Educational Software for Interference and Optical Diffraction Analysis in Fresnel and Fraunhofer Regions Based on MATLAB GUIs and the FDTD Method

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Abstract

Interference and diffraction of light are elementary topics in optics. The aim of the work presented here is to develop an accurate and cheap optical system simulation software that provides a virtual laboratory for studying the effects of propagation in both time and space for the near and far field regions. In laboratory sessions this software can let optical engineering undergraduates simulate many optical systems based on thin slits. The numerical method used is the Finite-Difference Time-Domain method that has been successfully applied in many engineering fields. Using this numerical method, the irradiance distribution can be successfully evaluated in different planes far from the simulation grid without degrading performance. In addition, an easy-to-use MATLAB GUI handles all the parameters of the FDTD simulation and computes theoretical values of irradiance for both the Fresnel and Fraunhofer regions. Therefore, by using this software the student is able to analyze the

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behaviour of the Fresnel and Fraunhofer expressions as a function of the distance. This distance is defined as the space between the planes that contains the virtual screen on which the irradiance pattern is represented, and the slits plane.

Index Terms

Diffraction, Education, Finite Difference method, Optics, Virtual laboratory

I. INTRODUCTION

Hands-on experiments in laboratory sessions play an important role in improving student knowledge. In optics education, students in this type of session have to use different instruments such as lasers, analyzers, detectors, and the like. All these instruments are usually very expensive and in many cases are not correctly handled. In these experiments, focused on demonstrating the wave nature of light [1], [2], the light diffracts through slits and illuminates a screen at a large distance compared to the separation between slits. This paper describes the development of software that simulates many optical experiments, such as Young's double slit experiment or diffraction gratings. The software is based on the Finite-Difference Time-Domain Method (FDTD), which is a direct solution method of Maxwell's time-dependent curl equations. With this method, the electromagnetic fields can be calculated as a function of time and space, letting students analyze how light diffracts through the slits, or perform other experiments related to electromagnetic wave propagation. Although several commercial packages (MEEP [3] and FDTD Solutions [4], for instance) compute this numerical method and are used in academia, in most cases these software packages are designed to solve high-level engineering problems such as photonic crystals or microwave antennas. In addition, using these packages would often require several input parameters that are not directly related to the physical experiment. The flexibility and potential offered by these packages requires an initial set up to be performed by an expert, or in this case, by students; as consequence, extra time must be allowed. However, this flexibility would be more appropriate for higher courses, whose students have acquired many skills that enable

them to easily understand the entire application. For that reason, a user-friendly educational software has been developed to easily simulate several basic optical experiments. Using this software in the first years of Optics or Physics degrees can give students the opportunity of evaluating many optical systems experiments with an easy and accurate software, without using expensive instrumentation.

On the other hand, it is also useful for students to understand that the closed theoretical expressions for diffraction analysis have a limited range of applicability. These expressions are usually obtained by approximating the integral vectorial expression of the electromagnetic field to an equation which is easier to handle. This approximation is based on omitting higher orders in the Taylor series or similar.

This software is structured in an API based on MATLAB [5] that invokes an executable file. This source file is compiled in an UNIX-based operating system. The MATLAB interface provided shows plots of the result, taking the values computed by the C++ simulation software. The user-friendly interface and the accurate results make this software an attractive and useful complement for student education.

II. OBJECTIVES AND SCOPE

In the authors' institution, optics, wave diffraction and interference are an integral part of Telecommunication and Computer Science degrees. The theoretical background of this topic is supplemented with theoretical lessons in the classroom and with laboratory work. However, there is neither enough time nor sufficient equipment to teach all the practical aspects of interference and diffraction of light.

The application of the European Space for Higher Education of The Bologna declaration implies the use of new technologies involved in education transfer. Moreover, the use of new technologies in education is a transversal competence of this new way of teaching. The virtual optical laboratory application described here is focused on helping students to develop their knowledge [6]–[9] and intuition for wave interaction. In addition, this software

allows the evaluation of the application range of the closed expressions, usually taught in theoretical sessions. The tool is aimed at speeding up learning, since it allows students to modify multiple parameters on the simulation and analyze the results. It is intended to complement rather than replace laboratory work, but in many cases it can be useful to start with this tool instead of the classical laboratory set-up.

