

# Accurate calibration of grating pitch

D. APOSTOL, P.C. LOGOFATU, S. FLOREA, V. DAMIAN, I. IORDACHE, M. BOJAN\*

Laser Department, National Institute for Laser, Plasma and Radiation Physics, PO Box MG-36, 077125, Magurele, Romania

A current issue insufficiently addressed in nanometrology is the accurate characterization of calibrators with nanoscale features. Gratings are such calibrators and their pitch is one of the features that are used for calibration purposes. In this article the classic method of determining the gratings pitch from the measurement of the angular position of the refracted orders is used. To ensure traceability one has to relate the measurements to the wavelength of a frequency stabilized laser and that can be accomplished by using such a laser as the light source in the experiment. The method is shown to have adequate accuracy for nanometrological needs. A salient feature of the method revealed by error analysis is the fact that the absolute estimation error decreases with the pitch, making the method especially suited for nanometrology. The modern use of the method rather than the method itself is the element of novelty here, of a technological rather than scientific nature.

(Received September 25, 2007; accepted February 7, 2008)

*Keywords:* Gratings pitch, Lateral calibration, Traceability, Diffraction orders

## 1. Introduction

Though insufficiently addressed, the issue of reliable calibrators with nano-scale features, traceably characterized is of outmost importance in nano- metrology [1,2]. Such calibrators are 1D and 2D gratings used as lateral standards to calibrate the length measurements and to characterize the image distortions in the transversal plane of observation of various types of microscopes, optical, confocal, AFM [3] or SPM [4]. The determination of the pitch of a grating is part of the characterization of the grating. A precise and traceable method for the determination of a grating pitch is the measurement of the diffraction angles for light incident on the grating using a frequency stabilized laser as light source, because its wavelength can be known with extreme precision and can be traced to the metre standard. Calibrations on several 1D gratings have been carried out in our lab using this diffractometric method. The instruments we used were a Zeiss goniometer, an autocollimator, and a frequency stabilized He-Ne laser with a wavelength of 632.8 nm. The diffraction angles of the diffraction orders of the gratings were measured with high precision and the results were statistically and analytically analyzed. From the measured value of the diffraction angles the mean pitch of the grating and its uncertainty were calculated.

## 2. Principle of the method

The Floquet theorem [5] applied to diffraction on gratings predicts the existence of preferred diffraction angles and their values. We use the grating in non-conical mounting, which means the incidence plane is parallel to the grating vector and all the diffracted orders lie in the same plane, which corresponds to the  $xz$  plane from Fig. 1.,

$$k_x^m = k_x^{inc} - mK, \quad (1)$$

where  $k_x^m$  is the tangent component of the wavevector of the  $m^{\text{th}}$  diffracted order,  $k_x^{inc}$  is the tangent component of the wavevector of the incident ray and  $K$  is the scalar value of the grating vector  $\mathbf{K}$  shown in Fig. 1.,

$$K = 2\pi/\lambda. \quad (2)$$

The angle of the zeroth diffraction order or the specular order  $\theta_0$ , is equal to the incidence angle  $\theta_{inc}$ , just as in the case of pure transmission. In our experiments, for simplicity, the incidence angle was always zero. For normal incidence only Eq. (1) may be rewritten as

$$\Lambda = -m\lambda/\sin\theta_m. \quad (3)$$

Eq. (3) was written purposely in this form for readily calculation of the pitch using experimental values of  $\theta_m$ . The wavelength  $\lambda$  is known with precision and is traceable,  $m$  can be identified by simple inspection and  $\theta_m$  can be measured with a goniometer. Hence, once we measured the diffraction angle  $\theta_m$  we can determine the pitch  $\Lambda$  from Eq. (3). One may determine the pitch also using the measured angle between two diffraction orders, say  $m_1$  and  $m_2$ ,

$$\Lambda = -\frac{(m_2 - m_1)\lambda}{\sin\theta_2 - \sin\theta_1}. \quad (4)$$

The relation (4) is valid also for other incidence angles than  $0^\circ$ , and is particularly useful when we want to maximize the precision of the pitch estimation and we chose  $m_1$  and  $m_2$  so that they are the last propagating orders before the evanescent orders and also the closest to the minimum and maximum of the exit angle,  $-\pi/2$  and  $\pi/2$ .

