Ultrashort pulse propagation in near-field periodic diffractive structures by use of rigorous coupled-wave analysis

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We present a method for near-field analysis of ultrashort optical pulse propagation in periodic structures—including subwavelength and resonant grating structures—based on the integration of Fourier spectrum decomposition and rigorous coupled-wave analysis (RCWA). We discuss the spectral decomposition, including considerations for computational efficiency, the application of the RCWA method to compute the internal and external fields of the structure, and the synthesis of the resulting fields to obtain the time-domain solution. We apply this tool to the analysis of two photonic structures: (1) a nanostructured polarization-selective mirror that exhibits the desired broadband performance characteristics when operated at the design wavelength but yields strongly diminished polarization selectivity and modulation of the pulse envelope at an offset wavelength and (2) a two-mode coupled waveguide structure that produces from one incident pulse two transmitted pulses whose temporal separation depends on the waveguide geometry. In both examples, we apply our new modeling tool to investigate the near fields and find that near-field effects are critical in determining the performance characteristics of nanostructured devices. Furthermore, detailed observation and understanding of near-field phenomena in nanostructures may be applied to the design of novel photonic devices. © 2001 Optical Society of America


1. INTRODUCTION

The long-standing desire to increase the bandwidth of optical communications and information processing systems has led to the rapid adoption of ultrashort pulse laser systems. However, to integrate ultrashort pulse lasers with various evolving photonic technologies, it is necessary to analyze the interaction of ultrashort optical pulses with these photonic devices—in particular, to investigate the preservation and the control of the unique properties of femtosecond laser pulses, such as high peak power, short duration time, and cross-spectral phase correlation. For example, recent advances in microfabrication techniques have enabled the rapid development of subwavelength diffractive photonic devices,

Although the finite-difference time-domain method is a powerful tool to investigate the near fields and find that near-field effects are critical in determining the performance characteristics of nanostructured devices. Furthermore, detailed observation and understanding of near-field phenomena in nanostructures may be applied to the design of novel photonic devices. © 2001 Optical Society of America


1. INTRODUCTION

The long-standing desire to increase the bandwidth of optical communications and information processing systems has led to the rapid adoption of ultrashort pulse laser systems. However, to integrate ultrashort pulse lasers with various evolving photonic technologies, it is necessary to analyze the interaction of ultrashort optical pulses with these photonic devices—in particular, to investigate the preservation and the control of the unique properties of femtosecond laser pulses, such as high peak power, short duration time, and cross-spectral phase correlation. For example, recent advances in microfabrication techniques have enabled the rapid development of subwavelength diffractive photonic devices; however, the interaction of ultrashort optical pulses with subwavelength diffractive structures has only recently begun to be investigated. In this paper, we present an approach for the analysis of ultrashort pulse propagation in subwavelength and near-field periodic diffractive optical structures based on the rigorous coupled-wave analysis (RCWA) method.

Previously, two approaches have been used to analyze the propagation of optical pulses through diffractive structures. The first is a direct numerical solution based on the finite-difference time-domain method, where the modeling domain is divided into a discrete grid in space and time and the fields are iteratively computed by using a finite-difference formulation of Maxwell’s equations. Although the finite-difference time-domain method is a potentially powerful tool for the analysis of ultrashort optical pulse propagation in a wide range of optical structures, at present the practical limits of the method in terms of accuracy, domain size, and convergence have not yet been thoroughly investigated. The second approach uses standard Fourier analysis techniques to transform the time-domain pulse propagation into the frequency domain, so that existing grating diffraction solutions may be applied. An algorithm of this type yielding the far-field diffracted mode amplitudes has already been described. Since we wish to investigate the interaction of ultrashort pulses with subwavelength gratings, near-field effects are extremely important, and thus explicit calculation of the internal fields of the structure is necessary. Our method uses RCWA (Ref. 6) for accurate modeling of the interaction of monochromatic fields with a subwavelength periodic structure. The strength of the RCWA method is that it has been demonstrated to be an accurate method of analyzing grating diffraction, especially for subwavelength and/or resonant structures, where evanescent and backward-propagating modes are extremely important. In addition, RCWA is formulated to be well suited for computer solution. In this paper, we describe a modeling tool for the analysis of near-field interactions of femtosecond pulses propagating in subwavelength and resonant periodic optical structures. This tool is based on combining the well-established monochromatic RCWA solution with the Fourier spectrum decomposition technique. We use this tool to study near-field optical physics in nanostructures and to design and analyze novel optical and photonic devices based on these near-field phenomena.

