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Laser wavelength with a ruler: easy made apparatus

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Abstract

We describe an easy-to-build low-cost apparatus by which the wavelength of a laser module can be determined by measuring just some lengths. The basic idea is to use a metallic workshop ruler in grazing incidence, similarly to what is done in x-ray spectrographs, where normal optical gratings are used in this configuration. We additionally propose a novel approach to the theory of the phenomenon, enabling exact calculations for a large number of diffraction maxima positions. This new scheme results in a substantial improvement in the accuracy of the calculated wavelength values compared to previous works. The apparatus has been designed for its maximum easy of construction, simplicity, availability of materials and flexibility of use. Detailed instructions on construction and alignment are given.

Keywords: wavelength of light, diffraction, grazing incidence, exact calculations, student project, project-based class

1. Introduction

The fundamental importance of diffraction and its related applications is well established. Diffraction underlies both many fundamental physical phenomena and numerous high-precision measurement techniques [1–5]. In this work, we present an instrument for the precise determination of the wavelength of a visible laser source. The device is particularly simple to set up, it is particularly suitable for educational purposes [6–8], and its theoretical description is straightforward to analyse.

If a well-collimated visible laser beam is sent at a very large angle of incidence onto a grating with a large pitch, such as a normal ruler, a fantastic Fraunhofer diffraction phenomenon is formed on a screen placed at a certain distance in the form of a succession of many dozen diffraction maxima, as shown in figure 1. These maxima are clearly visible even to a large audience, and the phenomenon is a source of wonder.

Diffraction gratings in grazing incidence were first proposed in 1924 by Carrara [9] for the analysis of x-rays. This possibility was later revisited by Bearden [10], Alvarez [11],

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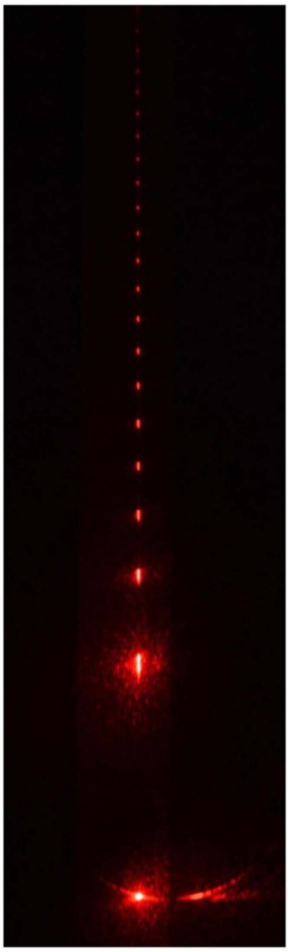

Figure 1. The diffraction maxima generated by a laser beam striking a normal ruler at grazing incidence as they appear on a distant screen.

Ditchburn [12], and subsequently by Schawlow in 1965 [13] for the determination of the wavelength in the visible range. It is interesting to note how even eminent physicists, future Nobel Prize winners, have been interested in the educational implications of their research fields. Other works propose the same technique, for example, to determine the diameter of a hair [14], also in combination with other devices [15].

This possibility is proposed again here following a new calculation of the wavelength of light which does not use approximations as in previous works, and a simple apparatus for the precise determination of the wavelength of light from a laser diode. This apparatus has been specifically designed for ease of reproduction using non-specialized tools, simplicity in alignment, and with the goal of creating an autonomous system that is always ready for use.

2. Grazing light diffraction gratings

The equation relating, for any grating, the angle of incidence α, the angle β_k at which the diffracted ray of order k is formed, the spacing p between diffracting elements of the grating and the wavelength λ, with α and β_k on opposite sides of the normal and both taken as positive, is [13]:

$$k\lambda_k = p\left(\sin\alpha - \sin\beta_k\right). \tag{1}$$

Since for grazing incidence the angle of incidence and consequently also the diffraction angles are very close to 90°, it can be seen from figure 2 that if equation (1) is written considering the complementary angles i and r_k of the respective α and β_k:

$$k\lambda_k = p\left(\cos i - \cos r_k\right) \tag{2}$$

it becomes possible to directly calculate the values of their cosines from the geometry of the system and thus determine the wavelength of the laser light for each one of the diffracted rays.