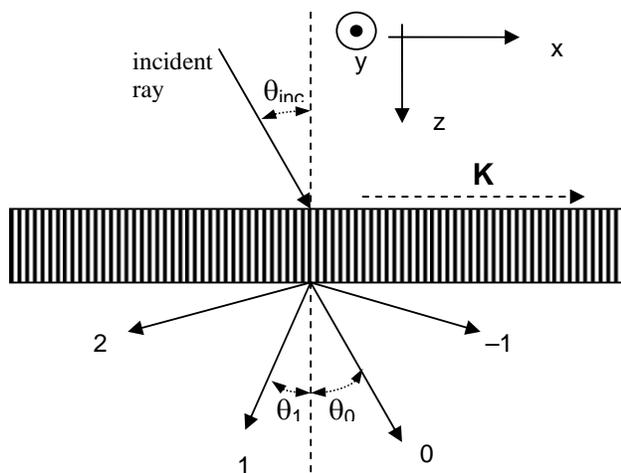


Fig. 1. Diffraction geometry for a transmission grating in non-conical mounting (the incidence plane is parallel to the grating vector). The representation is not, of course, realistic. It was made for illustration purposes only. One must imagine the rays having waists that span many periods of the grating, enough periods so that one may consider the waists span practically an infinite number of periods. The back-diffracted orders are not shown for simplicity.

The identification of the order  $m$  is quite simple. We know that the zeroth transmitted order and the incidence beam make the same angle with the normal direction to the surface of the grating. The non-zero orders follow sequentially to the left and to the right of the zeroth order with the sign determined by the sign convention adopted implicitly in Eq. (1).

The method presented here for measuring the pitch of gratings is not, of course, new [6]. But its simplicity and reliability makes it ideal for use for a very modern purpose: the calibration of traceable artefacts. This is the element of novelty, of a technological rather than scientific nature.

### 3. Experiment

The measurement of the angular position of the diffraction orders of gratings illuminated by laser light sources was made using an autocollimator and a goniometer. An autocollimator combines a collimator and a telescope in one instrument. The collimator reticule as well as the eyepiece (telescope) reticule is in the focal plane of the objective. The autocollimator projects the image of the collimator reticule in a parallel (collimated) beam of light onto a mirror that retro-reflects the light bundle back into the autocollimator. An autocollimation image is formed. If the mirror is exactly perpendicular to the optical axis of the autocollimator the beam of light is reflected along the same path. When the mirror is tilted the reflected beam enters the objective at an angle. Depending on the angle of the reflected light the auto-collimation image is displaced with a larger or lesser amount. The displacement of the auto-collimation image with respect to the eyepiece reticule provides the means for measuring the

angular displacement of the mirror by compensating for it with the matching rotation of the goniometer stage. Goniometers are instruments used for high resolution of large angle measurements. A precision rotary stage and an encoder are combined with a visual autocollimator to make measurements throughout a full  $360^\circ$  range. The rotary table with the inside coupled angle encoder (with a resolution of  $2''$ ) was used to rotate the studied specimen.

It is quite difficult to align the grating so as to ensure that its surface is at the centre of the goniometer (i.e. the surface of the grating contains the axis of rotation of the goniometer table), the diffracted orders lie in the same horizontal plane as the zeroth order and the normal to the grating plane is sent back into the autocollimator. Once these adjustments were made, the goniometer stage was rotated so that progressively higher diffracted orders were directed to the collimator. When the reticule of the diffracted order coincided with the collimator reticule the rotation angle was measured.

