sck cen mol

STUDIECENTRUM VOOR KERNENERGIE

CENTRE D'ETUDE DE L'ENERGIE NUCLEAIRE

A LASER INTERFEROMETER FOR HIGH PRECISION ANGULAR MEASUREMENTS

L. JACOBS

June 1981

144, avenue E. Plasky, BRUXELLES 4
(BELGIQUE)

BLG 545

E. Plaskylaan 144, BRUSSEL 4
(BELGIE)

L. JACOBS
BLG 545 (June 1981)

A LASER INTERFEROMETER FOR HIGH PRECISION ANGULAR MEASUREMENTS

Summary. - Using a commercial two-frequency laser a simple symmetrical interferometer has been built, covering a limited angular range of -6°/+6° with a precision of about 0.01 seconds of arc. The details of the design, including reference to the factors potentially limiting the accuracy, are presented.

L. JACOBS
BLG 545 (June 1981)

A LASER INTERFEROMETER FOR HIGH PRECISION ANGULAR MEASUREMENTS

Samenvatting. - Met behulp van een commerciële laser met twee frekwenties, werd een eenvoudige, symmetrische interferometer gebouwd. Deze bestrijkt een beperkt hoekbereik van -6°/+6° met een precisie van ongeveer 0,01 boogseconden. De details van dit ontwerp worden beschreven, waarbij tevens op de factoren gewezen wordt die de nauwkeurigheid mogelijk beperken.

L. JACOBS
BLG 545 (June 1981)

A LASER INTERFEROMETER FOR HIGH PRECISION ANGULAR MEASUREMENTS

Résumé. - A l'aide d'un laser commercial a deux fréquences, on a construit un interféromètre simple, symétrique, permettant des mesures angulaires de -6° à +6° avec des précisions de l'ordre de 0,01 secondes d'arc. Les détails de l'interféromètre à laser sont présentés ainsi que les facteurs qui peuvent détériorer la précision angulaire.

A LASER INTERFEROMETER FOR HIGH PRECISION ANGULAR MEASUREMENTS

L. JACOBS

June 1981

BLG 545

1. INTRODUCTION

During the last decennium one has become increasingly aware of the usefulness of a laser interferometer as a tool for measuring the (generally small) Bragg angles for bent crystal or double flat crystal diffractometers, at least whenever wavelengths or energies have to be determined with very high precision for γ- or X-rays from quite different sources (as e.g. radioactive decay,nuclear reactions or muonic channels). Indeed the use of nearly perfect crystals of Quartz,Silicon or Germanium led to smaller diffraction linewidths, typically of the order of a second of arc,whereby the corresponding statistical error on the determination of the peak maximum amounts to only a fraction thereof.
This could hardly be matched by (semi-)mechanical measurement techniques. An interferometer,however,with its intrinsic reference length of a fraction of a wavelength of the light source used, seems a priori well suited for measuring small movements as induced by the rotation of the diffraction crystal. In addition, the electronic detection of the interferometric light fringes allows fully automatic reading of the whole angular range to be scanned with small angular steps for both the bent crystal or double flat crystal diffraction instrument.

The present report describes the laser interferometer built for the bent crystal diffractometer used at BR2 for neutron capture gamma spectroscopy (ref. 10).

The reader who wants to look first at the concepts of an interferometer is referred to the optical textbook of ref. 11,or simply focus on the principles of a Michelson interferometer as briefly given here.
Hereby the light is first divided into two beams,whereby one of the beams is reflected on a fixed and one on a movable mirror. If the latter moves over a distance of $\lambda/4$ then this gives rise after recombination of the two beams to a shift from,say,constructive to destructive interference being seen as a bright or dark fringe. So the mirror movements can be measured by fringe counting.

2. ANALYSIS

2.1.General Considerations

As the inherent advantage of an interferometer for measuring the Bragg angle with high accuracy is evident,most bent crystal spectrometers (see e.g. refs. 1,3,4)or double crystal instruments (2,6) have been equiped with such a device,albeit with a different angular range and degree of sophistication and hence precision.

In several approaches, one has come up with a Michelson type of interferometer,whereby a change in optical pathlength is induced by rotation of the crystal unit. For use with bent crystal diffractometers,three different approaches along this line have been analysed by Borchert (3),from which we want to retain certainly the inherent advantage of completely symmetrical beampaths,leading not only to simpler mathematical relations between angles and beam path changes but also selfcorrection of certain errors induced e.g. by barometric changes.