The developed tool simulates, by means of the Finite Difference Time Domain (FDTD) method, the electromagnetic fields [10], [11] that define the wave propagation of light. Specifically, the software is focused on the simulation of the interference and diffraction of light when it impinges on a screen with thin slits or apertures. A well-known experiment related to this topic is the Young's double slit experiment, usually included in the curricula of physics and engineering degrees since it demonstrates the wave behavior of light. Moreover, this experiment provides a set of interference patterns in the far field region (Fraunhofer) that can be compared analytically with well-known closed expressions. The use of the tool described here thus makes an important contribution to improving student knowledge.

III. FRESNEL AND FRAUNHOFER DIFFRACTION

Considering an aperture of small area illuminated by a plane wave, the light emitted from the aperture plane onto a parallel screen placed near the aperture presents a pattern similar to the size of the aperture, with several fringes surrounding the edges [2]. As the plane is moved farther from the aperture plane (Γ), the image of the aperture can be identified, but the intensity of the fringes becomes more relevant. This phenomenon is known as Fresnel or near field diffraction. So if the distance between the screen (Υ) and the aperture (Γ) planes becomes greater, it is more difficult to identify the radiation pattern with the shape of the aperture. Once the distance is greater than a particular value, the diffraction pattern has no apparent changes. This distance determines the Fraunhofer region, and the pattern produced is also called Fraunhofer diffraction. As can be seen in Fig. 1, the electrical field at point P

Fig. 1: One Slit diagram

due to the whole aperture is defined by the next defined integral:

$$E = \epsilon_L \int_{-b/2}^{b/2} \frac{\sin(\omega t - kr)}{r} dz, \quad (1)$$

where ϵ_L is the source efficiency by unit length, k is the wavenumber, $r = r(z)$ is the distance between the field point P and the aperture and b is the width of the aperture. Two approximations are generally used to solve Eq. (1), Fresnel and Fraunhofer approximations.

A. Fraunhofer Diffraction

The Fraunhofer approximation is based on the condition of $R \gg b$. Under this configuration $r(z)$ has a value closed to R . The term $r(z)$ is redefined with the use of the Maclaurin series, neglecting all terms greater than the third one.

$$r = R - z \sin \theta + (z^2/2R) \cos^2 \theta + \dots \simeq R - z \sin \theta, \quad (2)$$

where θ is measured from the xz plane and $z = \pm b/2$ with R greater enough. Placing Eq. (2) into (1), the following expression can be obtained:

$$\begin{aligned} E &= \epsilon_L \int_{-b/2}^{b/2} \frac{\sin(\omega t - kr)}{r} dz = \\ &= \frac{\epsilon_L}{R} \int_{-b/2}^{b/2} \sin[\omega t - k(R - z \sin \theta)] dz, \end{aligned} \quad (3)$$

TABLE I: Limit region between Fraunhofer and Fresnel approximations

Fraunhofer	Fresnel
$F \leq 0.6$	$F > 0.6$

TABLE II: Limit region between Fraunhofer and Fresnel approximations

	1 aperture	2 apertures	N apertures
$\frac{I(\theta)}{I(0)}$	$\left(\frac{\sin \beta}{\beta}\right)^2$	$4\left(\frac{\sin \beta}{\beta}\right)^2 \cos^2 \alpha$	$\left(\frac{\sin \beta}{N\beta}\right)^2 \left(\frac{\sin N\alpha}{\alpha}\right)^2$

and finally

$$E = \frac{b\epsilon_L}{R} \frac{\sin \beta}{\beta} \sin(\omega t - kR), \quad (4)$$

with $\beta = (kb/2) \sin \theta$. Moreover, taking into account that the irradiance can be defined as $I(\theta) = \langle E^2 \rangle_T$ and that the independent term in the Eq. (4) is equal to $1/2$ [2], it is easy to obtain the following well-known equation

$$I(\theta) = I(0) \left(\frac{\sin \beta}{\beta}\right)^2, \quad (5)$$

with $I(0) = \frac{1}{2} \left(\frac{\epsilon_L b}{R}\right)^2$. The range of validity of this expression is defined by the Fraunhofer's condition $F = b^2/L\lambda \ll 1$, with b being the width of the aperture and L the distance between the Γ and Υ planes. However, several authors define a more accurate limit between the Fraunhofer and Fresnel region [12] shown in Table I. Furthermore, in Table II, several expressions according to the number of apertures are shown, where $\alpha = (ka/2) \sin \theta$, and the relation with the gap between apertures is defined as a .