In Fig. 2 is shown the image taken with an AFM of a grating whose pitch was determined using the method of diffraction angle measurement. The AFM measurement was done for comparison with the results obtained from the diffraction angles measurement method. The result of the AFM measurement was  $\Lambda = 23.746 \mu\text{m}$ . As far as the accuracy (not resolution!) of AFM instruments is larger than  $1\text{nm}$  [7] and generally not indicated by the producer this result could not be trusted. This is the reason for the great interest in calibrating artefact characterization in nanometrology.



Fig. 2. Image of a grating that illustrates the measurement process of the pitch done with an AFM.

The results obtained from the statistical analysis of the diffraction angles measurements for the sample from Fig. 2 are shown in Table 1. The diffraction angles for the orders  $-1$  and  $+1$  were measured several times, after the alignment of the zeroth order, and the pitch was estimated in three ways by applying the formula 3 to the pairs of diffraction orders  $(-1,0)$ ,  $(1,0)$  and  $(-1,1)$ . One may notice that the angle measurements were affected by systematic errors, because  $\theta_{-1}$  and  $\theta_{+1}$  are supposed to have identical absolute value. Also the comparison with the AFM measurement indicates that we were affected by systematic errors. One way to reduce the influence of systematic errors is to use orders that are far apart. In this way many systematic errors cancel each other out, and one

can see that this rationale was valid in our case, because  $\Lambda_{-1,+1}$  has a better standard deviation than  $\Lambda_{-1,0}$  and  $\Lambda_{1,0}$ , and also the mean value of  $\Lambda_{-1,+1}$  lies almost in the middle of the mean values of  $\Lambda_{-1,0}$  and  $\Lambda_{1,0}$ .

Table 1. The measured mean values of the angles for the diffraction orders  $-1$  and  $+1$  and the results of the statistical analysis of the data resulting from the estimation of the pitch.

Parameter	$\theta_{-1}$	$\theta_{+1}$	$\Lambda_{-1,0}$ ( $\mu\text{m}$ )	$\Lambda_{1,0}$ ( $\mu\text{m}$ )	$\Lambda_{-1,+1}$ ( $\mu\text{m}$ )
Values	$-1^{\circ}28'35''$	$1^{\circ}31'46''$	$23.66 \pm 0.15$	$24.59 \pm 0.03$	$24.13 \pm 0.02$

Table 2. The estimated values for the pitches of five gratings together with the absolute and the relative estimation error.

Pitch $\Lambda$ ( $\mu\text{m}$ )	1.945	4.158	9.923	24.134	48.136
Absolute error $\delta\Lambda$ (nm)	1.0	2.1	7.2	21	53
Relative error $\varepsilon\Lambda$	$5.5 \times 10^{-4}$	$5.0 \times 10^{-4}$	$7.3 \times 10^{-4}$	$8.5 \times 10^{-4}$	$1.1 \times 10^{-3}$

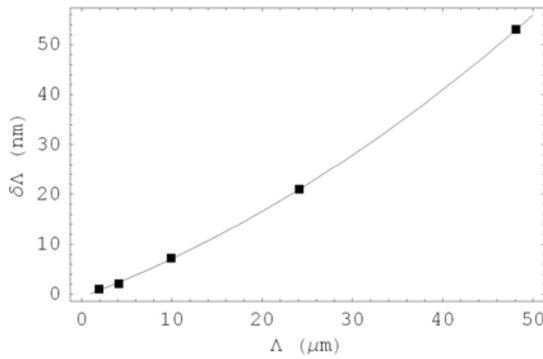


Fig. 3. The graphic illustration of the absolute estimation error of the pitch versus the pitch for the five gratings from Table 2.

