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From one slit to diffraction grating: optical physics lab by means of computer on-line sensors

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From one slit to diffraction grating: optical physics lab by means of computer on-line sensors

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Abstract. Diffraction is a crucial phenomenon and its interpretation bridges from geometrical to wave optics and from wave optics to quantum mechanics. Becoming familiar with the characteristics of the diffraction in the cases of one, two, many slits is an important experience for students not only from the subject point of view, but also on the methodological plan. The exploration of the relative interpretation by means of simulation and modelling offers to the students the opportunity to experience the typical methodological work in physics. An educational proposal was developed for the study of optical diffraction: from the analysis of a single slit diffraction, to a double slit and to a diffraction grating. It is based on a USB acquisition system designed and developed for experimental data acquisition in an educational lab, correlating position and light intensity measurements in one direction (Gervasio & Michelini 2009). Data can be exported in text format and data fitting can be done by means of a spreadsheet. The educational proposal about single-slit diffraction (Corni *et al.* 1993) has been tested with 114 students (aged 18-19) in 2008 and 2014. Many of these interventions were research-based educational path. Data concerning learning processes of 29 students are described in (Michelini & Stefanel 2015). We are now developing an educational path about optical spectroscopy for upper secondary-school and university students, and the need to extend the educational proposal to the case of diffraction from a diffraction grating has emerged: this is necessary in order to deal with lab activities involving the analysis of spectra and to study the conceptual knots emerged in the literature in the case of optical spectra generated by a prism (Ivanjek *et al.* 2015a, 2015b). The phenomenon laws obtained by data are interpreted under the wave nature of light by students and these laws are used for spectroscopic analysis of different light sources. Simulation software allows to build models of interpretation of phenomenology based on the first principles (Santi *et al.* 1993). The proposed IBL path based on the exploration of the multiple slit diffraction pattern has been used with 98 upper secondary school Italian students and 56 freshmen in biotechnology sampled from University of Udine. Data has been analyzed and the results are under discussion. This poster shows the experimental activity proposed to the students and its characteristics.

1. Motivations and basis of the proposal

The previous proposal: diffraction of light from a single slit

The single-slit diffraction educational proposal aims to obtain the formal laws describing the phenomenon by means of a gradual phenomenological analysis of the data acquired via on-line measurement with the Lucegrafo system (Fig. 1): this USB system for diffraction measurements is constituted by a photodiode inserted in a housing solid with the cursor of a linear potentiometer, so that the optic signal is correlated with the position by means of the resistance of the potentiometer (Fig. 1 left). The system acquires and represents on the screen, both in graphical and numerical way, couples intensity-

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position so that, moving the cursor by manual adjustment of the screw, the space distribution of light intensity on the screen is acquired (Fig. 1 right). The intensity in the graph is represented in arbitrary units, proportional to the light intensity incident on the sensor. Data can be exported in text format and further analysis can be done by means of a spreadsheet.

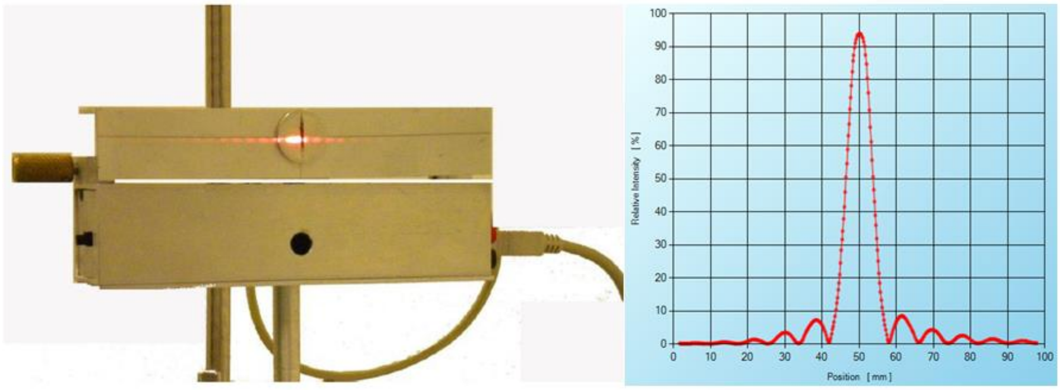

Fig. 1. The Lucegrafo system and the acquired graph light intensity vs position. Single slit (width a = 0,12 mm) at a distance of 155 cm from the screen with a laser (λ = 650 nm)