B. Fresnel Diffraction

The Fresnel approximation begins with a similar expression to Eq. (1), also in differential form:

$$dE_p = \frac{\epsilon_0}{\rho r \lambda} \sin[k(\rho + r) - \omega t] dS \quad (6)$$

Fig. 2: Fresnel diffraction by a rectangular aperture

As can be seen in Fig. 2, the phase term can be approximated by means of the following binomial series:

$$\left. \begin{aligned} \rho &= (\rho_0^2 + y^2 + z^2)^{1/2} \\ r &= (r_0^2 + y^2 + z^2)^{1/2} \end{aligned} \right\} \rho + r \approx \rho_0 + r_0 + \frac{(y^2 + z^2)^2}{2\rho_0 r_0}, \quad (7)$$

It is important to emphasize that the Fraunhofer approximation is simpler than that used in the Fresnel region. In the Fraunhofer region terms higher than the second order are neglected, Eq. (6) is thus given in complex notation and, taking into account Eq. (7), can be redefined as follows:

$$\begin{aligned} \hat{E}_p &= \frac{\epsilon_0 e^{-j\omega t}}{\epsilon_0 r_0 \lambda} \int_{-a/2}^{a/2} dy \int_{-b/2}^{b/2} e^{jk(\rho+r)} dz = \\ &= \frac{\epsilon_0 e^{j[k(\rho_0+r_0)-\omega t]}}{2(\rho_0 + r_0)} \\ &\quad \times \int_{u(-a/2)}^{u(a/2)} e^{j\frac{\pi u^2}{2}} du \int_{v(-b/2)}^{v(b/2)} e^{j\frac{\pi v^2}{2}} dv, \end{aligned} \quad (8)$$

where $u(y) \equiv y \left[\frac{2(\rho_0+r_0)}{\lambda \rho r_0} \right]^{1/2}$, $v(z) \equiv z \left[\frac{2(\rho_0+r_0)}{\lambda \rho r_0} \right]^{1/2}$ and the term preceding the integral represents the perturbation not blocked by Γ that can be collapsed in the term $\hat{E}_u/2$.

Both integrals are known as the Fresnel's integrals $C(\omega) = \int^\omega \cos(\pi\omega'^2/2)d\omega'$ and $S(\omega) = \int^\omega \sin(\pi\omega'^2/2)d\omega'$. For plane waves ($\rho \rightarrow \infty$), the variables u and v can be redefined as $u = y \left[\frac{2}{\lambda r_0} \right]^2$ and $v = z \left[\frac{2}{\lambda r_0} \right]^2$.

As a result, Eq. (8) can be easily rewritten as:

$$\hat{E}_p = \frac{E_u}{2} [C(u) - jS(u)]_{u_1}^{u_2} [C(v) - jS(v)]_{v_1}^{v_2} = \hat{\mathbf{B}}_{12}(u)\hat{\mathbf{B}}_{12}(v), \quad (9)$$

where, for the particular case of apertures infinitely greater along the y axis, the irradiance produced by an aperture at point P can be deduced as:

$$I_p = \frac{I_0}{2} |\hat{\mathbf{B}}_{12}(v)|^2. \quad (10)$$

From Eq. (10) and the superposition theorem, it is straightforward to calculate the irradiance pattern produced by several apertures.

Therefore, from the expressions collected in the Table I (Fraunhofer approximation) and Eq. (10), we can calculate the theoretical curves of irradiance in any point in Υ far away from Γ .