In figure 3 the spots—Y_0 and Y_0 correspond to the rays not deviated and to the zero-order diffracted (specularly reflected) beam, respectively. Their intermediate point O is the reference for the determination of the distances OY_k of the various diffracted maxima, as indicated in figure 2, which constitutes the measurable data for the calculation of the wavelength of the laser light.

From now on, we will use the symbol Y_k to indicate the various distances OY_k. In the original Shawlow's proposal, the determination of the laser wavelength from the position of the diffraction maxima uses the approximation $sin\,\beta \cong tan\,\beta$ that is valid only for small r_k angles. In the present proposal, without approximations, one can write:

$$\cos i = \cos r_0 = \frac{d}{\sqrt{\left(d^2 + {Y_0}^2\right)}} \tag{3}$$

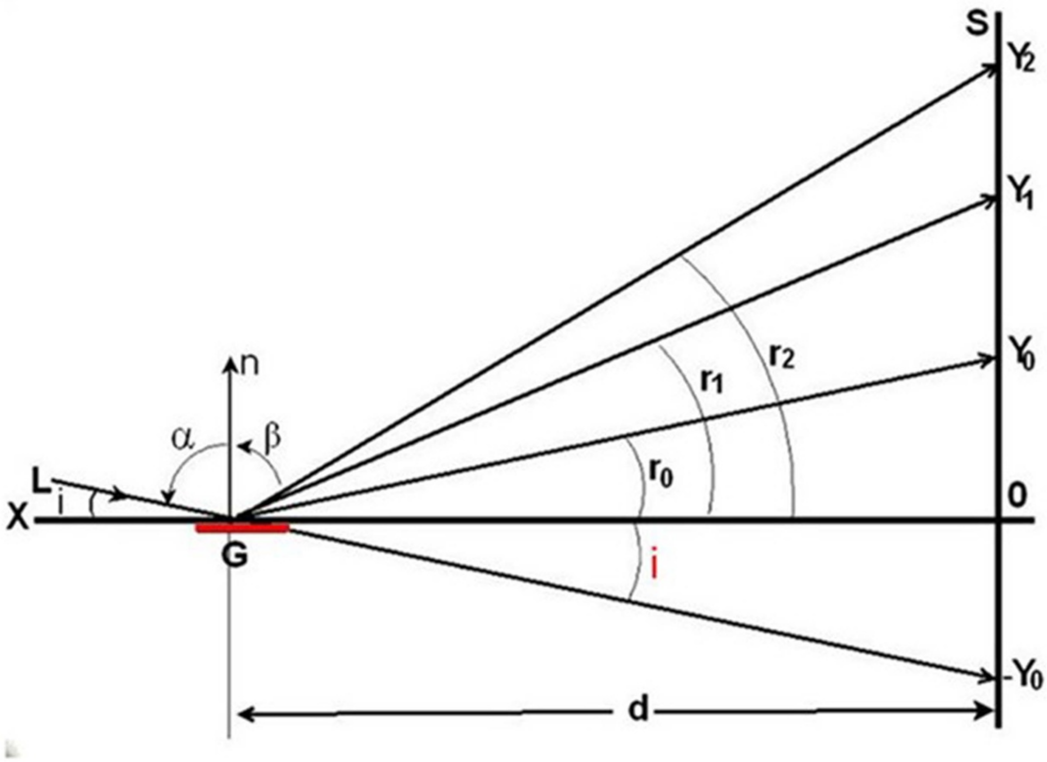

Figure 2. L is the collimated laser beam incident on the grating G. S is the screen on which the diffraction fringes form, placed at a distance d from the grating. The first maximum formed at angle r_0 is due to specular reflection by the grating, therefore $r_0 = i$, complementary of the incidence angle α, where i is evaluated starting from the OX plane of the grating, as are the other angles indicated r_k ($k = 1, 2, \ldots$). The fraction of the undeflected laser beam determines the maximum in the symmetric position—Y_0 of the screen. The angles are drawn much larger than the real ones for clarity purposes.