2.2.Light sources

As a light source for the interferometer, a laser seems of course well suited. A specific choice,however,still leaves many options open.
By way of example, the instrument at Jülich (3) or Gams 1 at Grenoble can use unpolarized laser light,while Gams 2-3 uses (linearly and circularly) polarized beams to build up ultimately the interference fringes for counting the displacements (1).
The interferometers for the double diffraction instruments at NBS (2) also start from linearly polarized light but are more sophisticated,aiming for a precision that exceeds the requirements for our BCD-spectrometer.
By means of an additional interpolation scheme in between two interference fringes,NBS has upgraded drastically (almost by a factor of 500) the sensitivity of the interferometer, in essence by determining the exact orientation of a resulting polarization vector,whereby its angle is a measure of the rotation of the crystal axis.
Again great care is taken to keep the design highly symmetrical, by forcing the two beams to travel together in the air as much as possible.

All the interferometers referred to sofar, can determine the direction of the rotation of the crystal axis as well by inducing in one of the beams an extra phase shift by 90° by different optical means,allowing to use some kind of sine-cosine fringe counting scheme (see by way of comparison refs. 1,2,6).

As is the case for the bent crystal instrument of the University of Fribourg (ref. 4),as for the previous interferometer at BR2 (ref. 10), our present interferometer is built around a commercial two frequency laser (Hewlett Packard).The main drawback of the previous interferometer is its sensitivity on barometric changes because of its asymmetrical design. Incidentally this same laser is used at NBS,without however exploiting this two frequency character,except for its polarization features.

2.3. Optical Components

For the optical components of either the movable part of the interferometer, that is connected to the rotation of the crystal axis, or the static part, that act as a reference position,again very many different options are open.

If one analyzes in detail the different existing devices mentioned sofar,it is clear that corner cubes (see for its theory refs. 7 and 8) are very practical components to build up the movable part. Indeed a corner cube keeps reflecting a light beam parallel to itself,regardless of the incoming angle.This allows to measure translation despite angular rotation of the reflecting component that may simultaneously occur. This is what happens if one were to mount the corner cubes on some arm attached to the rotation axis.

For the optical components, that constitute the static part, it is of importance to know the quality of the material used (homogeneity), its surface flatness, possible temperature dependence,coatings and so on, as the wavefront of the laser beam is affected by passing through or reflecting on these components. In the case the design of the interferometer depends on the polarization, then special care must also be taken not to affect this state by the components or reflecting layers and incident angles.

3. DESIGN DETAILS

The general design of the interferometer is given in fig. 1. It is built around a stabilized HeNe-laser,which emits 2 slightly different wavelengths due to Zeeman-splitting by an axial magnet. These two wavelengths are therefore left and right circularly polarized but already within the laserhouse transformed into linearly polarized light in the horizontal respectively vertical plane. Therefore these two wavelengths can simply be separated by the central polarization beamsplitter,each beam being directed further by additional components to a corner cube located symmetrically with respect to the rotation axis on an arm.The components are on assemblies (2) allowing adjustments.

In order to eliminate,rather than correct for,known sources of error when measuring with such a geometry the small angular range of +3°/-3° or occasionaly 0°/+6° of the BCD-spectrometer,the two incoming beams on the corner cubes are made parallel to each other within a few seconds of arc by means of a large Nikon autocollimator (Model 6D).The reflected beams are then also parallel within about a few sec of arc because of the quality of the retroreflectors (1") that are also dimensionally equal. (For checking purposes the corner cubes can easily be removed and the beams checked thru holes in the arm).

The corner cubes are oriented in such a way that the beam is simply lowered,so no attemp is made to double pass the corner cube as e.g. in refs. 2. and 4.,which requires only two additional roofprisms. Although this would in principle double the sensitivity of the interferometer it would,however,put stringent requirements on the stability of the positioning of the two roofprisms (at least relative to each other).The more it would allow to rotate the arm over a larger angle as the side wise walk of the two beams due to rotation would be compensated as it gradually decreases the necessary overlap of the two interfering beams. Again because of the limited angular range that we aimed for,these additional components (together with a slight change in orientation of the corner cubes) are as yet not excluded,but can be added later if the need arises. It would also have made the design more similar to that of ref.4. where e.g. angles up to 20° have to be measured.