In Section 2, we describe the new modeling tool based on the synthesis of Fourier spectrum decomposition and
2. PULSE PROPAGATION IN DIFFRACTIVE STRUCTURES BASED ON RIGOROUS COUPLED-WAVE ANALYSIS

The RCWA method is a well-established tool for characterization of monochromatic wave propagation through periodic diffractive nanostructures. However, since an ultrashort pulse contains a broad optical frequency spectrum, it is necessary to extend the existing RCWA method to analyze polychromatic fields. We consider the propagation of a periodic sequence of ultrashort pulses and use standard Fourier methods to obtain the corresponding spectrum, yielding a discrete number of monochromatic frequency components. Since we would like to develop an efficient tool for the analysis of pulse propagation in diffractive structures, we present general considerations for the minimization of the total number of components in the Fourier expansion. These discrete components are independently analyzed by using our recently developed RCWA internal field calculation technique. The obtained discrete multispectral results are then superimposed (i.e., transformed back to the time domain), revealing the interaction between the ultrashort pulses and the periodic diffractive nanostructure.

A. Ultrashort Pulse Representation

Consider a sequence of femtosecond optical pulses from a mode-locked laser incident on a periodic diffractive nanostructure. The output field $\mathbf{E}(\mathbf{r}, t)$ can be described by an infinite train of pulses with envelope function $p(\mathbf{r}, t)$ and carrier frequency $\omega_0$:

$$\mathbf{E}(\mathbf{r}, t) = \{\hat{a}_0 \tilde{P}(\mathbf{r}, \Omega) \exp[-j(\mathbf{k}_0 \cdot \mathbf{r} - \omega_0 t)]\} \otimes \sum_{n=-\infty}^{\infty} \delta(t - n \Delta T), \tag{1}$$

where $p(\mathbf{r}, t)$ is a function describing the shape of the pulse envelope, $\delta(t)$ is a delta function, position vector $\mathbf{r}$ and $t$ are space and time coordinates, respectively, $\hat{a}_0$ is a unit vector indicating the polarization of the incident field, $\mathbf{k}_0$ is the wave vector of the carrier frequency of the pulse, $n$ is an integer taking on values $0, \pm 1, \pm 2$, etc., $\otimes$ denotes the convolution operation, and $\Delta T$ is the time interval between pulses. The spectrum of the input field is given by the temporal Fourier transform of Eq. (1), yielding

$$\tilde{\mathbf{E}}(\mathbf{r}, \omega) = \{\hat{a}_0 \tilde{P}(\mathbf{r}, \Omega) \exp[-j(\mathbf{k}_0 \cdot \mathbf{r})]\} \sum_{n=-\infty}^{\infty} \delta(\Omega - n \delta \omega), \tag{2a}$$

where

$$\tilde{P}(\mathbf{r}, \omega) = \int_{-\infty}^{\infty} p(\mathbf{r}, t) \exp(-j\omega t) dt \tag{2b}$$

is the spectrum of the ultrashort pulse envelope function, $\Omega = \omega - \omega_0$, and the frequency domain sampling period is defined by

$$\delta \omega = \frac{2\pi}{\Delta T}. \tag{3}$$

The sequence of $\delta \omega$ functions in Eq. (2a) shows that the monochromatic spectral components of the pulse sequence interacting with the periodic diffractive nanostructure can be treated independently by using RCWA, and the resulting spectral field components at the output of the structure can be superimposed to yield the output field. In addition, the independent analysis of each spectral component facilitates the inclusion of material dispersion effects. Since the computational effort required scales with the total number of frequency components, it is advantageous to minimize the number of components to be considered. Thus, before we proceed, it will be useful to discuss two parameters: (1) the spectral resolution and (2) the spectral bandwidth of the pulse.