$$\cos r_k = \frac{d}{\sqrt{\left(d^2 + Y_k{}^2\right)}} \tag{4}$$

and then from (2) the value of the wavelength of the laser light can be derived:

$$\lambda_k = \frac{p}{k}\left(C - \frac{d}{\sqrt{d^2 + Y_k^2}}\right), \quad C = \frac{d}{\sqrt{d^2 + Y_0^2}}, \tag{5}$$

where C is a constant. These expressions also apply to diffraction orders much greater than 2, thereby enabling more precise determinations of the laser wavelength due to the availability of a larger dataset.

Table 1 reports the measurements of the first 12 Y_k values expressed in centimetres as detected on a screen placed at 2 m from the grating, consisting of 10 cm of a machinists' steel scale with the grooves spaced every half millimetre and therefore with $p = 0.05$ cm. The wavelength values are expressed in nm as usual for visible wavelengths.

A simple Python script allows to quickly calculate the values of the various wavelengths λ_k from (5). They are reported in table 1. The last column of the table reports the squared deviations from the mean $\lambda\mu$ for determining the standard deviation. An element of uncertainty that can lead to a systematic error is the fact that one does not know where to start measuring the distance d, from one of the ends of the grating or from its middle. This error is reduced if d is large compared to the length of the illuminated section of the grating, and this justifies the choice of the distance $d = 2$ m for this experiment.

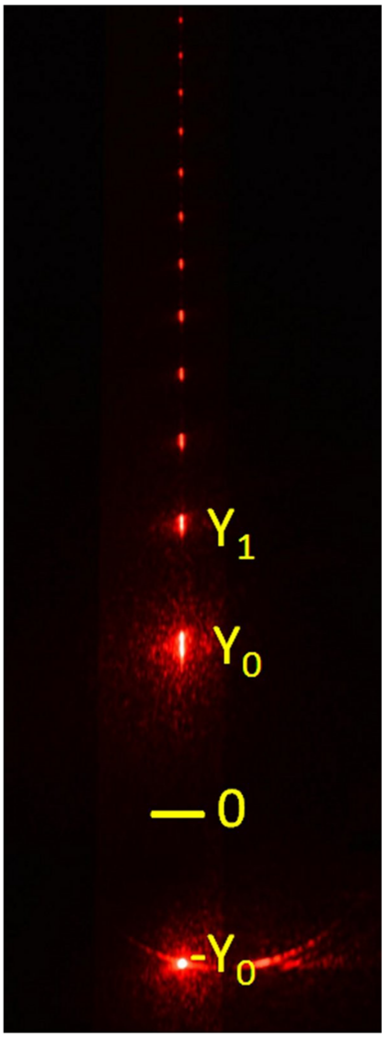

Figure 3. Photograph of the first 11 diffraction maxima projected on a screen at 2 m from the red laser, even though in reality and in a darkened environment diffracted maxima are visible up to the 25th order and more. In this photograph, the midpoint O between the spots-Y_0 and Y_0 has been also indicated.

The mean $\lambda_\mu = 645$ nm is obtained with a standard deviation of ± 2 nm, a precision of 3%.

The purpose of this note is not to carry out precision measurements on the particular laser diode used, but only to indicate an application of the surprising possibility of determining a microscopic quantity with great precision with a crude instrument, and of using it in laboratory practice, confident that the calculations fit well with the geometry of the phenomenon.

