Wavelet-based analysis of transient electromagnetic wave propagation in photonic crystals

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Photonic crystals and optical bandgap structures, which facilitate high-precision control of electromagnetic-field propagation, are gaining ever-increasing attention in both scientific and commercial applications. One common photonic device is the distributed Bragg reflector (DBR), which exhibits high reflectivity at certain frequencies. Analysis of the transient interaction of an electromagnetic pulse with such a device can be formulated in terms of the time-domain volume integral equation and, in turn, solved numerically with the method of moments. Owing to the frequency-dependent reflectivity of such devices, the extent of field penetration into deep layers of the device will be different depending on the frequency content of the impinging pulse.

To show how this phenomenon can be exploited to reduce the number of basis functions needed for the solution. To this end, we use spatiotemporal wavelet basis functions, which possess the multiresolution property in both spatial and temporal domains. To select the dominant functions in the solution, we use an iterative impedance matrix compression (IMC) procedure, which gradually constructs and solves a compressed version of the matrix equation until the desired degree of accuracy has been achieved. Results show that when the electromagnetic pulse is reflected, the transient IMC omits basis functions defined over the last layers of the DBR, as anticipated. © 2004 Optical Society of America

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1. INTRODUCTION

The ever-increasing importance of photonic crystals and optical bandgap structures for high-precision control of electromagnetic-field propagation calls for new time-domain efficient analysis and design tools. In this paper, a new time-domain solution method will be used to solve the transient interaction of a Gaussian pulse with a distributed Bragg reflector (DBR), which basically is a stack of layers of two alternating materials with different dielectric permittivity. This device exhibits high reflectivity at certain frequencies and is therefore an essential element in state-of-the-art applications, such as mirrors for solid-state lasers and hollow fibers.1–5

To solve the transient problem, we use a time-domain volume integral equation and cast it into a matrix form with the method of moments. Various methods of solution have been suggested to solve the resultant matrix equation and overcome the inherent instability of its more common explicit form.6–16 Other researchers have used the implicit formulation, which is known to be numerically stable.17–21 The solution of the implicit formulation can proceed in a way much the same as the explicit marching-on-in-time procedure, except that at each time instance a matrix equation has to be solved. In this paper we follow the implicit formulation but suggest that this entire series of matrix equations be solved simultaneously at all time instances. To reduce the increased computational complexity, the unknown field is expanded in terms of spatiotemporal wavelet basis functions.22,23 Owing to their multiresolution property, these functions can span the solution at different time instances and locations with varying levels of spatial and temporal scales.

The idea is to obtain a good approximation of the field by using a small-as-possible number of such basis functions and hence by determining a small-as-possible number of coefficients. The selection of the appropriate spatiotemporal wavelet expansion functions is effected by an iterative impedance matrix compression (IMC) technique. This technique was originally developed and applied to time-harmonic problems24–26 and has recently been extended to time-varying problems.27–29 Since in the case of the DBR under consideration, the extent of field penetration into deep layers of the device would be different depending on the frequency content of the impinging pulse, a considerable reduction in the number of basis functions needed for expanding the solution is expected.

The paper is organized as follows. Sections 2 and 3 present the problem and outline the method of solution, respectively, followed by numerical results in Section 4. Finally, a summary and conclusions are given in Section 5.

2. PROBLEM FORMULATION

We consider the transient interaction of a Gaussian electromagnetic pulse with a one-dimensional DBR, as shown in Fig. 1. The DBR consists of Nсло sections each characterized by dielectric permittivity ε and thickness dₙ in the z direction and is at a distance dₛ from its adjacent neighbors. The incident Gaussian pulse, given by

\[
E^{\text{inc}}(z, t) = \tilde{x} \tilde{E}_x^{\text{inc}}(z, t) = \tilde{x} \tilde{E}_0^{\text{inc}} \exp \left[ - \frac{\tau^2}{\Delta T^2} \right] \cos(\omega_0 \tau), \quad (1)
\]

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