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建立$\lambda/100$镀膜平面基准

陈耀煌　赵麟祥　曹维贵　李承业

摘要　本文描写的干涉仪是建立镀膜基准平面的基准仪器，它是利用克勒照明，F-P标准具与菲索干涉仪的联合产生叠加的干涉条纹，实现干涉条纹的光学细分，使灵敏度提高了N倍，即每一条干涉带代表$\lambda/2N$的光程变化。对ϕ80mm镀膜光学平面的平面度测量的不确定度为$<\lambda/100$，建立了我国镀膜平面基准。文中对仪器的整体结构，测量原理，数据处理等也都作了介绍。

为改变我国光学平面标准准确度长期与国际上的相比存在着较大差距的局面，经数年的努力，现研制成一台能作N次光学细分干涉条纹的干涉仪($N<20$)。干涉仪的分辨能力提高了N倍，用它可测量直径到80毫米的镀膜光学平面的平面度，测量的不确定度$<\lambda/100$，现已用它建立起我国$\lambda/100$镀膜光学平面基准。

仪器是基于以法布里—泊罗干涉仪作为光学过滤器，用两镀膜光学平面形成楔干涉仪，将此两干涉仪相联合以产生叠加干涉条纹。利用叠加干涉条纹的直线情况来表现出两组合平面由于平面性的偏差而导致的波前弯曲[1]。

当在白光照明下，法—泊干涉仪的两镀膜镜间的距离h_1为楔干涉仪两光学平面的平均距离h_L的N倍时，可得到叠加干涉条纹。此时，由于楔干涉仪的不重叠区

$$\Delta\lambda_R=\lambda^2/2h_2 \tag{1}$$

较之法—珀干涉仪的不重叠区

$$\Delta\lambda_R'=\lambda^2/2h_1 \tag{2}$$

大了N倍，在楔干涉仪的不重叠区内出现了法—珀干涉仪的N次谐振波长，法—珀干涉仪起到了波长滤波器的作用。由于法—珀干涉仪所滤出的谐振波长λ_{N+k}于楔干涉仪上产生的第m个干涉级次与由法—珀干涉仪所滤出的波长λ_k及相应在楔干涉仪上产生的$(m+1)$级的干涉条纹相重合，即有

$$m\lambda_{N+k}=(m+1)\lambda_k \tag{3}$$

此时，由N次谐振波产生的白光叠加干涉条纹就精密地N细分着通常干涉仪所产生的干涉级次。故在干涉仪的干涉场中包含有同等干涉条纹数目的情况下，由楔干涉仪其楔厚度的偏差，即平面度偏差所引起的干涉条纹对直线形的偏差量，较之在单色光照明下通常的多光束干涉条纹的移动量增加了N倍，仪器对平面度偏差的分辨能力比通常的平面干涉仪提高了N倍。在$N=10$下，测量平面度的不确定度可达到小于$\lambda/100$。图1示出不同细分数下对同一组合平面所拍摄下的干涉条纹。

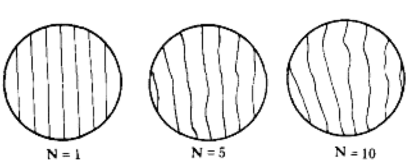
N=1　N=5　N=10

图　1

所研制成的干涉仪的结构系统如图2所示。它由

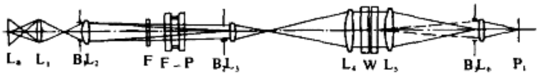

图 2

La 溴钨灯， P1 照像底片，FP 法-珀干涉仪，F 滤光片，W 楔干涉仪 B 可变光阑

白光光源、扩束用的光学系统、法—珀干涉仪，被测镀膜光学平面形成的楔干涉仪、装载镀膜光学平面的微动工作台及观察、拍摄干涉条纹图像的系统所组成。各光学元件组装在支座后安装拉长导轨上，用电感测微仪指示微动工作台的位移量来判断细分数 N 的数值。整台仪器置于隔振效果十分良好，自振频率为 1.6Hz 的空气弹簧减振平台上[2]，故可观察、拍摄下稳定的叠加干涉条纹。仪器采用‘科勒’照明方式，这样就使光源亮度分布的不规则性不致引起视场照明强度的不均匀，有利于产生协调一致的干涉条纹。精细调节的微动工作台上装有三组 PZT 压电陶瓷，利用 PZT 的伸缩来达到在 x，y 两个旋向上作微转动和在 Z 方向上移动，使 0 级叠加干涉条纹移动到干涉场的中心位置上。

