Research of mode pulses propagation in a waveguide with a one-dimensional diffraction grating

S V Krasnov and S I Kharitonov

1Samara National Research University, Moskovskoe Shosse 34, Samara, Russia, 443086
2Image Processing Systems Institute - Branch of the Federal Scientific Research Centre “Crystallography and Photonics” of Russian Academy of Sciences, Molodogvardeyskaya str. 151, Samara, Russia, 443001

e-mail: ctac-red@mail.ru, prognoz2007@gmail.com

Abstract. In this paper, we simulate the propagation of mode pulses in a waveguide with a one-dimensional grating. The diffraction of continuous radiation and a short pulse on a grating with subwavelength period in a waveguide with reflecting walls is investigated using the FDTD method. The possibility of differentiating the reflected short Gaussian pulse is reported.

1. Introduction

Recently, the problem of realizing the basic operations of converting optical signals using the optical element base is actual. Despite the large possibilities of digital technology, completely optical signal processing provides high speed and efficiency [1, 2]. The paper [1] examines the role of optical and electronic technologies in future high-capacity routers. In particular, optical and electronic technologies for use in the key router functions of buffering and switching are compared. Various operations, including addition, differentiation, integration, amplification, deceleration, filtering, switching, detection, etc. [3-9] we can perform using photonic crystals [10-23], gratings [24-30], layered films [31-34] and waveguides [35-45]. Paper [5] reports on the first realization of optical microring resonators in submicrometre thin films of lithium niobate. In paper [8], a spectroscopic sensor formed by a silicon-on-insulator waveguiding Bragg grating ring resonator working in linear and non-linear regime is proposed. Paper [13] presents a theoretical and numerical study of this radiation problem for several three-dimensional mirror geometries which are important for light confinement in micropillars, air-bridge microcavities and two-dimensional PC microcavities. A highly sensitive refractive index sensor based on an integrated hybrid plasmonic waveguide and a Metal–Insulator–Metal micro-ring resonator is presented in paper [23]. Propagation of an optical pulse through a diffraction grating that has a resonance near the pulse central wavelength is discussed in paper [27]. The articles [33-34] are devoted to hyperspectrometer modeling based on the use of filters with linearly varying parameters. The paper [36] proposes a method to excite and detect the mechanical modes of dielectric microspheres. In work [43] proposes a silicon strip waveguide at 3.39 μm for CH4 gas sensing based on the evanescent field absorption.
In this work, we simulate the passage of the cosine signal in the form of continuous radiation and a short pulse in a waveguide with a one-dimensional subwavelength grating using the FDTD method. The possibility of differentiating a short Gaussian pulse is investigated.

2. Simulation
Simulation of the passage of the cosine signal in a waveguide with reflecting walls c and diffraction on a grating with a period on the order of the wavelength is performed using the FDTD method in the MEEP software. The free software MEEP uses a system of units in which the speed of light, the electric and magnetic constant are taken as one. This means that for a unit of time, light travels in vacuum a unit of distance. The choice of units is determined by how we interpret one of the parameters. For example, if we assign a linear dimension of 1 $\mu$m to a unit of distance, then the unit of time in standard values is approximately $3.3 \times 10^{-15} \text{s} = 3.3 \text{ fs}$.

2.1. Propagation of the cosine signal in a waveguide
Consider a waveguide with a large refractive index at the walls, which in this case will act as reflectors. We will use a wavelength equal to 0.8 $\mu$m. The resonator width is $h = 10$ wavelengths, i.e. $h = 8 \mu$m. Pulse length: 3.3 fs.

The signal has a cosine form: $\cos(2\pi nx/h)$.

Figures 1-3 show the results of modeling the propagation of the cosine signal in a waveguide for various parameters $n$ at different instants of time.

As can be seen from the results shown in Figures 1-3, the short pulse propagates in the waveguide not only broadens but also is transformed. Moreover, the modes of higher order undergo much larger changes than the modes of smaller order (see for comparison Figures 1 and 2). Note that not a mode pulse ($n = 1.4$ - not an integer, Fig.3) for small $n$ is also quite stable.

