

## SIMULATION OF FRESNEL LENSES AND BINARY PHASE GRATINGS WITH BEAM PROPAGATION METHOD

Mihai KUSKO<sup>1</sup>, Dana CRISTEA<sup>2</sup>, Paul ȘCHIOPU<sup>3</sup>

*În această lucrare sunt prezentate rezultatele simulărilor obținute cu BPM (Beam Propagation Method) asupra a două tipuri de elemente optice difractive: lentile Fresnel și rețele binare cu contrast de fază. A fost realizată o comparație între rezultatele teoretice și cele obținute prin simulare în vederea identificării parametrilor optimi de simulare.*

*In this paper are presented the simulation results obtained with BPM Beam Propagation Method regarding two types of diffractive optical elements: Fresnel lenses and binary phase gratings. A comparison has been done between theoretical results and the results obtained by simulation in order to obtain the optimal simulation parameters.*

**Keywords:** BPM, simulation, Fresnel lenses, Binary grating

### 1. Introduction

Beam propagation method BPM has been developed decades ago [1] and its primary use is simulation of radiation propagation in integrated optical circuits and optical fibers. Since this method has been proposed for the first time, the method has been evolved from the Fourier transform approach to the finite element and finite differences based methods [2]. At this moment, the most widespread solution for implementation of BPM is based on the finite difference method. Unlike Finite Differences Time Domain - FDTD method which solves exactly the Maxwell equations in space and time with the accuracy limited only by the mesh size, the BPM is based on the approximation of the Kirchhoff equation which describes propagation of the radiation in space. BPM has the advantage over FDTD because it requests more reduced computational resources (BPM needs much less RAM than FDTD and it is much faster). Many BPM solvers or engines rely on the paraxial approximation. However, in many cases, it is required the use of BPM solvers that work beyond the paraxial approximation. These BPM solvers are based on methods known in literature as “wide-angle BPM” [3]. The

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<sup>1</sup>Physicist, National Institute for R&D in Microtechnologies, Bucharest, Romania, mihai.kusko@imt.ro

<sup>2</sup>PhD, National Institute for R&D in Microtechnologies, Bucharest, Romania

<sup>3</sup>Prof., Faculty of Electronics, Telecommunications and Information Technologies, University POLITEHNICA of Bucharest, Romania

above mentioned methods use the so called “Pade approximants” of order 1, 2, 3, etc, the simulation accuracy increasing with the order number.

The small dimensions of the microoptical components allow the use of BPM giving the possibility to perform wide-angle simulations which can offer accurate results. Another reason to use BPM in simulation of the microoptical components is the high costs of the photonic simulation softwares which limits in many cases the possibility to have available all needed softwares based on various simulation methods. In the past, some research groups have employed BPM simulations in order to study microoptical components even if BPM simulation of the microoptical components can be more time - consuming than the treatment with the other methods [4], [5]. It is important to notice that in many cases BPM cannot offer accurate results any longer and it is required the use of FDTD method. Those situations are met when the microoptical components sizes are very small. In this paper, we will limit only at BPM simulations.

Recently, results of designing Fresnel lenses using BPM and fabrication of reflective Fresnel lenses obtained by RIE etching of silicon dioxide substrate have been reported [6]. The approach for designing Fresnel lenses with OptiBPM software provided by Optiwave is presented there. Here, in this paper we will presents the results of BPM simulations of Fresnel lenses with various simulations parameters (mesh size and order number of the Pade approximants) and lens parameters (number of levels and focal length). A finer mesh grid and the use of higher Pade order improve the simulation accuracy, but in the same time slow down the simulation. That is why we need to find a simulation scheme that offers a satisfactory accuracy and also a reasonable time of simulation.

Another component studied here is the binary diffraction grating based on the phase contrast. They can be used as beam splitters or demultiplexers. Here, we will confront the theoretical results with the results obtained using BPM simulations.

## **2. Simulation of Fresnel lenses**

The Fresnel lenses have been simulated using BPM solvers based on finite differences and finite element method available in OptiBPM software package [7].