拍摄调整好的干涉条纹时，在光路中插入带宽 10nm 的彩色滤光片，干涉条纹的对比度增加，用 DIN27 黑白底片曝光 30 秒至 1.5 分钟，所摄下的底片冲洗后经等密度处理来突出干涉条纹的边沿轮廓，并放大成直径 230 毫米的干涉条纹图象，在其上面依干涉条纹的方位作图画出理想平面的干涉条纹中心位置[3]，然后由眼睛直接判读出各被测点上实际干涉条纹对理想平面干涉条纹位置的偏移量，然后按组合测量的原理，求取出被测平面的平面度偏差值。

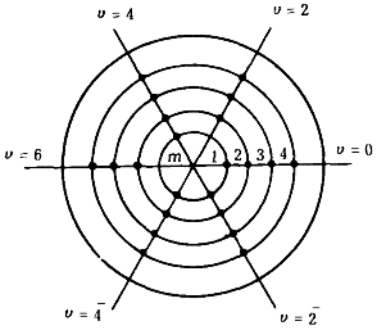

图 3

现已对新近研磨出的三块直径为 78mm 厚度 20mm 的石英平晶作测量，以建立光学平面基准。三块平晶的互组合除了按 XY，YZ，ZX 作为楔干涉仪以 N=10 产生叠加干涉条纹外，还把 Y 平晶相对于原有安装位置逆时针转 120° 与 X 组合成 XY′。对摄得放大了的干涉条纹图片，我们把平晶的整园划分为 6 个等分角 ν_i，并把沿径向等分为四个等分园 m_i 如图 3，等分角线与等分园相交点的平面度为待测点的平面度，这样可得到下列四个方程式组：

$$
\begin{aligned}
X_{\nu m}+Y_{-\nu m}&=a_{\nu m}\\
Y_{\nu m}+Z_{-\nu m}&=b_{\nu m}\\
Z_{\nu m}+X_{-\nu m}&=c_{\nu m}\\
X_{\nu m}+Y_{(4-\nu)m}&=a'_{\nu m}
\end{aligned}
\qquad (4)
$$

式中 $X_{\nu m}$，$Y_{\nu m}$，$Z_{\nu m}$，分别是描述 X、Y、Z 平晶各自平面上 ν 与 m 交点处待求点其对理想平面的平面度偏差值，$a_{\nu m}$，$b_{\nu m}$，$c_{\nu m}$ 和 $a'_{\nu m}$ 是实测得到的实际干涉条纹对理想平面干涉条纹位置的偏移量。在全部数据测量出后，将其代入组合方程式(4)，再按最小二乘法，以 BASIC 语言编程求解，解算的依据是由计算机自动寻找实际表面对理想平面的偏差量。当代回组合方程式(4)后其误差的平方和为最小，依此得出各点对理想平面偏差值和测量不确定度[4]。经误差分析计算，得出测量结果其合成的不确定度 $\sigma<\lambda/200$。

表 1 列出所测得的对 Z 平晶各待测点上的平面度偏差值(单位 $\lambda/100$，$\lambda=0.55\mu m$)

表 1

Z 平晶

径向编号 ν_i 圈数 m_i	0	2	4	6	$\bar{4}$	$\bar{2}$
1	−0.7	−0.5	−0.7	−1.0	−0.7	−0.8
2	−0.4	−0.4	−0.4	−0.5	−0.5	−0.7
3	−0.1	−0.2	−0.2	−0.1	0	−0.7
4	+0.4	+0.1	+0.4	+0.4	+0.8	+0.5

从表列数据可见，Z平晶的平面度在直径 ϕ50 毫米范围内已达到 $\lambda/100$，由于整个工作面上各点处的平面度偏差值均已测得，测量的总不确定度为小于 $\lambda/200(2\sigma)$，故还可对它的偏差值作修正。为此，Z平晶可作为 $\lambda/100$ 镀膜平面基准并依之进行平面度的传递。

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TO ESTABLISH AN $\lambda/100$ OPTICAL FLATNESS STANDARD

Chen Yaohuang　Zho Linxiang　Cao Weigui　Li Chengye

ABSTRACT

An interferometer which can optically divided the space of fringes in N fold subdivision has been constructed. This instrument can be used to measure the flatness of plates with fimls in a uncertainty better than $\lambda/100$. This paper describes the construction of combined interferometer, the white light fringes appear, the measuring principle and establishing a $\lambda/100$ fused silica optical flatness standard covered with dielectric films.