The arm is made of a nickel iron alloy (Nilo 36) with a low thermal expansion coefficient of 1.35×10^{-6} in the range 20-100°C,this in order to keep the distance between the corner cubes constant,as it enters in the angle calibration factor.
In order to facilitate positioning of the corner cubes and the arm relative to the laser beams by means of autocollimation techniques, the front surfaces af the arm and the separate mounts of the corner cubes are all ground,while,as mentioned before,holes are foreseen in the arm.
The corner cube mounts itself locate the corner cubes at its optical center (4) around which slight rotations may occur without directly affecting the total internal optical pathlenght.

The tolerances set on the precision of the surfaces are not too extreme. Indeed as the laser light hits a small area on the components and does move very little on these, one needs only small components that do show little wavefront distortion for almost the whole aperture of the components typically not exceeding $\lambda/20$. All the surfaces are antireflex coated.
In order to keep the polarization state of the beams, mirror coatings are, where possible, of Ag. Although it is known that corner cubes can have some effect on the polarization state, no special precautions as in ref. 2 had to be built in, as the polarization in itself is not used to measure interferometrically the angle of rotation but merely to separate easily the two wavelengths.

The real measuring scheme makes use of the fact that, while the arm is rotating, the two frequencies are Doppler shifted. If then later on these two beams are recombined and made to interfere as two beams with (slightly) different wavelengths then the resulting "beatfrequency" (see ref. 11) by which the resulting amplitudo modulates, is also affected by these Doppler shifts (see ref. 9). From this the displacement itself of the arm is deduced by the electronics that go together with the lasersystem (HP,5526A), so that one in fact measures a deviation :

$$\Delta L = F \sin\phi$$

whereby F is regarded as a calibration factor. Strictly speaking F is completely determined by the distance between the optical centers of the corner cubes,which equals here about 208mm.One can,however, not determine this distance with high enough precision.
Correction factors to this simple sine law,as discussed in full detail in refs. 2,4,5 ,should be largely reduced here.

Let us point out here that the Bragg law that is applicable for the symmetrical Laue geometry used in all the diffractometers referred to, is also a pure sine law and known in its standard notations as :

$$n\lambda = 2\ d\ \sin\theta$$

So the sine dependence on the rotation angle ϕ is ideally suited to measure the Bragg angle θ. This requires a close match of the zero Bragg angle (θ_0) and the optical zero (ϕ_0), being defined as the position whereby the laser beams are orthogonal to the line of the optical centers, and whereby from the design the two interferometer arms are equal. As pointed out in ref. 1 this match can be made by checking a left and right diffraction and requiring the readings to be symmetrical.

After proper adjustments the wavelengths or energies of gamma- or X-rays can then be determined relative to a reference γ- or X-ray line. It was not intended to perform an energy calibration from first principles.

The displacements can be measured with a highest resolution of 0.01 micron corresponding to angular steps of about 0.01 seconds of arc. Because of the mentioned symmetry of the optical beam paths, insured by autocollimation techniques using in addition an optical square (Nikon pentaprism; $90° \pm 2''$), no systematic barometric effects result in the zero position. So corrections for it will be due only for the small displacements from the zero position.

The author wants to point out that this work was performed at the Nuclear Center in Mol within the formal framework of an Association between the Catholic University Leuven and the SCK/CEN, and financially supported by the IIKW. Most of the necessary experience on interferometers was acquired as a guest scientist at NBS, Washington D.C., in the group of Dr. Deslattes, whereby he wants to mention especially Dr. E. Kessler and Dr. W. Schwitz.

REFERENCES

{1} H.R. KOCH, Jül-Spez.-10; ISSN 0343-7639 (May 1978)

{2} R.D. DESLATTES, E.G. KESSLER Jr., W.C. SAUDER, A. HENINS; Ann. of Phys. 129, (1980) 378
and private communications

{3} G.L. BORCHERT, O.W.B. SCHULT; N.I.M. 124 (1978) 107

{4} W. SCHWITZ; N.I.M. 154 (1978) 95
and private communications

{5} E. DEBLER; Feinwerktechnik and Messtechnik 85 (1977) 4

{6} H.M. BIRD; Rev. Scient. Instr. V42,10 (1971) 1513

{7} E.R. PECK; J. Opt. Soc. of Am. V38,12 (1948) 1015

{8} J.G. MARZOLF; Rev. Scient. Inst. V35,9 (1964) 1212

{9} HEWLETT PACKARD documentation on the Model 5526A

{10} L. JACOBS; Thesis Leuven (1977)

{11} F.A. JENKINS, H.E. WHITE; FUNDAMENTALS OF OPTICS (4th Ed.) McGraw-Hill

FIGURE CAPTIONS

Fig. 1.a. : Beampaths in the interferometer.