Students are involved in an experimental problem solving activity and then in an interpretative challenge by means of the following steps:

1. Qualitative analysis of the diffraction pattern allows them to recognize that it is an angular distribution, constituted by a sequence of maxima and minima of intensity symmetrically distributed with respect to the position of the central maximum.
2. Acquisition of the light intensity vs the transverse position using the on-line system Lucegrafo.
3. Analysis of the relation between angular position of minima and maxima as a function of their order with the help of a spreadsheet (Fig. 2).

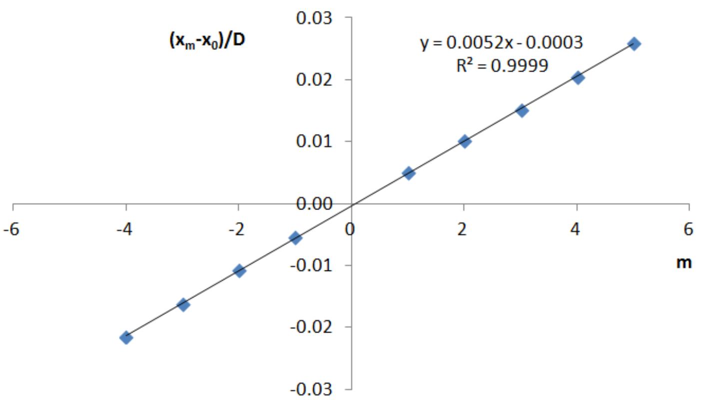

Fig. 2. Angular positions of minima vs order m. D is the screen-slit distance, X_0 is the position of the central maximum and x_m is the position of each minimum. The relation is linear

Phenomenological exploration (step 1) and data analysis from the on-line acquisition (steps 2-3) lead to discover that the slit width a is a fundamental parameter. From the phenomenological laws (Fig. 3) another fundamental parameter emerges, and it must have the dimension of a length and his a physical quantity characterizing the light used (usually indicated with λ).

$$\left.\begin{array}{l}\sin\theta = m\dfrac{\lambda}{a}\\[2ex] \sin\theta \approx \dfrac{x_m - x_0}{D}\end{array}\right\} \Rightarrow \frac{x_m - x_0}{D} \approx m\frac{\lambda}{a} \quad m = \pm 1, \pm 2, \ldots$$

Fig. 3. The slope in the graph of Fig. 2 depends both on the slit width a and on another parameter named λ. This is associated with the color of the light. In an wave model it is the wavelength

4. Analysis of the relation between intensity of the maxima and their position (Fig. 4), as bridge to interpretation.

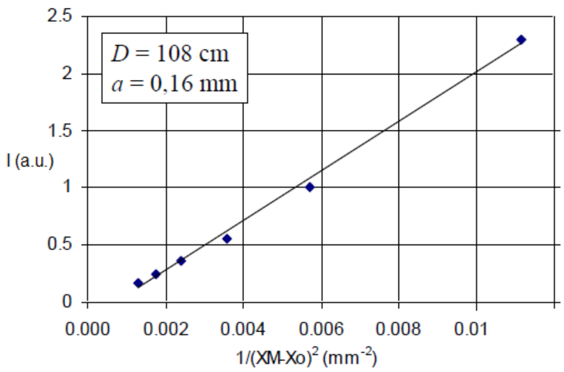

Fig. 4. Intensity of maxima vs their position (x_M-X_0). The relation is linear if one plots the intensity as a function of the squared inverse position

5. Reconstruction of the diffraction pattern trough models/simulations based on the Huygens-Fresnel and the superimposition principles (Fig. 8). Applying these principles accounts for the distribution observed, helping the interpretative process.