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The Beat Wave Interferometer with Zeeman Laser for Measuring Short Range

Wu Yunlung Chen Yunchang Zhang Yongnian Tang Rendao

ABSTRACT This paper introduces a new scheme of Zeeman laser for measuring short range. The frequency difference (beat frequency) produced by Zeeman laser can be directly used as length unit. The beat frequency in prototype equipment is about 1 GHz. Costant error is less than 0.04mm. The sensitivity is better than one over ten thousandth of the beat wavelength. Measurement uncertainty of the equipment is 0.04 mm$+1.5\times10^{-6}$L (where L is measured length). The measurement range is up to 100 meters.

Preface

In 1983, at the 17th International Conference of Metrology, the new definition of meter based on the costant velocity light in vaccum was adopted. Thus, the expectation for a unified definition of length and time has come true by the laser. It gives impetus to nations in the research of linear measurement by means of frequency or time measurment.

Interferomentry is an old and great fascination method. Since the famous experiment by Michelson and Morley, light interferometry has become one of the most accurate way for length measurement. However, since light wavelength is very short and single value measuring range is within several tenth of micrometers, its application is rather limited and expecially, traditional interferometry measurement is not so convenient for long length measurement. In the early 70s, two frequency laser interferometer has been produced and served in workshop for measuring long length. But it is necessary to have a rail long enough for carriage movement and the light can not be broken off in whole measuring circulation. So we propose a new method on length measurement with Zeeman laser beat wave interferometry.

The prototype equipment based on beat wave interference principle has been developed. In this paper, it show the aqreement of measuring a length with HP interferometer against the prototype beat wave interferometer (BWI). This instrument may find a vast application field for heavy manufacturing industry and other large structure installation.

Beat Wave

It is well known that an interference field will appear in space while two light sources with same frequency and epoch are combined. Another phenomenon was first observed in 1955 by Forrester, Gudmundsen and Johnson. That is an interference phenomenon caused at time coordinate while two monochromatic light sources with some frequency difference are combined. At present this phenomenon is used as a sensitive and convenient method for meassuring tiny optical frequency difference.

If two waves of same amplitude $E_1(w_1)$, $E_2(w_2)$ are combimed and propagated along Z axis, the comined electro-vector can be expressed as:

$$E=E_{01}[\cos(K_1z-w_1t)+\cos(K_2z-w_2t)] \tag{1}$$

or

$$E=2E_{01}\cos(K_mz-w_mt)\cos(\overline{K}z-\overline{w}t) \tag{2}$$

where

$$\overline{w}=\frac{1}{2}(w_1+w_2) \qquad w_m=\frac{1}{2}(w_1-w_2)$$

$$\overline{K}=\frac{1}{2}(K_1+K_2) \qquad K_m=\frac{1}{2}(K_1-K_2)$$

$K=\frac{2\pi}{\lambda}$ is wave number. $\overline{w}$,$\overline{K}$ is avarage angular frequency and avarge wave number respectively. W_m and K_m is modulation angular frequency and modulation wave number.

The composition E can be seen as a wave of w_m frequency. The amplitude $E_0(z, t)$ is the function of time.

$$E(z,t)=E_0(z,t)\cos(\overline{K}z-\overline{w}t) \tag{3}$$

where

$$E_0(z,t)=2E_{01}\cos(K_mz-w_mt) \tag{4}$$

The beat frequency (w_1-w_2) equals to two time of w_m. Fig(1) shows the beat wave composition from two waves different frequency. Beat wavelength can be got from equation (5).

$$\lambda_B=\frac{\lambda_1\cdot\lambda_2}{\lambda_1-\lambda_2} \tag{5}$$

In this way, composition wave be taken as a longer electromegnetic wavelength, and the smaller is the difference, the longer is the beat length. So the length is changeable in a fairly large range and a suitable wavelength can be got if a proper laser is chosen. The output of photodetector is proportional to the intensity of the resulting light. That is

$$\begin{aligned}E^2(z,t)&=E_0^2(z,t)\cos^2(K_mz-w_mt)\\&=\frac{1}{2}E_0^2(z,t)[1+\cos^2(K_mz-w_mt)]\end{aligned} \tag{6}$$

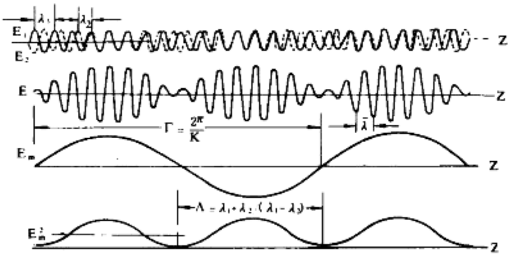


FIG 1 Composition of two different frequency wave

The light source

To choose suitable kind of light source, it is very important for realization of entire project. The basic requirement for interferometric light source are that the wavelength should be stable, the wave-front shoule be flat enough. There are three ways of using small power He-Ne laser to produce two modes with slight frequency difference.

