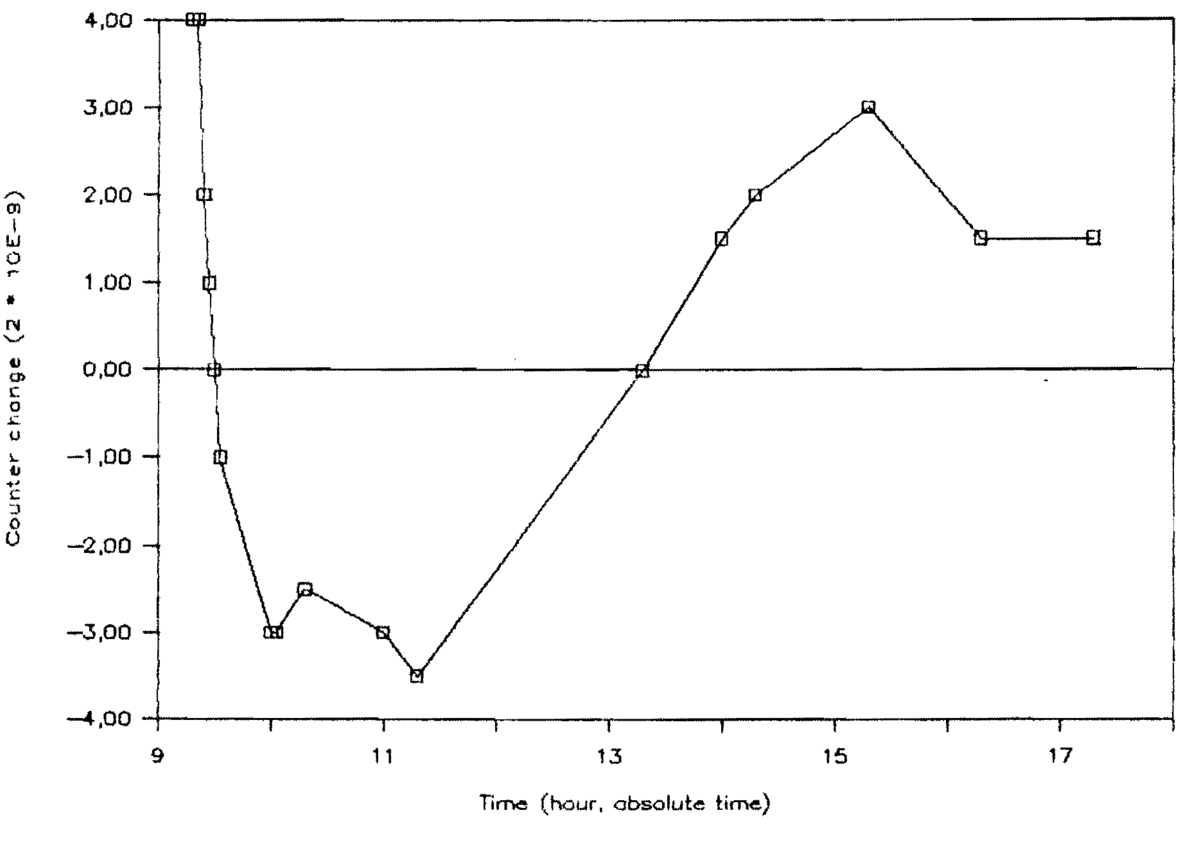


Fig. 8 The test result of PPCR set-up

4.3 Experiment on the PPPM Interferometer Optical System

Prelimenary experiments did not make the system work. It may be due to the unqulified quality of optical elemnets. The observed phnomone is that very weak intensity in the receiver position from back beams. It need to be confirmed in the further works. This system really shows very interesting features, especially for the need of increasing accuracy of refrectometer.

The big problem in PPPM arrangement is alignment of beamsplitter. The sensitive axies are X-, and rotations around X-,Y-, and Z-. The further experiment must pay more attention on this point.

5. New Refractometer Based on the Penta Prism Interferometer

Interference refractometer mostly based on the Michelson type of interferometer. In this application only one end reflect mirror is used, because the optical difference change is not from the mechanical displacement but the change of media difference in which two beams pass through. New class of refractometer can be designed by using principle of PP type interferometer Interferometer system adopted from the PP type interferometer can be arranged so that one plane reflecting mirror may be used as the end cover and chambers may be separated for each beam in every attachment. In this way end corvers can be a big window for the four small charmber. The chambers may be the holes in a aluminium block, which has four seprated holes for tow beams doulbe attatchments (each beam goes through two times in the part of chamber length). Each two holes passed through same beam is connected by an additional hole. The pressure, temprature in the sample chamber can be measured by seprately pressure sensor and thermalmeters. The end mirror can be designed as a end cover of chambers block and $\lambda/4$ plate may be the front cover if seal can be well designed. In this design windows are used in one solid glass for the total four holes. This arrangement will eliminate the the thinkening and bending deformation of the windows, which were confirmed that it would introduce optical path length change [6]. Small working hole reduces thichening effect and whole window for four holes as one solid peice elimates the bending detortion. This arrangement will mimimise the possible sources of error, which is the main base of this development.

APPENDIX DEFINATION OF INTERFACE AND NON-COMMON-PATH ERRORS

In general, the optical length can be written as the form :

$$OL = \Sigma\ ML * n = \Sigma\ (ML + \Delta ML) * (n + \Delta n)$$

Ommitting the high order error of optical length and taking out the measuring part we can writes the expression of optical length error as follow:

$$OLE = \Sigma\ \Delta ML * (n_1 - n_2) + \Sigma\ (ML_m - ML_r) * \Delta n$$

When two beams are considered together, the optical length error can be expanded. The first part of this expression is due to the unwanted mechanical length change. it is obvious that this error is significant only when the laser beam meet the interface which is boundary of diffrent refractive indexes, e.g. the beam goes into an optical element from the air. This part error is logically defined as interface error. The second part error comes from the unequal mechanical lengthes between two beams. This part is defined as the non-common-path error.

Acknoledgement

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