In this section we presents the results of simulation for Fresnel lenses with 2 and 4 levels with diameter value of 1000 microns and focal length values of 1500 and 3000 microns, respectively. We considered various mesh size and various propagation schemes. In all simulation we have used PML (Perfect Matched Layers) boundary condition which allows all radiation incidents on to computational domain boundary to pass through without returning in the computational domain. Simulation using PML is much faster than the

corresponding simulation using Transparent Boundary Condition TBC. The input field is considered uniform on the transversal direction. We have considered only 2D simulations because of the large computational resources required for the 3D simulation.

Design of the Fresnel lenses started with an approximate expression for the lens surface. This approximate expression is simpler than the exact expression for the lens surface and it can be more easily implemented [6]. The difference between the exact form and the approximate form becomes more pronounced if the focal length decreases and the lens diameter remain constant. The simulation results obtained with finite difference and finite element methods for the case of 1500 microns focal length if it is used a very small transversal mesh and the highest available Pade order demonstrate there is a very close match with the theoretical results. This means that the option to use the approximate form for describing lens surface was correct.

We have studied intensively the case of the lens with 3000 microns focal length. Deviation of the focal length obtained from simulation from the expected value for various mesh sizes and Pade order numbers are represented in Fig. 1.

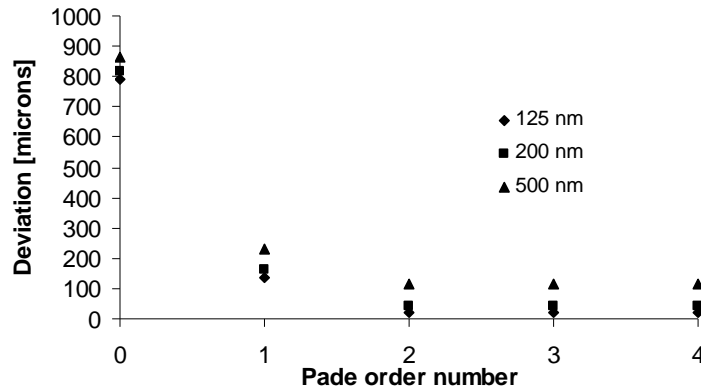


Fig. 1. Focal length deviation from theoretical value function of Pade orders numbers and dimension of the transversal mesh size

We have found that the optimum transversal mesh size is 200 nm which provides a high degree of accuracy at reasonable simulation speed. We understand the accuracy as the convergence between the expected values and the results obtained by simulation. We have simulated the radiation propagation through Fresnel lens using various Pade orders. As expected, the accuracy increased at higher Pade orders on the expense of simulation speed. We have found that the most suitable Pade order number is 2 for our simulations. The propagation step is 100 nm and divides the minimum feature on the z axis with an integer number. This fact is very important in simulation for obtaining accurate results. In Fig. 2a and b is represented the field distribution for a Fresnel lens with 2 and 4 levels

respectively. Both simulations have been obtained with a wide-angle BPM solver based a Pade order equal to 2. The wavelength is 800 nm. One can notice that the simulation obtained with a four level Fresnel lens is more accurate. The efficiency is 41% for the two-level Fresnel lens and 75% for the four-level Fresnel lens, respectively.

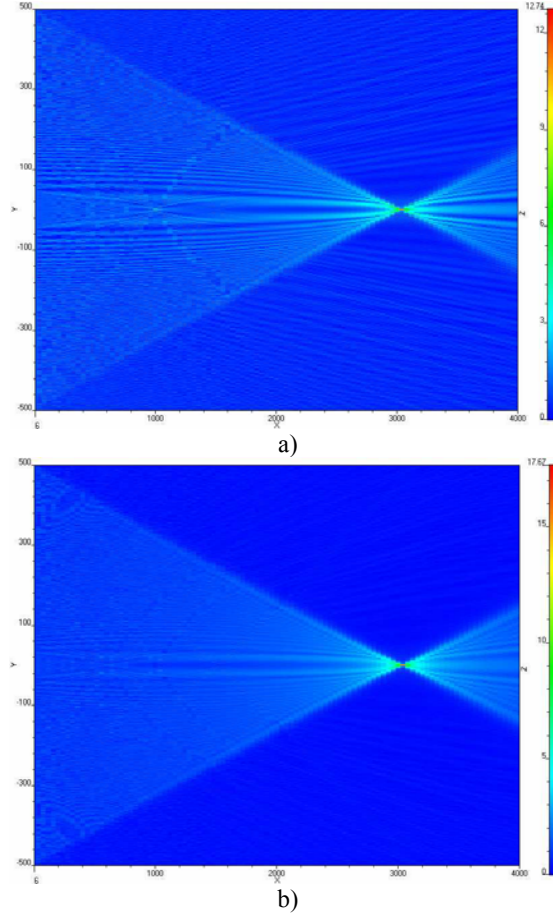


Fig. 2. Radiation propagation through a Fresnel lens with  
a) two levels; b) four levels