B. Spectral Resolution

The spectral resolution $\delta \omega$ determines the period $\Delta T$ of the ultrashort pulse sequence [see Eq. (3)]. If the objective is to study the interaction of a single pulse with the structure, the temporal separation of adjacent pulses must be long enough for the interaction of one pulse to be completed before the next pulse arrives. In practical terms, the interaction time corresponds to the time interval required for the energy of a pulse to be dissipated from the region inside or immediately surrounding the structure, either by absorption or radiation. In simple structures, this corresponds to the time of flight through the structure (accounting for changes in path length that are due to reflection, refraction, or diffraction). However, for more complex structures (e.g., with strong resonances in the direction of propagation, or coupling into waveguide and/or surface modes), the interaction time of the pulse with the structure may be significantly longer. Also, as the transmitted or reflected pulses emerging from the structure may exhibit significant temporal broadening as a result of modulation effects of the device on the pulse spectrum, the period of the incident pulse train must be sufficiently large in order to avoid aliasing effects. However, increasing the temporal separation of the pulses also increases the number of independent frequency components that need to be calculated with RCWA, increasing the computational workload. For
computational efficiency, we minimize the pulse separation while still observing the limit imposed by the interaction time of the pulse in the nanostructure.

C. Spectral Bandwidth
To understand the spectral bandwidth effects, we consider a transform-limited, band-limited Gaussian-shape incident pulse envelope:

\[ p(\mathbf{r}, t) = \exp \left[-\left( \frac{t - \frac{\hat{k}_0 \cdot \mathbf{r}}{v_g} - t_0}{2\tau^2} \right)^2 \right], \tag{4} \]

where \( \tau \) is the width parameter of the Gaussian envelope, \( v_g \) is the group velocity of the pulse, \( \hat{k}_0 \) indicates the direction of propagation, and \( t_0 \) is the time at which the pulse peak arrives at spatial coordinate \( \mathbf{r} = 0 \). The corresponding Gaussian frequency spectrum is obtained by substitution of Eq. (4) into Eq. (2b), yielding

\[ \tilde{P}(\mathbf{r}, \omega) = \sqrt{2\pi} \exp \left[-j \omega \left( \frac{\hat{k}_0 \cdot \mathbf{r}}{v_g} + t_0 \right) \right] \exp \left(-\frac{\tau^2\omega^2}{2} \right). \tag{5} \]

With the subsequent substitution of the Gaussian spectrum of Eq. (5) into Eq. (2a) and by imposing a finite truncated bandwidth \( \Delta \omega = 2M\delta \omega \) centered at \( \omega_0 \), we obtain

\[ \tilde{E}(\mathbf{r}, \omega) = \hat{a}_0 \sqrt{2\pi} \exp \left[-j \hat{k}_0 \cdot \mathbf{r} - j \Omega \left( \frac{\hat{k}_0 \cdot \mathbf{r}}{v_g} + t_0 \right) \right] \]

\[ \times \exp \left(-\frac{\tau^2\Omega^2}{2} \right) \sum_{n=-M}^{M} \delta(\Omega - n\delta \omega), \tag{6} \]

where \( \delta(\Omega) \) is the Dirac delta function.

The truncation of the spectral bandwidth introduces an error into the field representation, since \( \tilde{P}(\mathbf{r}, \Omega) \) diminishes monotonically as \( |\Omega| \) increases [see Eq. (5)], this error can be reduced to an arbitrarily small value by a sufficient increase in the spectral bandwidth. Thus the spectral bandwidth can be adjusted to achieve the desired level of accuracy compromised with the computational intensity of the solution.

In this paper, we assume a typical femtosecond laser pulse of width FWHM = 167 fs, corresponding to a Gaussian width parameter of \( \tau = 1 \times 10^{-13} \) s. In Section 3, we assume a pulse interval of \( \Delta T = 100 \) ps, while in Section 4 we assume that \( \Delta T = 10 \) ps, corresponding to frequency sampling intervals of \( \delta \omega = 2\pi \times 10^{11} \) rad and \( \delta \omega = 2\pi \times 10^{10} \) rad, respectively. We also choose a truncated bandwidth of \( \Delta \omega = 3\pi \times 10^{13} \) rad, corresponding to a total number of spectral components of \( 2M + 1 > 151 \) and \( 2M + 1 = 1501 \), respectively, and a spectral envelope magnitude at the cutoff frequencies of \( |\tilde{P}(\mathbf{r}, \omega)| \approx 1 \times 10^{-4} \). In Section 3, the effects of material dispersion in Si (Ref. 13) and SiO\(_2\) (Ref. 14) are included in the analysis. In Section 4, because of the absence of resonances in the propagation direction and the anticipated minimal dispersion effect on the pulse envelope over the interaction length under consideration, the effects of material dispersion have been omitted for simplicity.