C. Basis of the FDTD Method

Taking into account the relationship between v in the Eq. (10) and the space coordinates, it can easily be seen the two-dimensional simulation of the FDTD is adequate to ensure good accuracy. Therefore, the principles of the FDTD method in two dimensions is based on the discretization of space and time in the following way:

$$u(i\Delta x, j\Delta y, n\Delta t) = u|_{i,j}^n, \quad (11)$$

where u is a function that depends on space and time, that in particular corresponds with each component of the electromagnetic field. The following terms Δx , Δy and Δt are the spatial (in x and y) and time resolution respectively. The integer indexes i , j and n are used

to define u at a particular point in the space and time.

Taking into account that light is an electromagnetic wave whose behavior is defined by the well-known Maxwell's Law:

$$\frac{\partial \widetilde{\mathbf{D}}}{\partial t} = \frac{1}{\sqrt{\epsilon_0 \mu_0}} (\nabla \times \mathbf{H} - \sigma \widetilde{\mathbf{E}}), \quad (12)$$

$$\widetilde{\mathbf{D}}(\omega) = \epsilon_r^*(\omega) \cdot \widetilde{\mathbf{E}}, \quad (13)$$

$$\frac{\partial \mathbf{H}}{\partial t} = -\frac{1}{\sqrt{\epsilon_0 \mu_0}} \nabla \times \widetilde{\mathbf{E}} - \frac{\sigma_m}{\mu_0} \mathbf{H}, \quad (14)$$

where ϵ_0 is the electrical permittivity in farads per meter, ϵ_r^* is the medium's relative complex permittivity constant, μ_0 is the magnetic permeability in henrys per meter, σ_m is an equivalent magnetic resistivity in ohms per meter and σ is the electric conductivity in siemens per meter. The flux density is denoted by $\mathbf{D}$ and both $\mathbf{D}$ and $\mathbf{E}$ are normalized with respect to the vacuum impedance η_0 , using

$$\widetilde{\mathbf{E}} = \sqrt{\frac{\epsilon_0}{\mu_0}} \mathbf{E}, \quad (15)$$

$$\widetilde{\mathbf{D}} = \sqrt{\frac{1}{\epsilon_0 \mu_0}} \mathbf{D}. \quad (16)$$

Here only the z -component of $\mathbf{D}$ and the x -component $\mathbf{H}$ field are used as examples. From Eqs. (12) and (14), and assuming a nonmagnetic and lossless medium, the following expressions are obtained:

$$\frac{\partial \widetilde{D}_z}{\partial t} = \frac{1}{\sqrt{\epsilon_0 \mu_0}} \left(\frac{\partial H_y}{\partial x} - \frac{\partial H_x}{\partial y} \right), \quad (17)$$

$$\frac{\partial H_x}{\partial t} = \frac{1}{\sqrt{\epsilon_0 \mu_0}} \left(\frac{\partial \widetilde{E}_z}{\partial y} \right), \quad (18)$$

$$(19)$$

The first step is to approximate Eqs. (17) and (18) by finite differences:

$$\widetilde{D}_z|_{i,j}^{n+1/2} = \widetilde{D}_z|_{i,j}^{n-1/2} +$$

Fig. 3: Yee cell for 2-D

$$\frac{\Delta t}{\sqrt{\epsilon_0 \mu_0}} \left[\frac{H_y|_{i+1/2,j}^n - H_y|_{i-1/2,j}^n}{\Delta x} - \frac{H_x|_{i,j+1/2}^n - H_x|_{i,j-1/2}^n}{\Delta y} \right], \quad (20)$$

$$\widetilde{E}_z|_{i,j}^{n+1/2} = C_z|_{i,j} \widetilde{D}_z|_{i,j}^{n+1/2}, \quad (21)$$

$$H_x|_{i,j+1/2}^{n+1} = H_x|_{i,j+1/2}^n - \frac{\Delta t}{\sqrt{\epsilon_0 \mu_0}} \left[\frac{\widetilde{E}_z|_{i,j+1}^{n+1/2} - \widetilde{E}_z|_{i,j}^{n+1/2}}{\Delta y} \right], \quad (22)$$

where C_z is a matrix related with the physical parameters of the medium (13) and the spatial and time resolution of the method [11].