![Figure 1](image_url)

**Figure 1.** Pulse propagation in the waveguide at $n = 1$: a) $t = 50 \text{ fs}$, b) $t = 200 \text{ fs}$, c) longitudinal section: $t = 50 \text{ fs}$ (red color), $t = 200 \text{ fs}$ (blue). The resonator width is 8 $\mu$m.
2.2. *Signal propagation through various gratings in a waveguide*

Let us consider the pass cosine signal $\cos(2\pi nx/h)$, $n=1$ of different duration in the waveguide through diffraction gratings with different period.

![Figure 2. Propagation of a pulse in a waveguide with $n = 3$: a) $t = 50$ fs b) $t = 200$ fs.](image)

![Figure 3. Propagation of a pulse in a waveguide with $n = 1.4$: a) $t = 50$ fs b) $t = 200$ fs.](image)

Figures 4-6 show the results of modeling the signal through the gratings with a period of $T=2\lambda$, $\lambda$, $\lambda/2$.

As can be seen from the obtained results, at $T=2\lambda$ (Figure 4) the signal is divided equally into the reflected and the past. At smaller (subwavelength) periods (Figures 5, 6) more complex transformations occur. The continuous signal is mainly reflected, and the energy of the short pulse passes through the subwavelength grating to a greater extent, since the short pulse also contains high-frequency components.

Figure 7 shows the longitudinal cross section of the pulse amplitude of diffraction gratings passing through 3 with different periods at time $t = 200$ fs. It can be concluded from Fig. 7 that a grating with a period of half a wavelength dissipates the incident radiation.
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Figure 4. Propagation of a pulse through the grating at $T = 2\lambda$: a) $t=50\ fs$ b) $t=200\ fs$.

Figure 5. Propagation of a pulse through a grating with $T = 2\lambda$: a) $t=50\ fs$ b) $t=200\ fs$. c) continuous radiation.

2.3. Differentiation of the optical signal

In [25-30], the construction of a diffraction grating for performing the operation of differentiating an optical signal, both in transmission and in reflection, is considered.

We carry out a simulation of the propagation of single-pulse pulses in a wave-like one-dimensional grating using the grating parameters obtained in [25-30].

Figure 8 (a) shows the geometry of differentiating grating with parameters: $d=1010\ nm$, $h_1=620\ nm$, $r=530\ nm$, $h_2=0$, $\varepsilon_{gr}=5.5$, $\varepsilon_{sub}=2.1$, and Figure 8 (b) the form of the differentiating grating obtained in MEEP is shown.
Figure 6. Propagation of a pulse through a grating with $T = \frac{\lambda}{2}$: a) $t=50$ fs b) $t=200$ fs c) continuous radiation.

Figure 7. Propagation of a pulse through a grating: red - $T = 2\lambda$; the black - $T = \lambda$; blue - $T = \frac{\lambda}{2}$.

Figure 8. The geometry of the differentiating grating.
Figure 9. Pulse propagation in the waveguide: a) $t = 50$ fs b) $t = 150$ fs c) $t = 165$ fs.

Figure 9 (a-c) shows the propagation of a pulse in a waveguide of width $h = 8$ μm with a given grating at the center at different instants of time. In Fig. 9 (a) and 9 (b), the diffraction grating is in the center of the waveguide. In Figure 9 (c), the grating is located on the left side of the waveguide.

Figure 10 shows the longitudinal cross section of the pulse amplitude at different instants of time. Figure 10 (a) corresponds to Figure 9 (b) at $t = 150$ fs. Figure 10 (b) corresponds to Figure 9 (c) at $t = 165$ fs.

As follows from the resulted results of modeling, clear differentiation occurs only in the reflected signal. The last part of the signal is distorted and mixed with high-frequency components.
3. Conclusion
In this paper, we simulate the propagation of mode pulses in a waveguide with a one-dimensional grating using the FDTD method implemented in freely distributed MEEP software. It is shown that high-order modes undergo large changes than those of a smaller order. It is shown that the nature of the passage of a pulse through the grating becomes more complicated with a decrease in the lattice period. The investigation of the application of the differentiating grating in the waveguide has shown that explicit differentiation occurs only in the reflected signal, while the transmitted part of the signal is distorted and mixed with high-frequency components.

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