Interpretative problems about single slit diffraction

Following the single slit diffraction proposal sketched before, research-based experiments in the schools were carried out with 114 Italian high school students using tutorial monitoring the learning process. The analysis of data concerning learning processes (Michelini & Stefanel 2015) showed that more than 80% of students become familiar with the new phenomenology and the phenomenological relations describing it. However, the relationship between experimental results and the interpretative model based on the Huygens-Fresnel principle remained an open problem: about 60% of students used the phenomenological laws to remain on a descriptive plan; about 30% attempted to explain the features of the phenomenon using a geometrical model, focusing only on those aspects that can be justified within that model (i.e. the “enlargement of the beam”); 10% evidenced that a new model is needed.

Widening the context to gain interpretative ownership: from a single slit to diffraction grating

As pointed out in literature (Vosniadou 2008), the context is crucial in gaining the conceptual understanding in the learning process. In particular, it activates the interpretative elements. Assuming that build the basis for interpretative inquiry is of fundamental importance, we hypothesize that the application of the wave model in a wider and more complex contexts, faced once again on a phenomenological plan, can activate the students’ gain of a new interpretative perspective. This imply to study diffraction using two, three slits and a diffracting grating, to analyze the role of the various parameters, as the number of slits or their separation in order to gain descriptive and interpretative ownership of the phenomena concerning a diffraction grating. In this perspective we developed a new proposal, described in the following. We start from our researches, that evidence the difficulties of students in changing interpretative model, and from that of McDermott's group, that showed the need to specify the role of the diffraction grating (Ivanjek *et al*. 2015a, 2015b). Our research questions are:

- RQ1: How does experimental activity contribute in identifying the new phenomenology and the model underlying it?
- RQ2: How does experimental activity contribute in identifying the role of the various parameters?
- RQ3: How does experimental activity contribute in identifying the role of a diffraction grating?

2. The experimental activity

The interpretative problems emerged in the single-slit experimentations are mainly related to the Huygens-Fresnel principle. To produce a personal involvement and a gradual understanding we suggest an experimental-based activity in which students gradually face optical phenomena whose interpretation require the understanding of the wave superimposition principle. In particular increasing the number of slits (steps 1-4 below) allows further investigations, related to the resolving power of a diffraction grating (step 5). The activity lab work and simulation activities interplay in order to offer a gradual understanding, both on the phenomenological and interpretative plan, of the main characteristics of the diffraction pattern caused by the interaction of light with different obstacles.

Light diffraction from 2 and 3 slits

1. The first step is linked to the previous path replacing the single slit with a double slit. The pattern is the convolution of a pure interference pattern, modulated by a diffraction sync, easily detectable with the Lucegrafo system (Fig. 5). The interference pattern shows new regularities, as the distance between two maxima, that can be studied in function of new parameters: the number of slits and their spatial density.
2. The distance between the two slits has consequences on the resulting distance between contiguous maxima of the interference pattern, in particular, reducing the distance leads to a greater linear separation between two continuous maxima.
3. An increasing number of slits (three rather than two) shows that, all conditions being equal, the maxima remain in the same positions but they become sharper and more intense (Fig. 6).

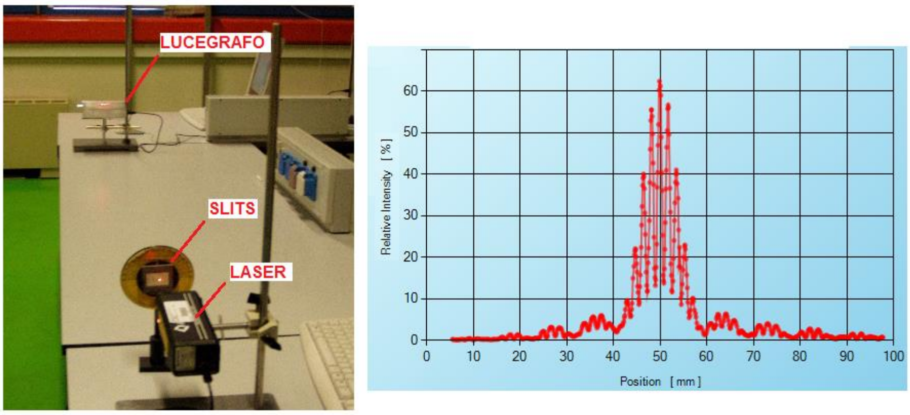

Fig. 5. Experimental setup and non-zero-width double slit diffraction pattern as obtained with the Lucegrafo system