D. Synthesis of Time-Domain Pulse Propagation
The RCWA method\(^6\) is applied to solve for the diffraction of each frequency component of the finite-size discrete Fourier transform representation of the incident optical pulse sequence [see Eq. (6)]. For the structures presented in Sections 3 and 4, the RCWA technique with 25 total orders (12 on each side plus the zero order) in the space-harmonic field expansion (see Ref. 6 for more details) is found to be sufficient to achieve accurate results while minimizing computational effort. The internal fields of the grating are computed by using a modified version\(^1\) of the numerically stabilized RCWA algorithm described by Chateau and Hugonin.\(^1\)

To observe the propagation of the pulse as it interacts with the nanostructure, it is necessary to obtain a time-domain representation of the total field by coherently superposing the fields of each frequency component \( \omega_n \) at each point of observation \( \mathbf{r}(x, y, z; t) \). This coherent superposition corresponds to the inverse of the Fourier decomposition performed on the incident pulse train in Subsection 2.A. The inverse of the Fourier decomposition performed in obtaining Eq. (2a) from Eq. (1) is given by

\[ \mathbf{E}(\mathbf{r}, t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \mathbf{E}(\mathbf{r}, \omega) \exp(j\omega t) d\omega. \tag{7} \]

Since the frequency-domain representation of the fields is discrete and finite, we replace the integral of Eq. (7) with the corresponding Riemann sum. Assuming that the Fourier kernel of Eq. (7) is included in the expression for the field \( \mathbf{E}(\mathbf{r}, t; \omega_n) \), we obtain

\[ \mathbf{E}(\mathbf{r}, t) = \frac{1}{2\pi} \sum_{n} \tilde{\mathbf{E}}(\mathbf{r}, t; \omega_n) \delta \omega. \tag{8} \]

Equation (8) describes the time-domain field resulting from the interaction of the ultrashort pulse with the nanostructure at the desired observation point in space and time. In practice, the superposition is carried out for an array of points, and the resulting data are introduced into a variety of visualization tools to facilitate observation, analysis, and interpretation of the results.

3. PULSE PROPAGATION IN A NANOSTRUCTURED POLARIZATION-SELECTIVE MIRROR
To verify the modeling tool as well as to better understand the near-field phenomena associated with optical pulses in nanostructures, we examine ultrashort optical pulses propagating through a microstructured polarization-selective mirror (PSM).\(^1\) shown schematically in Fig. 1. The structure is composed of seven layers of alternating materials having high (Si) and low (SiO\(_2\)) indices of refraction in a 50% fill factor subwavelength square grating. The subwavelength grating introduces form birefringence, producing a large effective refractive-index difference for the TE- and TM-polarized fields at normal incidence. The depth of each layer is chosen to...
correspond to a $\pi/2$ phase delay for the TE polarization. Thus, for the TE polarization, the structure is a distributed Bragg mirror, while for the TM polarization, as a result of the lower effective index values, the structure is nonresonant and transmits the incident wave. The structure is assumed to be surrounded by air on the side from which the incident pulses arrive and by an infinite substrate of refractive index $n_{\text{sub}} = 1.44$ on the opposite side. The PSM structure is designed to operate at a wavelength of $\lambda = 1.523 \, \mu m$, reflecting TE-polarized fields and transmitting TM-polarized fields as shown in Fig. 2. No diffraction orders are observed, as the grating period ($\Lambda = 0.6 \, \mu m$) is significantly smaller than the optical wavelength ($\lambda = 1.523 \, \mu m$).

The TE-polarized incident illumination is fully reflected from the structure in the broad wavelength range $1.3 - 2.0 \, \mu m$ (see Fig. 2). The TM-polarized light is fully transmitted at the design wavelength of $\lambda = 1.523 \, \mu m$, with a falloff to 90% transmission over a range of $\pm 0.1 \, \mu m$. Since we have set the pulse bandwidth to be $\Delta \omega = 3 \pi \times 10^{13} \, \text{rad}$, corresponding to a wavelength bandwidth of $\Delta \lambda \approx 0.12 \, \mu m$, we expect that the spectral and temporal characteristics of the ultrashort pulse will not be affected by the PSM.