Note that the $\mathbf{E}$ and $\mathbf{H}$ fields are assumed to be interleaved around a cell whose origin is at the location (i, j) (as can be seen in Fig. 3). A quadrilateral cell is assumed ($\Delta x = \Delta y$). Every $\mathbf{E}$ field is located half a cell width from the origin in the direction of its orientation; every $\mathbf{H}$ field is offset by half a cell in each direction except that of its orientation.

Due to the dependence between the electric and magnetic fields, the previous values of the electric field are used to calculate the magnetic field and so on. This algorithm is illustrated in Fig. 4 where the detailed Leap Frog algorithm [10], [13] is summarized.

Fig. 4: Scheme of the Leap Frog Algorithm

In Fig. 3 the spatial discretization for two dimensions, known as the Yee cell, is illustrated. It must be said that several add-ons were added to correctly simulate optical applications. To simulate quite large media the so-called Perfectly Matched Layers (PML) developed by Berenger [14]–[17] were implemented. These layers, situated at the borders of the simulation area, permit the absorption of waves that travel straight to these edges. Not using the PML results in undesired reflections of all the waves that reach the border of the simulation. With this formalism an infinity medium, such as vacuum, can be simulated. But it is also necessary to have the capability to simulate plane waves, for which purpose Total-Field Scattered-Field (TF-SF) formulation was implemented in the algorithm [10], [11], [18]. This add-on permits the simulation of plane waves, defining two separate regions in the simulation: the Total Field and Scattered Field regions. The first region is calculated taking into account the plane wave excitation source, whereas in the second region only the scattered field due to the interaction between the plane wave and the medium under study is considered. All this is possible because of the linearity of the Maxwell equations. Also, a formalism to propagate the near field distribution to points located outside the simulation region is quite useful, since the cells' size and number can be reduced, dramatically improving the performance of the simulation. This formalism is known as the Near-Field to Far-Field transformation [11], [18]–

[21].

IV. TOOL DESCRIPTION

The implemented tool is composed of three parts: a Matlab-GUI application, an executable file that implements the FDTD method, and a set of M-files that evaluate the analytical expressions detailed above in Table II and Eq. (10) respectively. The FDTD method implemented is completely transparent for end-users, and is executed when the simulation is started by the user. This application was implemented in C++; a reader interested in the implementation and associated issues can find more information in [10], [11], [18]. The layout of the application is shown in Fig. 5. Its interface displays all the parameters that users can modify, such as the number of slits, the width and their gap. The position of the screen on which the diffraction pattern is analyzed can also be defined by the user.

The design of the Matlab-GUI is easy to perform using the MATLAB GUIDE. This toolkit permits dragging of the bottoms the axes bottoms, and so on. Each button and text field have a region code that is executed. This function is called callback. With the use of the command “>> system”, binary files can be executed, and this function permits the use of input parameters that in here was useful to set the simulation parameters: the number of slits, width, etc. This and more is explained in the MATLAB-GUI manuals and related papers [5], [22].

A. Classroom Experience

The tool was created during the 2008-2009 and 2009-2010 academic years at the University of Alicante in Spain, and has been used in physics and optics courses in various degrees such as Technical Telecommunication Engineering, Computer Science or Optics and Optometrics. The first advantage of the tool presented here is that it allows the instructor to set up simulations with minimal effort, which obviously helps in showing many different cases, and is also useful for showing the near field pattern, which is usually difficult to analyze in a laboratory experiment. Until now, the application was used in theoretical lectures as a

Fig. 5: Front-end of the application DifSim.

support to the lecturer teaching wave diffraction and interference subjects. With the advent of the new degrees, it is planned that this tool should also play an important role in the laboratory sessions, since handling lasers and detectors in the first years of their degrees is quite difficult for new students. For that reason, a new structure has been planned for the laboratory sessions. Since this tool can be used in students' own time, as a virtual laboratory in which they can measure diffraction patterns as they would in a real laboratory, they can save time and the university could save money, since no duplication of expensive equipment is necessary.