The two-frequency laserbeam is separated by the polarization beamsplitter S and steered, by the prism P_1 and the mirror M together with prism P_2 towards the corner cubes C_1 and C_2.

If the arm rotates then the frequencies (f) are Doppler shifted (f'). The returned beams are detected within the laserhead, where they give rise,by interference, to a beatfrequency.

Fig. 1.b. : Picture of the test setup of an interferometer system to control the angular position of the bent crystal table. The laserhead (type HP 5500-C) can be seen on the right.

The optical components of the static part of the interferometer are mounted on little assemblies (ref. 2) to fine adjust the horizontal and vertical direction of the beams.The whole is fixed on a heavy steel plate.

The movable part consists of 2 cubecorners connected to a low expansion arm.(Behind this arm,one can see the Autocollimator to check the directions of the beams)

The laserdisplay (5505A) can be seen on the left,indicating here,in its normal measuring mode,an angular displacement of the arm of 6°.

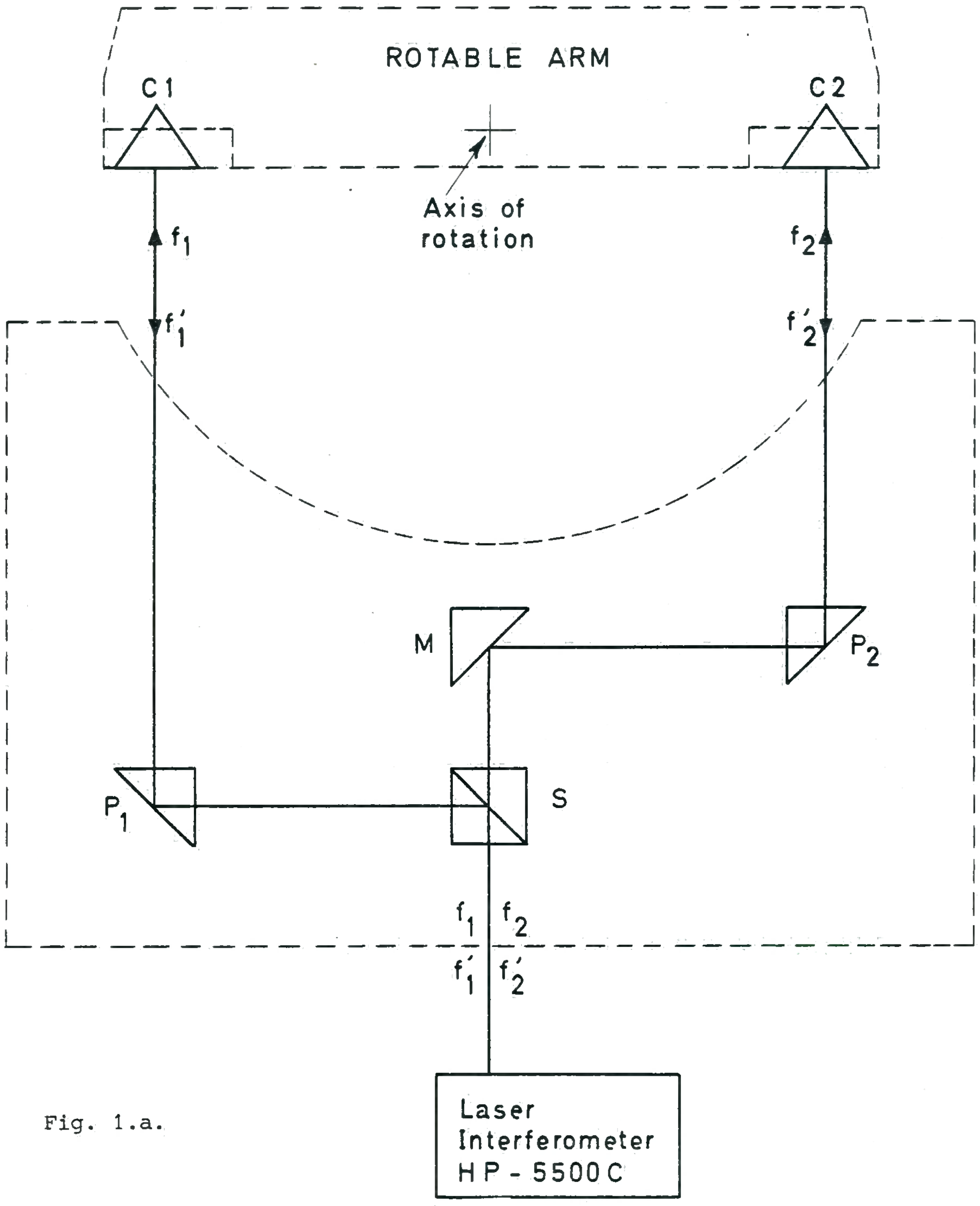
ROTABLE ARM
C1
C2
Axis of rotation
f_1
f_2
f'_1
f'_2
M
P_2
P_1
S
f_1 f_2
f'_1 f'_2
Laser Interferometer HP-5500C