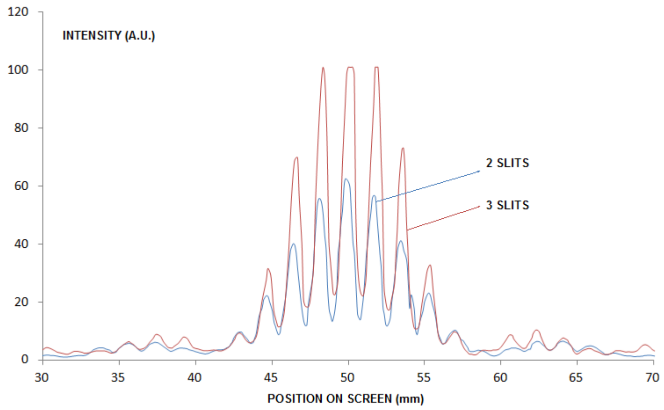

Fig. 6. Comparison between two and three slits patterns. Data obtained with the Lucegrafo system, processed with a spreadsheet (Excel)

4. Those observations, together with the fact that the intensity pattern depends on the color of the light, outlines that a large number of little-spaced slits allows to distinguish two maxima of different wavelengths of the same order.
5. The previous explorations provide the phenomenological basis to guess the characteristics of a diffraction pattern caused by a diffraction grating, characterized by a high density of narrow slits. The maxima are very sharp and highly-spaced, and the features of the interference pattern prevail on the diffraction ones (Fig. 7). If a superposition of wavelengths is used, the grating allows therefore effective maxima separation, and the possibility to carry out spectroscopic analysis.

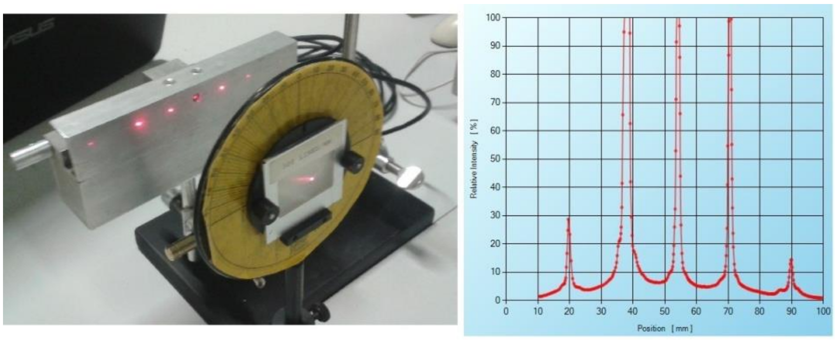

Fig. 7. Diffraction of laser light (λ = 650 nm) from a grating (300 lines/mm). Acquisition with the Lucegrafo system

Modeling and simulation

Beyond phenomenological exploration, modeling and simulation provide effective tools to support the proposal.

In modeling, a physical situation is represented by means of an abstract system described by the equation relating the variables, starting from first principles. In this perspective, a C++ script has been written (Santi *et al*. 1993): given the number of slits, their width and separation, the distance between them and the screen and the number of secondary sources along every slit, the software computes the superposition of the waves on every point of the screen using a wave hypothesis on the nature of light and the Huygens principle (Fig. 8 upper left). The same results can be obtained using a spreadsheet (Fig. 8 upper right).

On the other hand, in a simulation environment, students do not have access to the model, but they can appreciate in real time the consequences of a change in the values of the parameters (wavelength of the light, number, distance and width of slits) and they can see how a diffraction pattern changes changing the parameters. An example of such a simulation (Fig. 8 bottom) has been developed using Easy Java Simulation.