We have considered the case when the radiation wavelength is 850 nm and 750 nm respectively. The Fresnel lens is designed to focus the radiation after 3000 microns if the wavelength is 800 nm. We notice that the focal length becomes shorter if the radiation wavelength is longer, and the focal length becomes longer if the wavelength is shorter. The simulations results for the two wavelengths are represented in Fig. 3. We have considered the previous simulations parameters for a four-levels Fresnel lens.

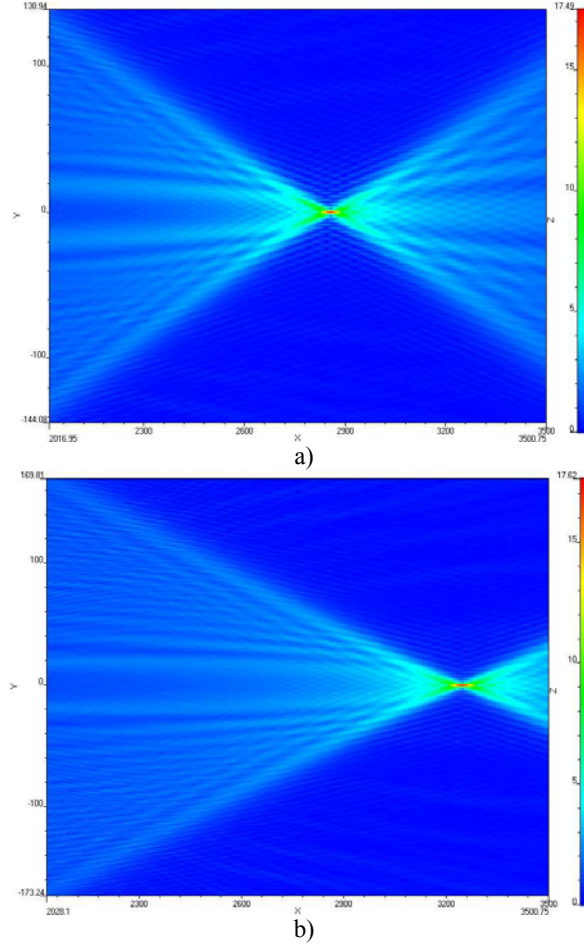


Fig. 3. Radiation propagation through a Fresnel lens (detailed view) if the radiation wavelength is a) 850 nm; b) 750 nm

### 3. Simulations of binary phase gratings

Binary phase gratings studied here have a 1D constant rectangular profile as one can see in Fig. 4. We consider the line width “w” to be half of the period “Λ”. The groove depth “d” may have various values in order to obtain the desired phase difference between “hills” and “valleys”. The radiation wavelength is 800 nm. The binary phase gratings work in transmission, so the relation between the groove depth  $d$  and the phase difference  $\Delta\varphi$  is

$$\frac{2\pi}{\lambda}(n-1)d = \Delta\varphi \quad (1)$$

where  $n$  is the refractive index of the binary grating, and  $\lambda$  is the radiation wavelength.

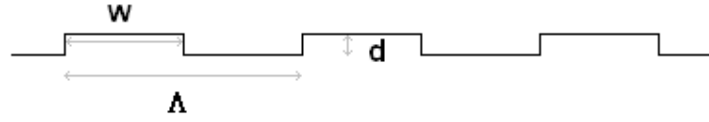


Fig. 4. The binary phase grating

The incident radiation is divided by the grating in a multitude of beams corresponding to the diffraction orders 0, -1, +1, etc. The angles  $\theta_m$  of the diffraction orders  $m$  depends on the radiation wavelength as is expressed in the next equation:

$$\Lambda \sin \theta_m = m\lambda \quad (2)$$

The theoretical radiation intensity corresponding to each order is written in [8]. There are two particular cases, when the phase difference is  $\pi$  (as in the case of two - levels Fresnel lenses) and the phase difference is  $0.64\pi$ , respectively.