Fig. 1.a.

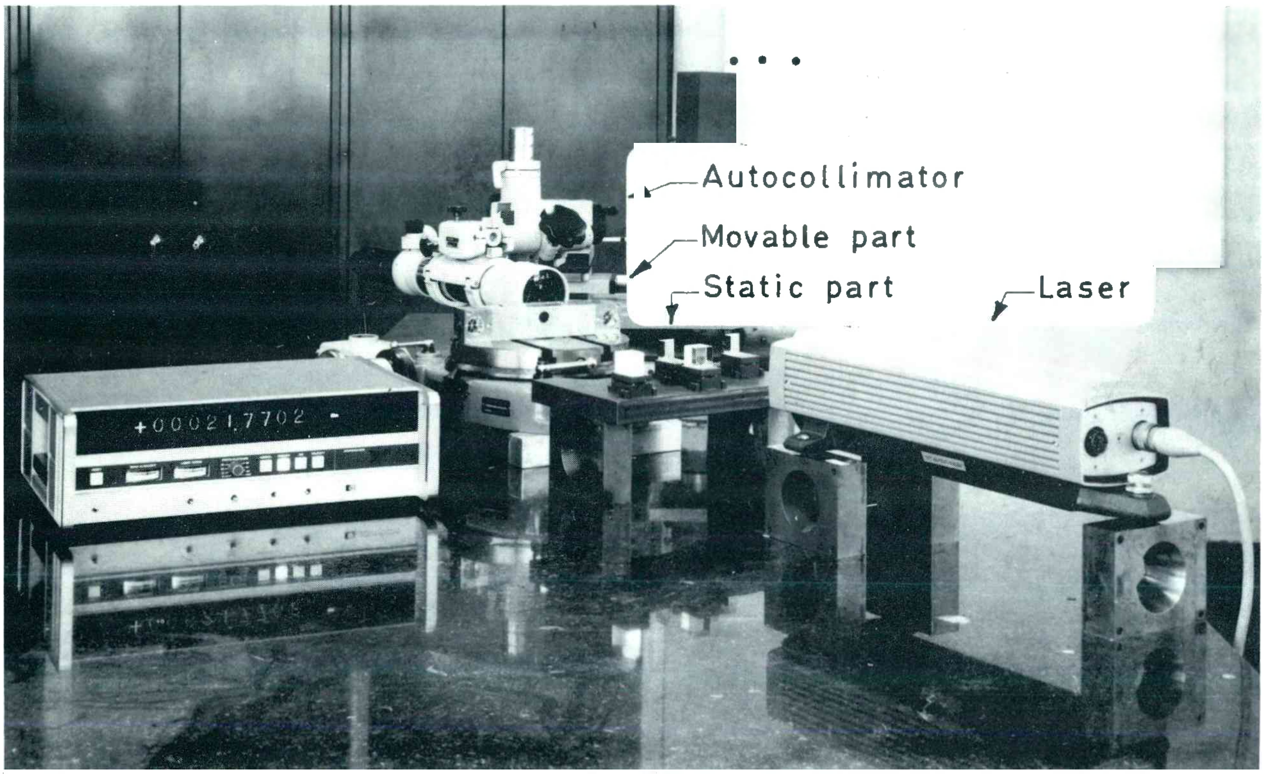

Fig. 1.b.