#### 4. Error analysis

In order to obtain some more general information about the error estimation of the pitch, valid for any grating, we have to calculate literally the precision by working on Eqs. (3) or (4). Differentiating Eq. (4) we obtain

$$\delta\Lambda = (m_2 - m_1)\lambda \frac{\cos\theta_2 - \cos\theta_1}{(\sin\theta_2 - \sin\theta_1)^2} \delta\theta, \quad (5)$$

where we took into account the fact that the laser is frequency stabilized ( $\delta\lambda = 0$ ) and  $m_1$  and  $m_2$  are discrete and hence their differentiation also gives 0. We also assumed that the measurement error of the angle  $\theta$  is independent of its value. Eq. (5) explains the behaviour of the pitch estimation error from Fig. 3, namely the fact that it increases with the pitch. Indeed, for the cases shown in Table 2 and Fig. 3, Eq. (5) takes the form

We have shown above the experimental results for the sample from Fig. 2 in some detail. But we measured several other samples and the corresponding results are shown in Table 2 and Fig. 3. For the estimation of the pitch was used the angular difference between the orders  $-1$  and  $+1$ . From Table 2, and, more intuitively, from Fig. 3 one may see that the estimation error of the pitch  $\delta\Lambda$  increases with respect to  $\Lambda$ . The relative estimation error increases too with respect to  $\Lambda$  but not so strongly.

$$\delta\Lambda = \lambda \frac{\cos\theta}{\sin^2\theta} \delta\theta = \frac{\Lambda}{\lambda} \sqrt{\Lambda^2 - \lambda^2} \delta\theta, \quad (6)$$

where  $\theta$  is the diffraction angle of the orders  $\pm 1$  taken with positive sign.

The inspection of Eq. (5) further reveals the fact that we can minimize the estimation error of  $\Lambda$  by setting the angles  $\theta_1$  and  $\theta_2$  as far apart as possible, that is both close to  $\pi/2$  in absolute value but of opposite signs. Of course, these values of  $\theta_1$  and  $\theta_2$  must correspond to diffraction orders, which is a limitation of our ability to optimize the estimation precision by manipulating the experimental measurement configuration. In the following considerations we will assume we attained the optimum measurement configuration, the one that ensures minimum estimation error for the pitch. One may assume that the position of the angles  $\theta_1$  and  $\theta_2$  are about the same for various gratings with different pitches (close to  $-\pi/2$  and  $\pi/2$ ). Then the only difference between the estimation error for a large pitch and a small pitch is the orders indexes. Their difference decreases for small pitches. Indeed, the maximum visible order for normal incidence is

$$m_{\max} = \text{Floor}(\Lambda/\lambda), \quad (7)$$

that is the largest integer smaller than the ratio  $\Lambda/\lambda$ . Therefore one can conclude that the absolute estimation error decreases with the pitch. However, the relative estimation error,  $\delta\Lambda/\Lambda$  is about the same for all pitches. From Eqs. (5) and (4) one deduces the relative estimation error to be

$$\frac{\delta\Lambda}{\Lambda} = -\frac{\cos\theta_2 - \cos\theta_1}{\sin\theta_2 - \sin\theta_1} \delta\theta, \quad (8)$$

which is independent of the diffraction orders indexes and does not change much with  $\Lambda$  if the angles  $\theta_1$  and  $\theta_2$  are close to the extremes of their range, i.e. they are in the optimum configuration. (It should be mentioned that the

data shown in Table 2 and Fig. 3 was not obtained using an optimum measurement configuration.) The optimum configuration depends on the incidence angle, therefore we don't have a unique solution. The most simple solution is to assume normal incidence and then we can use formula (7), and we will have  $m_2 = -m_1 = m_{\max}$  and  $\theta_2 = -\theta_1 = \sin^{-1}(m_{\max} \lambda / \Lambda)$ , but this solution does not give the best results when the wavelength is close to the pitch, or even does not offer a physical solutions for the angles at all. The fact that the absolute value of the estimation error of the pitch decreases with the pitch makes this method particularly suited for nano-metrology. *The smaller the pitch, the better the estimation error.* There is however a limitation imposed by the existence condition of real, propagating, non-evanescent orders. Namely if the pitch is less than or equal to half of the laser wavelength then we don't have propagating orders. Therefore, for this method to work, we have to use a short enough wavelength, at most twice the pitch.