First, two laser tubes with the same performance can be used to produce modes with slight frequency difference. Under taking some optical measures, it can make the light beam of the two lasers coaxal. If the frequency difference of the two modes were controlled properly, a expecting beat wave would be produced. Because the two lasers independent each other. Technically speaking, it is very trouble to make light beam coaxal and frequency difference stable.

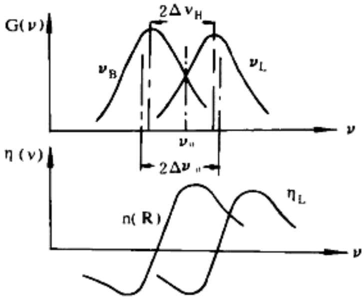


Fig.2 The characteristics of Zeeman laser

Second way is to use a two longitudinal modes laser. The two mode components of the light beam are coincident with each other. The frequency difference of the two modes depends mainly on the length of the cavity, so it is more stable than that produced by two laser tubes. But, owing to the mode competition and the couple effect between modes, the beat wave signal obtained by detector carries a lot of noise and it is bed to the system. Of course, this situation could be improved through proper stabilizing steps.

Third way, the method are adopting in the equipment is to produce two modes by a Zeeman laser. The frequency difference of the modes produced by Zeeman laser is much more stable than the two ways mentioned above. Due to longitudinal Zeeman effect, each of the gaincurve and dispersion coure will be spllitted into two. Thus, two modes of weakly coupled He-Ne laser become independent.

The output frequancy of laser can be expressed as:

$$\gamma_q = q\frac{C}{2n_0L} \tag{7}$$

where

c——velocity of light in vaccum

n_0——refractive index in cavity

L——cavity length

q——plus integral number

The interval of the two modes is

$$\Delta\gamma = \frac{c}{2n_0L} \tag{8}$$

From the following equation, it can be seen that there is a violent dispersion near the gain curve center of laser mudium, and while the gain factor of working medium growing up the dispersion value become bigger.

$$\Delta n(\gamma) = \frac{C}{2\pi^{3/2}\gamma} G_i^0(\gamma) e^{-4\ln\left(\frac{\gamma-\gamma_0}{\Delta\gamma_D}\right)^2} \int_0^{2\sqrt{\ln 2}\left(\frac{\gamma-\gamma_0}{\Delta\gamma_D}\right)} e^{t^2} dt \tag{9}$$

where $\Delta\gamma_D$——the doppler width.

γ_0——the frequency of spectral line center.

$G_i^0(\gamma)$——the gain factor of small signal.

The expression of frequency pulling is shown as following:

$$\gamma_q - \gamma_q{}^0 = -\frac{C(\gamma_q - \gamma_q^0)}{n^0\pi^{3/2}\Delta\gamma_D} \sqrt{\ln 2}\, Gi(\gamma_q, I_{\gamma q}) \sqrt{1 + \frac{I_{\gamma q}}{I_s}} \tag{10}$$

where

$$Gi(\gamma_q, I_{\gamma q}) \sqrt{1 + \frac{I_{\gamma_q}}{I_s}} = G_i^0(\gamma_0) e^{-4\ln 2\left(\frac{\gamma_q - \gamma_0}{\Delta\gamma_D}\right)^2}$$

n^0——The refractive index while gain factor is zero.

I_{γ_q}——light intensity in cavity.

I_s——the saturated intensity.

$G_i(\gamma_0, I_\gamma)$——the gain factor.

In a general $Is \gg I_{\gamma_q}$. It is for stable laser.

$$\gamma_q - \gamma_q^0 = -\frac{C(\gamma_q - \gamma_q^0)\sqrt{\ln 2}(a+t)}{2\pi^{3/2}\Delta\gamma_D n^0 L} \tag{11}$$

where

(a+t)——the loss of laser.

From above, it can be seen that pulling value is getting bigger when the resonating mode deviates from gain center. In other word, if resonating mode approaches center of gain, so that the beat frequency of two modes will be more stable. If following requirement is fulfilled

$$\frac{C}{2n_0L}=29\frac{\mu_0H}{h} \tag{12}$$

i.e

where

μ_0——Bohr magneton.

h ——the Planck's constant.

g ——the land's factor, g=1.3 for 633nm spectroline of Ne.