Table 1. Measurements for Y_0 and the first 12 Y_k values as detected on a screen placed at 2 m from the ruler-based diffraction grating described in this work. The corresponding wavelength λ_k from (5) and the squared deviation from the mean λ_μ are reported in the third and fourth columns, respectively.

k	Y_k (cm)	λ_κ (nm)	$(\lambda_\kappa - \lambda\mu)^2$ (nm)^2
0	7,1		
1	12,4	643,4	4
2	16,1	648,7	11
3	19,0	642,1	11
4	21,6	643,9	2
5	24,0	649,3	15
6	26,1	648,2	8
7	28,0	644,9	0
8	29.9	647,6	5
9	31,5	641,5	15
10	33,3	647,4	4
11	34,8	644,2	1
12	36,3	643,5	3
		$\lambda_\mu = 645.4$	$\Sigma = 79$

The values of the Y_k distances reported in table 1 are the result of a single determination carried out without particular care. They are taken from the diffraction maxima marked with a pencil line on the screen, and this is evident from the large dispersion of the data, and consequently from the relatively high value of the standard deviation. Much more precise results can be obtained by carrying out several determinations for each Y_k, averaging them and proceeding as usual. In this way, precisions of fractions of nm can be achieved in the determination of the wavelength, because the overall data obtained from a large number of diffraction maxima can be used in the calculations and without approximations.

3. Construction details

The red laser modules (figure 4) can be purchased on the web in groups of ten at a cost of a few euros (they can be purchased on eBay by searching for ‘mini laser 650 nm 5 V 5 mW red.’) They consist of a 5 mW laser diode mounted with its collimating lens in a 6 mm diameter and 10 mm long cylinder. The device can be powered without any particular requirements with a voltage of 5 V and a current of 30 mA.

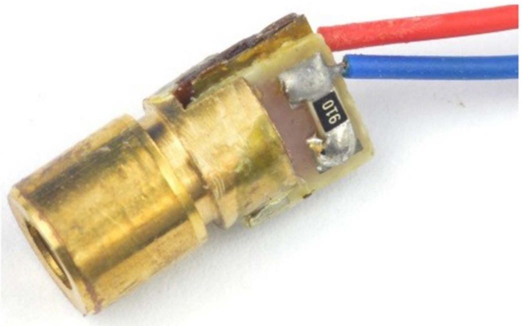

Figure 4. The laser diode module employed for the experiment. This component has the power supply wires already soldered to the small circuit board to which the small resistor (91 Ω) is also soldered. The collimator is the ring on the left.