The effect of the PSM on the profile of the 167-fs ultrashort pulse is analyzed next by using our modeling tool to investigate the reflection and the transmission of TE- and TM-polarized optical pulses having center frequencies corresponding to the design wavelength of $\lambda = 1.523 \, \mu m$ (see Fig. 3) as well as the offset wavelength of $\lambda = 1.18 \, \mu m$ (see Fig. 4).

As expected, the PSM has no effect on the shape of the TM transmitted and TE reflected pulses at the design wavelength [see Figs. 3(a) and 3(b)], as the complex TE reflection and TM transmission coefficients of the PSM exhibit minimal variation across the spectrum of the pulse [see Figs. 3(c) and 3(d)]. Because of the geometry of the structure, the incident and reflected pulses propagate in air while the transmitted TM-polarized pulse propagates in the substrate material, which has a higher index of refraction than that of air. Consequently, the magnitude of the TM transmission coefficient [as shown in Fig. 3(d)] is not unity but rather approximately 0.83 in order to conserve the total energy of the pulse. In addition, although both the incident and transmitted TM pulses have the same FWHM (167 fs) in time, the transmitted TM pulse appears spatially narrower than the incident pulse in Fig. 3(b) because of the lower group velocity in the substrate of refractive index $n = 1.44$.

At the offset wavelength of $\lambda = 1.18 \, \mu m$, shown in Fig. 4, we note that the TE and TM polarizations both yield reflected and transmitted pulses, because the magnitude of the PSM TE reflection coefficient [see Fig. 4(c)] and the TM transmission coefficient [see Fig. 4(d)] deviate significantly from their respective values for the design wavelength. The magnitude of the PSM transmission coefficient for the TM polarization varies slowly from approximately 0.80 to 0.65 across the bandwidth of the pulse, while its phase profile stays close to linear, yielding both reflected and transmitted pulses while approximately preserving the temporal width of the incident pulse. In contrast, for the TE polarization both the amplitude and the phase of the PSM transmission coefficient vary dramatically across the bandwidth of the pulse, resulting in broadening of both the transmitted and reflected pulses to a FWHM of 173 and 206 fs, respectively. In effect, at $\lambda = 1.18$ the PSM acts as a partial reflector for TM-polarized pulses, while for TE-polarized pulses the structure also acts as a passive frequency filter, modulating the temporal envelope of the reflected and transmitted pulses.

Further insight into the propagation of ultrashort pulses through the PSM is achieved by observing the near-field interactions, which reveal radically different behavior for TE-polarized pulses from that for TM-polarized pulses. Figures 5(a) and 5(b) show TE- and TM-polarized pulses, respectively, at the design wavelength $\lambda = 1.523 \, \mu m$ as they approach the PSM structure, and Figs. 5(e) and 5(f) show the TE reflected and TM
transmitted pulses, respectively. Figures 5(c) and 5(d) show a magnified view of the internal fields in a single period of the PSM structure. We observe that for both the TE and TM polarizations there exists a strong transverse field localization when the pulse is propagating through the subwavelength structure. The TE-polarized field is reflected, localizing in the multilayer region of the grating structure [see Fig. 5(c)], while the TM-polarized field is transmitted, localizing in the air gap of the structure [see Fig. 5(d)]. This effect can be explained by observing the physical behavior of the fields on the boundaries. For the TM-polarized light, the electric field is normal to the grating groove interfaces, requiring continuity of the electric displacement and thereby resulting in a stronger electric field in the low-refractive-index (i.e., air gap) regions of the grating structure. For the TE-polarized light, the electric field is parallel to the grating groove interfaces, requiring continuity of the electric field across the boundary. Although no transverse field concentration is imposed by the boundary conditions, the field mode pattern is localized in the high-refractive-index region. A QuickTime movie of the pulse propagation through the PSM structure can be found at http://uno.ucsd.edu.