Under the above conditions beat frequency unstability caused by pulling effect can be reduced greatly. The stability can be improved obviously. If take the push effect into account and give equation (12) some correction, the beat frequency stability can be improved greatly. That's why a Zeeman laser is chosen as a beat interferotry light source. According to above analysis, the characteristics of the light source is shown in Fig (2). The principle of beat frequancy stabilization is to balance left against right circular polarzed light with servo system. So dextro and levo light have same intensity. Therefore, the beat frequency could be stabilized.

Beat frequency measurement

The light containing slightly different freauency forms the beat in optic path. The beat wavelength is used as the standard length unit in distance measurement. It can be calculated from following expression

$$\lambda_B=\frac{C}{2n_g\Delta\gamma} \tag{13}$$

where

n_g——group refrative index. (n_g=1.00027923 for 633nm He-Ne laser in p=760 mmHg, t=20°C, e=10mmHg)

$\Delta\gamma$——beat frequency of two modes.

c ——velocity of light in vaccum.

From above analysis, $\Delta\gamma$ dependes on many factors. Such as magnetic field, cavity length of the laser. Q value of the cavity, working current of laser, cross coupled in working medium of laser and frequency pulling and so on. So, it is very trouble to obtain beat frequency by calculation directly. In a general, under some stabilization steps is taken, real time measuring beat frequency is necessary, namely, while the length value is taken, the beat frequency is read out. The beat frequency in prototype equipment is about 1GHz. There is a set of device for measuring UHF light beat frequency in the equipment. Measuring schematic diagram is shown in Fig(3).

Equipment construction

The schematic block diagram of BWI is shown in Fig (4). Longitudinal Zeeman

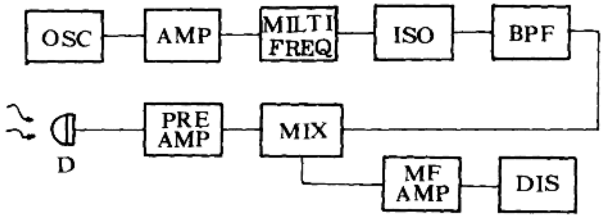
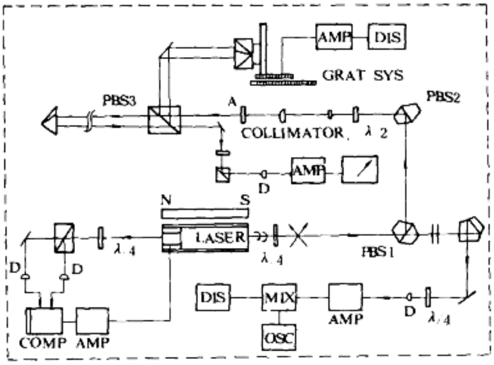


Fig 3. The block diagram of beat frequency measurement



FID4 Schematic diagram of BWI

laser 1 emits a beam of light that contains two components with a slight frequency difference. After the beam pass through a $\lambda/4$ plate. Two components will change into linear polarized light f_1, f_2 which would be perpedicular to each other. The $\lambda/4$ plate and polarized beam splitter PBS1 hould be placed so that the two components from PBS 1 have same intensity. The reflective beam from two PBS passes through a $\lambda/2$ plate so there is a cross angle of 45 degrees in light polarizing plane. Then after the beam passes through a collimator c analyzer A and PBS3. The beam is split into two, each of them contains two components f_1, f_2. Then, the beam from measurement and reference retroreflector are assembled in PBS3. The analyzer is plased so that the two components of same frequency change into coherent light of maximum intersety. Detector D receives the beat interference signal which measuring retroreflector moves reletively to reference prizm. The amplitude of output signal from detector change periodically. The position of the measurement retroreflector is a functions of the signal amplitude. In order to raise measuring accuracy, we adopt discriminsting minimum method. In other words, by moving position of the reference prizm we can obtain the optical path difference of a integral beat wavelength, thus, alternating amplitude of interference signal will be smallest, thereby, high magnification amplifier could be adopted so that measuring sensitivity and accuracy could be improved. At present, the measuring sensitivity is better than 1×10^{-4}. Due to a serious steps of restraining noise is taken. The accuracy of the equipment could be raised greatly.

Two components transmitting PBS1 are reflected by penta prizm and mirror to $\lambda/4$ plate. The $\lambda/4$ plate here is used for preventing light feedback into laser. The beam from $\lambda/4$ plate passes through a lens to a UHF PIN sillicon photodiode. It is used for

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