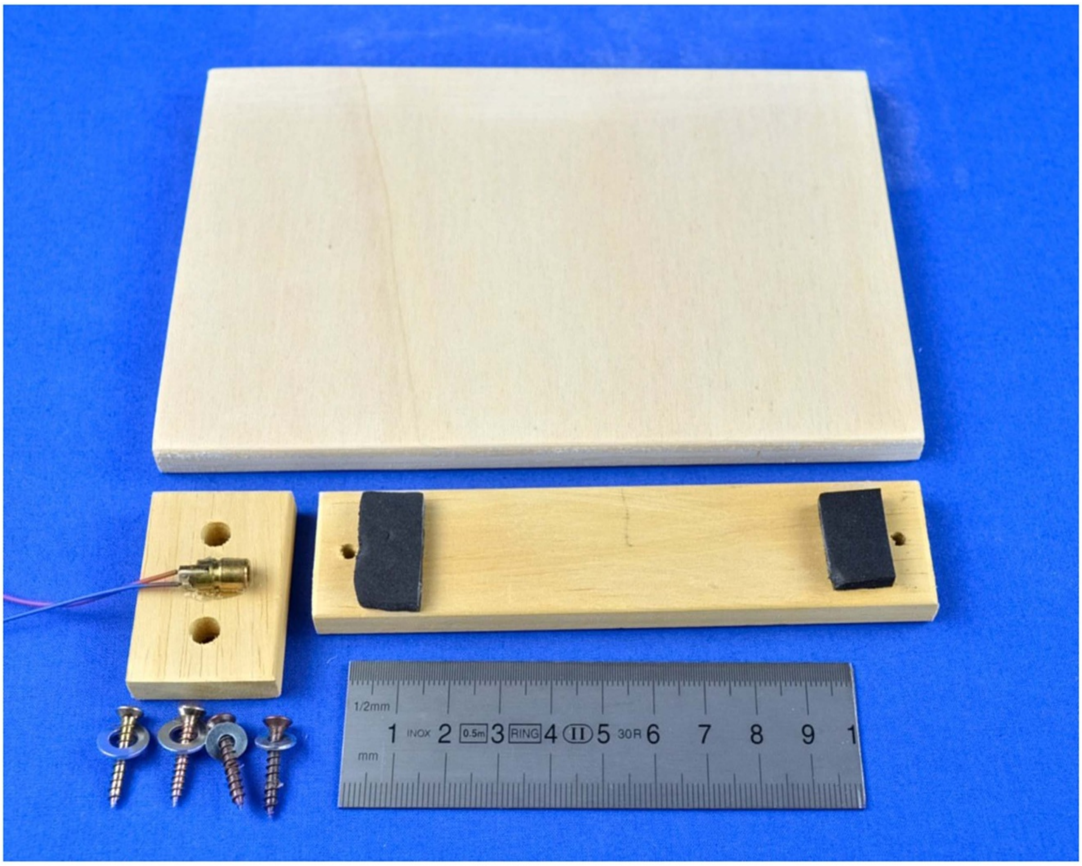

Figure 5. Individual pieces of the ruler-based diffraction grating.

Both normal 4.5 V batteries and USB power supplies, now very common for charging mobile phones and for powering many electronic devices can be used. These laser modules generate a very intense and collimated beam. The collimator is screwed to the body of the module and may be adjusted by rotating till the diffraction maxima as small as possible are obtained

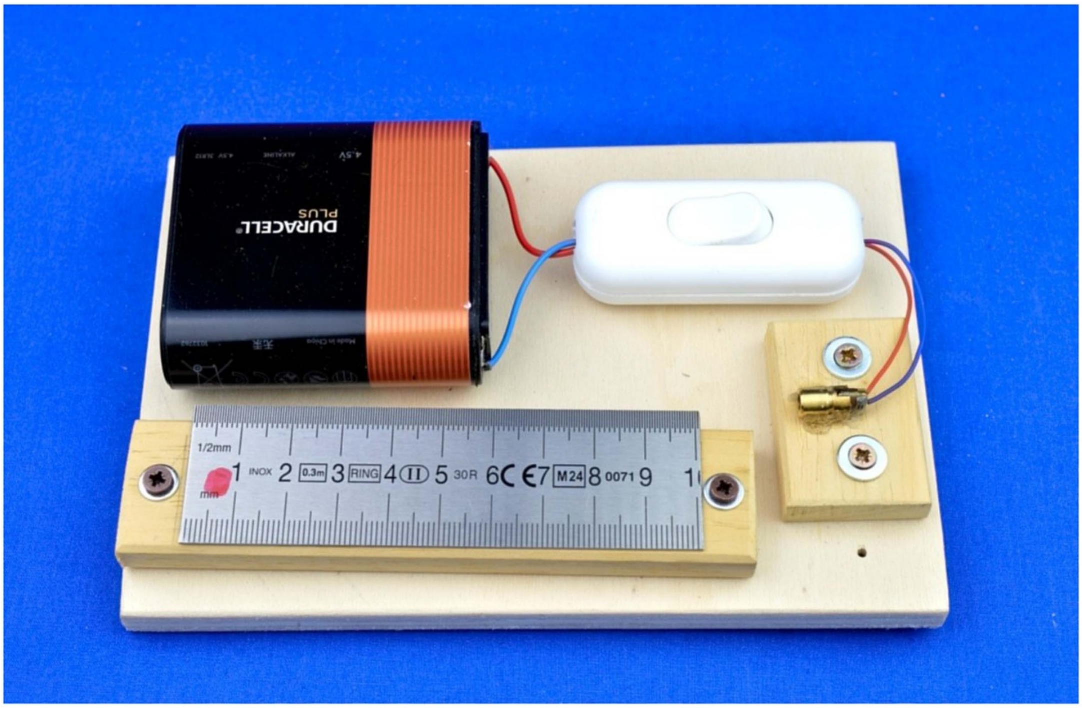

Figure 6. General view of the apparatus, with all the components mounted on a wooden base. The ruler section is simply resting on his support to allow easy replacement with other samples.

on the screen, although normally this is not necessary.