In the first case, the binary phase grating diffracts the radiation mainly in -1 and +1 orders (40.5 % from incident power for each order). There is no radiation diffracted in the zeroth order. In Fig. 5 is presented the simulation results for a binary phase grating with phase difference equal to  $\pi$ . We have considered a binary phase grating with ten microns period. The Pade order is 2. The transversal mesh size is 200 nm. The propagation step is 100 nm. Since the refractive index of the grating is 1.5, the groove depth is 800 nm.

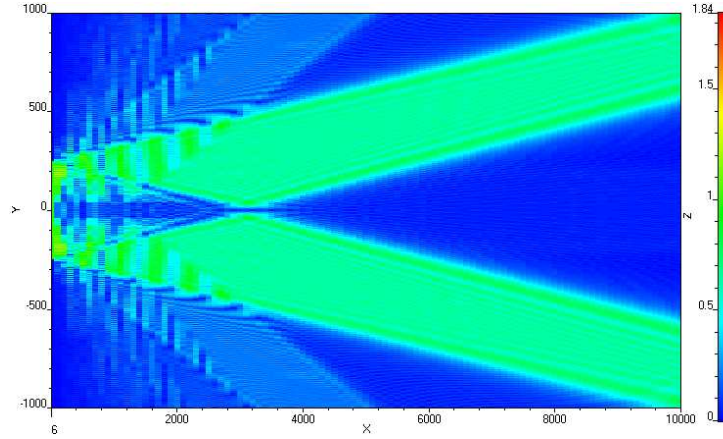


Fig. 5. Radiation propagation through a binary phase grating if the phase difference is  $\pi$

One can notice that the central maxima corresponding to the zeroth order is eliminated and the radiation power is concentrated mainly in the +1 and -1

orders. The intensity measurements show very close results to the theoretical results.

The other case of interest is when the phase difference is  $0.64\pi$ . The binary phase grating diffracts the radiation mainly on 0, -1 and +1 orders (29 % from incident power for each order). The simulation results are represented in Fig. 6. The groove depth is 500 nm in order to contain an integer number of propagation steps. This groove depth value is very close to the theoretical value of 512 nm. The results of simulation shown in Fig. 6 confirm the theoretical results.

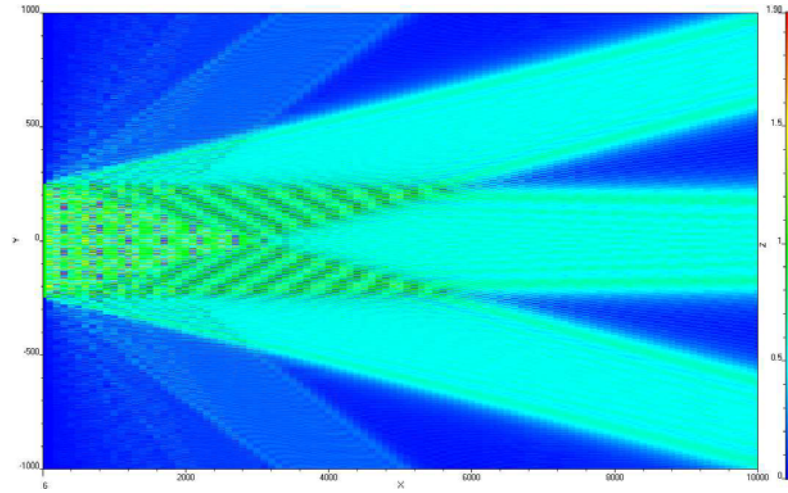


Fig. 6. Radiation propagation through a binary phase grating if the phase difference is  $0.64\pi$

#### 4. Conclusions

In this paper we have shown some results regarding simulation of two important microoptical components, i.e. Fresnel lenses and binary phase gratings with BPM. We have found the optimal simulation parameters (mesh size, Padé order number) for the simulation of Fresnel lenses. We have noticed the dependence on wavelength of radiation propagation through a Fresnel lens. We have also studied binary phase gratings and we have confronted the simulation results with theoretical results. The convergence of the simulation results with theoretical results for both Fresnel lenses and binary phase gratings allow the simulation with BPM of complex devices which include these components. These devices may have applications in various domains, especially in optical communications as wavelength demultiplexers or beam splitters.

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