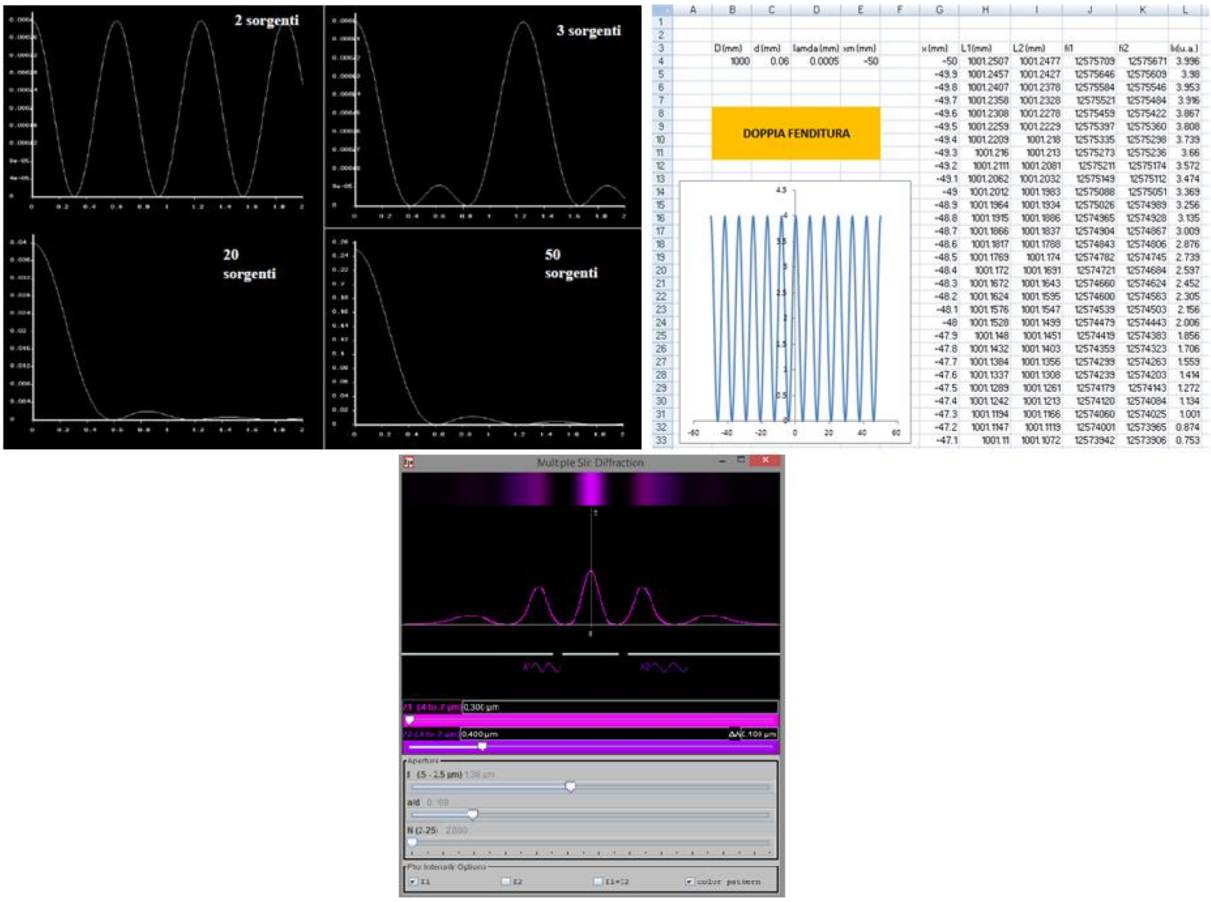

Fig. 8. Modeling: output of the C++ script (upper left) and calculus of a double-sit interference pattern by means of a spreadsheet (upper right). Simulation (bottom): user panel of the Easy Java Simulation (http://www.compadre.org/osp/items/detail.cfm?ID=8888). Parameters that can be adjusted are the number of slits, their width and their separation

3. A case study

Case study on the lab activity

The proposed path has been used as an interactive lecture demonstration with 98 upper-secondary school Italian students and 56 freshmen in biotechnology sampled from University of Udine (IT). In particular in the 2016 Summer School in Modern Physics at University of Udine it has been used as an interactive lecture demonstration after the experimental activity about single-slit diffraction proposed to 32 selected talented upper-secondary school students. Before the activity, a pre-test was submitted to all students. Concerning the present contribution we consider a question asking to say what had to be changed in an experimental setup in order to see a line spectrum rather than a continuous one. Moreover, here we discuss a case study carried out by means of detailed analysis of the final reports on experimental activity, written by 4 of them. The experimental activity has been proposed in a conceptual form, together with a paper for data collection, rather than a laboratory sheet. Therefore students wrote an argumentative synthesis outlining the conceptual framework of the experiment completing it with graphs and tables of data acquired.