All the components of the optical assembly are shown in figure 5, while the complete autonomous apparatus is reported in figure 6. The base is a 11 $\times$ 16 cm slab of 10 mm thick wooden plywood. The supports for the laser module and the ruler are cut from a 29 $\times$ 9 mm wooden batten respectively in 4.2 and 12.5 cm length.

The laser module is glued to its wood batten support with clear neoprene glue (in particular, the neoprene glue used in this mount was kendaprene). Since the section of the laser beam is elliptical with the major axis perpendicular to the plane of the small printed circuit board to which the two power wires are soldered, it is advisable that this plane is oriented vertically, as can be seen in figure 6.

As can be seen in figure 5, two small pieces of neoprene mousse are glued to the ends of the ruler support. They allow precise adjustment of the height and incidence angle of the laser beam on the grating by tightening the end screws. In the same figure, 6 mm diameter holes are visible in the laser support. They allow small adjustments of the horizontal angular direction of the laser beam on the ruler's grating.

The grating is a 10 cm section cut from a workshop steel ruler. Not all the rulers, even if taken from the same shelf, are suitable. We had to buy three of these before finding the right one that provided well-defined diffraction maxima.

Gluing the laser to its support requires some attention and patience. First, screw both laser and grating supports in their final position on the wooden base. The centre of the laser holder should be aligned two or three millimetres inside one of the edges of the grating holder as shown in figure 7.

To begin with, place one of the available laser modules at the centre of its support and power it on. Next, adjust the height of the grating and the position of the laser until the beam illuminates the millimetre markings on one side of the ruler along its maximum length. The laser beam produced by these modules is rarely perfectly coincident with

Figure 7. Positions of laser and grating supports on the wooden base of the apparatus.

the axis of the module; in most cases, it deviates by a small angle. Therefore, it is necessary to identify the module whose beam has the correct inclination when positioned with its printed circuit board approximately vertical but in such a way that a small part of the beam passes undisturbed alongside the edge of the ruler and is deflected below. This part of the laser beam is particularly important because it generates the spot-Y_0 on the screen (figure 3), which serves as a reference for determining the midpoint O from which to determine all the Y_k values of the diffracted beams. The process of selecting the appropriate laser module and adjusting the grating height should be iteratively refined until the optimal beam illumination on the ruler is achieved. This is determined by observing the spots on the distant screen, until they reach their optimal size and sharpness. At this point, place a drop of glue on the laser holder and secure it, taking care that his position remains unchanged. The ruler may be left simply resting on its support. This allows, for example, to compare the distances of diffraction maxima from the half-millimetre scale with that of the other 1 mm side of the ruler. For a more practical and easier transport apparatus, the ruler may be glued to its support or fixed with thin double adhesive tape.

4. Conclusions

We have revisited a beautiful and little-known phenomenon: if a well-collimated visible laser beam strikes a grating with a very large pitch (millimetres), a series of many dozen diffraction maxima is formed on a screen placed at a given distance. A certain number of them are visible even to a large audience. It is possible to show that the experiment falls within the Fraunhofer regime by moving the device closer to the screen and observing that the spots gradually become less and less defined.

Thanks to this extraordinary phenomenon and simple calculations with no approximations such as reported in previous works, it has been shown how it is possible to determine the wavelength of a laser with considerable precision. In fact, given the geometry of the set-up, the wavelength can be calculated from the position of each of the large number of observed diffraction maxima.

The apparatus was designed with the primary aim to be easy to assemble, to require a minimum of operations for its construction with a minimum of tools, and using common materials of easy availability: only four wooden screws and no welding of electrical conductors. Alignment operations are non-critical and have been accurately described. The apparatus is lightweight and very flexible, allowing immediate reticle replacement.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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