The tool is planned to be used to analyze the diffraction pattern of an array of slits in different planes parallel to slits placed at arbitrary distance. The student, by means of this tool, can compare and contrast the diffraction pattern produced by the FDTD simulation with the analytical values provided by the Fraunhofer and Fresnel approximations. In addition, students can draw several conclusions from the analysis of the accuracy of the analytical expressions as a function of the screen distance. The nearer the diffraction pattern plane, the greater error in the Fraunhofer approximation. On the other hand, the Fresnel approximation behaves more accurately over a wider range, due to the approximation applied being less restrictive than that used in the Fraunhofer region. It is important that students can discuss the classical closed expressions learned in theoretical lectures, since these expressions are not correctly handled in many cases. This is because the students do not notice that Eq. (9) and Eq. (4) are obtained from approximations of the integral field expressions (1).

The student can also analyze the numerical method that is used to calculate the Fresnel's integrals Eq. (9). This method produces oscillations on the result when $|u|$ or $|v|$ are greater than 20 or 25 due to the Fresnel's integrals being quite near their limit values of $1/2$ [2].

B. Result and Discussion

In this section, two examples based on one- and two-slit simulations are shown. The simulation parameters are defined as follows: $\lambda = 633$ nm, spatial resolution $\lambda/10$ and Δt as $1.06 \cdot 10^{-16}$ s. Firstly, the diffraction pattern for both cases as a function of the distance between the Γ and Υ planes are shown in Fig. 6. The (a), (c) and (e) curves of this illustration represent the results for the simulation of one unique slit. The (b), (d) and (f) curves are the results for the Young's experiment based on two slits. As can be seen, the Fraunhofer approximation for the nearest position of the plane Υ (L smaller), is more inaccurate than the Fresnel. As the distance between planes becomes greater, both approximations are closer to the numerical FDTD simulation.

In addition, the simulation represents an animation of the irradiance ($\propto |E|^2$) as a function of time. This visualization is quite useful to students because it permits visualizing

Fig. 6: Comparison between analytical and numerical irradiances for different distances between slits and measurement planes. (a), (c) and (e) shows the results for one slit case. The (b), (d) and (f) illustrations show the results for two slits.

Fig. 7: Simulation sequence. (a) $t = 50\Delta t$, (c) $t = 150\Delta t$, (e) $t = 250\Delta t$, (g) $t = 350\Delta t$ for one aperture ($b=40$ cells) and (b) $t = 50\Delta t$, (d) $t = 150\Delta t$, (f) $t = 250\Delta t$, (h) $t = 350\Delta t$ for two apertures ($b = 40$ cells and $a = 80$ cells).

the transition between the Fresnel and Fraunhofer patterns. In Fig. 7 a sequence of the simulations mentioned above (one- and two-slit simulations) is shown. Concretely, the left

column of illustrations (a), (c), (e) and (g) in Fig. 7 are for the simulation of one unique slit as a function of the time step, and the right column (b), (d), (f) and (h) are the sequence for the two slit simulation. As can be seen in both simulations, the diffraction pattern up to the position of the $x = 50$ cell is dramatically different from the distribution of $|E|^2$ at $x = 100$ cells approximately, whose diffraction pattern is more similar to the far field pattern.

V. CONCLUSION

In this paper, the development of a MATLAB/C++ application for diffraction and interference simulation and its use in the classroom have been described. The tool gives students the possibility of analyzing many different configurations, which would be expensive and take too much time in a real laboratory. The virtual laboratory presented here is based on three different parts that take advantage of various commercial software. Firstly the GUI is implemented in MATLAB, commonly used by students since their first years of studies. Secondly, the FDTD simulation was programmed in C++ due to the improvement in the performance compared with MATLAB processing. And thirdly, the analytical solutions for Fraunhofer and Fresnel approximations are supplied to students as M-Files, easy to understand, that they can analyze and modify. The interaction with the tool is straightforward and is done essentially with text labels and buttons. Finally, extensive use of this tool can give students an enhanced intuition and help them to gain better understanding of the analytical expressions learned in the classroom and their range of validity across the Fraunhofer and Fresnel diffraction regions. Additionally, this tool has been used in theory classes with successful results. The tool helped students to understand, by means of video animations, the basic principles of wave interaction in near field region.

It can be concluded that the objectives outlined when this virtual laboratory was created have been achieved. More applications based on laboratory experiments in optics can be included in the near future, due to the power and the accuracy of the numerical FDTD method implemented.

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