Main learning outcomes

In a multiple-choice pre-test question students were asked to say what had to be changed in an experimental setup in order to see a line spectrum rather than a continuous one. Students evidenced difficulties in recognizing the role of the various elements: 14/32 students would not change the light source in order to see a line spectrum, but they would change the grating (5), the width of the slit (4) or the distance from the screen (5). In the reports students focused mainly on:

- Describing the pattern, that is: a symmetrical (4/4) angular distribution (2) of dark and bright fringes (3) in which the central maximum is the brightest (3).
- Mentioning the wave nature of light (2) and the Huygens-Fresnel's principle (4) to account for the observed pattern in terms of secondary sources (3) and wave fronts as envelopes (2). The principle is qualitatively described. A quantitative description that accounts for the observed pattern is missing.
- Reading the interference in terms of superimposition (2) and phase difference (1). Students identify these as fundamental elements but a deeper justification is missing (even a qualitative one).
- Identifying the parameters which determines the pattern, that are: number of slits (3), width of the slits (1), slits-screen distance (1), and wavelength (1). Only in the case of the width of the slit the dependence is specified.

18/32 answers to change the source, but 14/32 students suggest to change grating (5), the width of the slit (4), or the distance grating-screen (5), evidencing difficulties in recognizing the role of these parameters (as emerged in Ivanjek *et al*. 2015). Considering the final reports these difficulties don't appear, and moreover a rich pattern of aspects are mentioned or deeper discussed by students as resumed in the following table (including only main aspects).

Table 1. Mentioned aspects from students in their reports

	DESCRIBING THE LIGHT PATTERN				HUYGENS-FRESNEL			INTERFERENCE			PARAMETERS INVOLVED			
STUDENT	SYMMETRY	ANGULAR DISTRIBUTION	FRINGES	CENTRAL MAX	Just MENTION	SECONDARY SOURCES	WAVEFRONT AS ENVELOP	Just MENTION	SUPERIMPOSITION	PHASE DIFFERENCES	NUMBER OF SLITS	WIDTH OF SLIT	DISTANCE SLIT-SCREEN	WAVELENGTH
1	✔		✔	✔	✔			✔						
2	✔		✔	✔	✔	✔	✔	✔	✔		✔		✔	
3	✔	✔	✔	✔	✔	✔	✔	✔			✔	✔		✔
4	✔	✔			✔	✔		✔	✔	✔	✔			

4. Main results

From the analysis of the final reports, despite the exiguity of the sample, it has been possible to observe that following the proposed path student acquire confidence with the role of the parameters involved in the phenomenology, and activate the construction of a new interpretation of the phenomenology. Every student recognized the need to change from a ray model to a wave one, using the Huygens principle to describe the phenomenology. The description remains however on a qualitative plan, regarding both the principles (Huygens-Fresnel and superposition) and the dependencies from various parameters (number and width of the slits, wavelength…).

5. Conclusions

Starting from a previous didactical proposal about single-slit diffraction, a path concerning diffraction from multiple slits has been developed. It takes into account the learning results emerged from the experimentations concerning the single-slit diffraction educational proposal that aims to obtain phenomenological laws describing the phenomenon starting from the analysis of experimental data.

- Results from pilot studies conducted with upper-secondary school students and freshmen in biotechnology confirm the hypothesis that the path about multiple-slits diffraction helps the acquisition of a new modality in which students see phenomena related to the wave nature of light. Students' personal involvement in phenomenological analyses, as the one described here, offer them the opportunity to experience the way in which experimental research is carried out.
- Students gain ownership in focusing the relevant quantities and laws describing the phenomenon, and the role of the various elements. Such activities, moreover, activate the relationships between the phenomenon and the interpretative models.
- Our future work will be in two directions: to adjust the proposed path on the basis of the results emerged, enriching it with tests, tutorials, didactical materials and activities in modeling, and to experiment the path with students, to deepen its implications for learning, and teachers, for their professional development.

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