For illustration purposes let us apply the formula (8) when the wavelength  $\lambda$  is 633 nm to two cases of gratings, one of 24  $\mu\text{m}$  pitch, like the real grating for which experimental data is shown in Table 1, and another grating of 330 nm pitch, cutting close to the condition of existence of propagating diffraction orders. For the 24  $\mu\text{m}$  pitch grating we assume normal incidence. For the 330 nm pitch grating, however, we cannot assume normal incidence because then we cannot have propagating orders and the method cannot be applied. Instead we imposed the condition that the incidence angle is the same but of opposite sense as the diffraction angle of the order +1. A measurement error of the angles of 10'' was assumed (the measurement error is not necessarily the same as the reading resolution). The results were gathered and organized in Table 1. We notice that, indeed, the absolute estimation error of the pitch is much smaller for the grating with the smaller pitch than for the grating with larger pitch, but the relative estimation error is about the same for both gratings. The values for the grating with larger pitch shown in Table 3 are very different compared to those of Table 1, although the grating has about the same value of the pitch. The reason is that the values from Table 1 do not correspond to the optimum configuration for which the values from Table 3 were calculated. However, as we mentioned before, we have to keep in mind that in most practical cases the optimum configuration may not be usable due to weak, difficult to measure or even to detect high diffraction orders.

*Table 3. The results of theoretical error analysis for two gratings with very different pitches. The optimum measurement configuration defined by the pair of angles  $(\theta_1, \theta_2)$  is determined for normal incidence in the case of the first grating and for oblique, near grazing incidence for the second grating. The measurement error of the angle was assumed to be 10''.*

Pitch $\Lambda$	$\theta_1$ ( $^\circ$ )	$\theta_2$ ( $^\circ$ )	$m_1$	$m_2$	$\delta\Lambda$ (nm)	$\delta\Lambda/\Lambda$
24 $\mu\text{m}$	77.4	-77.4	-37	37	0.26	$1.1 \times 10^{-5}$
330 nm	73.6	-73.6	0	1	$4.7 \times 10^{-3}$	$1.4 \times 10^{-5}$

## 5. Conclusion

Although the diffractometer is not very good at estimating the uniformity of gratings, it is very effective in measuring the mean pitch. One interesting feature that we demonstrated in this article is that the absolute estimation error for the pitch decreases with the pitch itself, and in order to have comparable estimation errors for the determination of large and small pitches we must use the highest diffraction orders available. Moreover, because the higher diffraction orders are oftentimes weak and hard to measure or even detect, in practice even the relative estimation error may be smaller for gratings with smaller pitches. This means the method is appropriate for nano-metrology, particularly for our purpose to measure the average pitch of gratings with sub-nanometer accuracy. Of course, all these considerations are valid if the wavelength satisfies the condition of existence for propagating diffraction orders, that is  $\lambda \leq 2\Lambda$ .

## References

- [1] L. Koendersand, F. Meli, in *Nanoscale calibration standards and methods*, Wiley-VCH GmbH, Weinheim, 205-219 (2005).
- [2] I. Iordache, D. Apostol, O. Iancu, G. Stanciu, P. C. Logofatu, V. Damian, F. Garoi, B. Savu, M. Bojan, *Proc SPIE* **6635**, 03 (2007).
- [3] I. Misumi, S. Gonda, T. Kurosawa, K. Takamasu, *Meas. Sci. Technol.* **14**, 463-471 (2003).
- [4] J. Joergensen, J. Jensen, J. Garnæs, *Appl Phys A-Mater* **66**, S847-S852 (1998).
- [5] G. Floquet, *Ann. École Norm. Sup.* **12**, 47-88 (1883) (in French).
- [6] D. Rittenhouse, *Trans. Amer. Phil. Soc.* **2**, 201 (1786).
- [7] <http://www.veecoprobes.com>

\*Corresponding author: mihaela.bojan@inflpr.ro