4. PULSE PROPAGATION IN A COUPLED WAVEGUIDE ARRAY SUPPORTING TWO MODES

The second example demonstrates a periodic waveguide structure designed to support two propagating modes with different propagation constants, producing from one incident pulse two transmitted pulses separated in time. The structure consists of an infinite one-dimensional periodic array of two materials of different indices of refraction with a period close to the center wavelength of the incident ultrashort pulses. This type of structure can be considered an infinite series of coupled waveguides. In a single slab waveguide surrounded by vacuum on both sides, the number of propagating modes in the guide is determined by the relationship between the electromagnetic wave frequency and the cutoff frequencies of the various modes, which depend in turn on the waveguide geometry and material properties. The number of allowed modes inside the waveguide will increase as the thickness of the waveguide is increased. Similarly, in our periodic waveguide structure, the number of allowed modes in the guide is a function of the widths of the high-
and low-index materials. Since we are using a rigorous analysis technique, all of the near-field effects that are due to interwaveguide interaction are taken into account in determining the mode structure of the device. We have chosen the geometry of the structure to yield a waveguide structure supporting exactly two propagating modes, with very different transverse spatial profiles. Since these two modes have significantly different propagation constants, an incident pulse will produce two transmitted pulses corresponding to the two modes emerging from the waveguide at different times. When the waveguide depth is made sufficiently large, the temporal separation of these two pulses will be long enough so that at the output the two pulses can be clearly distinguished.

We have designed the structure to operate with optical pulses having center wavelength of $\lambda = 0.92 \, \mu m$ and to have refractive indices of $n_1 = 3.57$ and $n_2 = 1.63$. We examine two waveguide geometries, each of which supports exactly two modes. The first structure (shown in Fig. 6) consists of high- and low-refractive-index materials with widths $w_1 = 0.2 \, \mu m$ and $w_2 = 0.5 \, \mu m$, respectively, while the second structure is composed of widths $w_1' = 0.25 \, \mu m$ and $w_2' = 0.45 \, \mu m$, respectively. A waveguide depth of $d = 250 \, \mu m$ is chosen to ensure full separation of the two output pulses. Using our modeling tool, we analyze the propagation of a TE-polarized ultrashort optical pulse with FWHM = 167 fs through the first structure geometry ($w_1 = 0.2 \, \mu m$ and $w_2 = 0.5 \, \mu m$, as shown in Fig. 6). The simulation results at three instances in time are shown in Fig. 7: (a) the incident pulse approaching the structure from below at time $t = -0.3 \, ps$ (the pulse peak arrives at the front of the structure at time $t = 0$); (b) the two modes separated in time inside the structure, with different transverse profiles, at time $t = 1.3 \, ps$; and (c) the two transmitted pulses after they exit the structure, producing at the output a pair of pulses with a temporal separation of $\Delta t = 1.37 \, ps$ at time $t = 3.5 \, ps$. A QuickTime movie showing the time-domain propagation of the pulses through the structure can be found at http://uno.ucsd.edu.

Although the pulses are propagating through a transverse grating structure, the transmitted pulses exhibit a uniform transverse profile that is due to the subwavelength period of the grating (no diffracted orders are observed). A cross-section profile through the center of the grating period at time $t = 3.5 \, ps$ is shown in Fig. 8. The first and second transmitted pulses, which correspond to waveguide modes having propagation speeds of approximately $0.49c$ and $0.27c$, respectively (where $c$ is the speed of light).
of light in vacuum), as well as the first reflected pulse, which corresponds to reflection of the incident pulse from the front surface of the structure, are observed. Although two transmitted pulses are produced from a single incident pulse, the transmitted pulses maintain approximately the same pulse width as that of the incident pulse. In addition to both pulses inside the structure (one in the "fast" mode and one in the "slow" mode) producing a transmitted pulse, each pulse will also partially reflect from the back surface of the waveguide and produce a fast and a slow reflected internal pulse, yielding a total of four pulses inside the waveguide at time \( t = 3.5 \) ps. In Fig. 8, the first of the four pulses has reached the front surface of the structure, transmitting part of its energy to produce a...
second reflected pulse outside the structure. The $z$ positions of the second reflected pulse and the subsequent three pulses inside the structure correspond to energy propagation in the fast mode forward/fast mode backward, fast/slow, slow/fast, and slow/slow cases, respectively.

A cross-section profile of pulse propagation through the second two-mode waveguide geometry ($w'_{1} = 0.25 \mu m$ and $w'_{2} = 0.45 \mu m$) is shown in Fig. 9. As in the previous case, two transmitted pulses are produced; however, the positions of the first and second transmitted pulses correspond to waveguide modes having propagation speeds of $0.42c$ and $0.27c$, respectively. The first reflected pulse (corresponding to reflection of the incident pulse by the front surface of the structure) and three pulses inside the structure (corresponding to reflection of the two waveguide modes by the back surface of the structure) are also observed. The $z$ positions of the three pulses inside the structure correspond to energy propagation in the fast mode forward/fast mode backward, fast/slow, and slow/slow cases. The pulse corresponding to the slow/fast case is not visible, as its intensity is small compared with that of the slow/slow pulse (as in Fig. 8) and the separation of the two pulses is not sufficiently large. Comparison of Figs. 8 and 9 shows that a change in the geometry of the two-mode waveguide results in a different temporal separation between the two transmitted pulses corresponding to the two waveguide modes.

In this example, it is the time-domain effects of pulse propagation through the structure, as opposed to the spectral domain properties as in the case of the PSM, that constitute the functionality of the device. However, as in the example of the PSM, we observe that the interaction of an ultrashort pulse with a subwavelength diffractive structure produces a modulation of the incident pulse spectrum that depends on the structure geometry. In addition, the dramatically different transverse profiles exhibited by the two modes of the coupled waveguide array

Fig. 6. One-dimensional subwavelength grating structure that supports two modes for incident pulses with center wavelength of $\lambda = 0.92 \mu m$. The structure is composed of alternating layers of materials having refractive indices $n_{1} = 3.57$ and $n_{2} = 1.63$, and widths $w_{1} = 0.2 \mu m$ and $w_{2} = 0.5 \mu m$, respectively. The depth of the structure is $d = 250 \mu m$. The black rectangle represents the modeling domain consisting of one period.

Fig. 7. Ultrashort pulse propagating through the two-mode waveguide structure shown in Fig. 6. Each frame shows the intensity in one period of an infinitely periodic structure at various times: (a) $t = -0.3$ ps, incident pulse approaching the structure from below (the pulse peak arrives at the front of the structure at $t = 0$), (b) $t = 1.3$ ps, pulse propagating inside the structure, where two distinct modes with different transverse profiles are clearly visible, (c) $t = 3.5$ ps, two transmitted pulses observed after exiting the structure, with temporal separation of $\Delta t = 1.37$ ps.
illustrate the significance of a modeling tool that enables investigation of the near-field properties of optical nanostructures.

5. CONCLUSIONS

We have presented a new method for the modeling and the analysis of ultrashort optical pulse propagation in periodic structures—including subwavelength and resonant grating structures. The method is based on the integration of two well-established analysis techniques: Fourier spectrum decomposition and rigorous coupled-wave analysis (RCWA). In addition, our approach permits the explicit computation of the internal fields, enabling the direct investigation of near-field phenomena in periodic nanostructures. We also discussed the spectral resolution and bandwidth of the incident pulse train and their impact on the accuracy of the modeling results as well as on the computational intensity of the solution. Finally, we described the synthesis of the time-domain dynamics of the propagation of the optical pulse employing coherent superposition of the discrete monochromatic frequency component solutions calculated by RCWA. This new tool enables the accurate analysis of the interaction of ultrashort optical pulses and a variety of periodic photonic structures, facilitating the design and the investigation of novel photonic devices based on near-field phenomena.

We applied this tool to the analysis of two example structures, examining ultrashort pulse propagation in a nanostructured polarization-sensitive mirror (PSM) and in a two-mode coupled waveguide structure. In investigating the PSM, we analyzed the spectral properties of the structure, including both amplitude and phase modulation of the pulse spectrum, for incident pulses both at the design wavelength and at an offset wavelength. For ultrashort pulses at the design wavelength of the PSM, we found that the PSM performs as predicted by the monochromatic design, since the complex reflection and transmission coefficients of the PSM are approximately uniform over the bandwidth of the pulse. However, at the offset wavelength, where the reflection and transmission coefficients vary significantly over the pulse bandwidth, our results show that both the polarization selectivity of the PSM and the temporal profiles of the reflected and transmitted pulses are dramatically altered. In addition, our near-field modeling results show that at the design wavelength the TE- and TM-polarized fields exhibit significantly different transverse profiles inside the PSM structure, illustrating the importance of near-field phenomena inside the nanostructure in determining the performance characteristics of the device. We also examined the two-mode coupled waveguide structure, which produced from one incident pulse two transmitted pulses whose separation depends on the waveguide geometry and which demonstrates nanostructured device functionality in the time domain as opposed to the spectral domain. These examples illustrate the applications of this new modeling tool to the investigation of near-field phenomena resulting from ultrashort pulse propagation in periodic nanostructures, as well as to the design of novel optical devices based on these near-field effects.

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