Time-domain analysis of bandgap characteristics of two-dimensional periodic structures by use of a source-model technique

Alon Ludwig* and Yehuda Leviatan

Department of Electrical Engineering, Technion–Israel Institute of Technology, Haifa 32000, Israel
*Corresponding author: ludwig@technix.technion.ac.il

Received June 4, 2007; revised November 21, 2007; accepted November 25, 2007; posted November 27, 2007 (Doc. ID 83730); published January 28, 2008

We introduce a time-domain source-model technique for analysis of two-dimensional, transverse-magnetic, plane-wave scattering by a photonic crystal slab composed of a finite number of identical layers, each comprising a linear periodic array of dielectric cylinders. The proposed technique takes advantage of the periodicity of the slab by solving the problem within a unit cell of the periodic structure. A spectral analysis of the temporal behavior of the fields scattered by the slab shows a clear agreement between frequency bands where the spectral density of the transmitted energy is low and the bandgaps of the corresponding two-dimensionally infinite periodic structure. The effect of the bandwidth of the incident pulse and its center frequency on the manner it is transmitted through and reflected by the slab is studied via numerical examples. © 2008 Optical Society of America

OCIS codes: 050.1950, 260.2110, 000.4430, 230.1480, 290.0290, 320.5550.

1. INTRODUCTION

Photonic crystals have been the subject of considerable interest in recent years. The drive for the extensive research in this field stems from a basic property that those periodic structures exhibit, namely, the photonic bandgap [1,2]. A photonic bandgap is a frequency range for which electromagnetic fields cannot propagate inside the photonic crystal in any direction. Thus, the propagation of a pulse whose spectral content is confined within the bandgap region can be fully controlled by the photonic crystal. This type of propagation control opened the door to many new technological applications.

The creation of novel photonic-crystal-based applications relies on the development of new analytical and numerical techniques for efficient modeling of electromagnetic scattering by photonic crystals. Numerical techniques for the analysis of photonic crystal structures in the frequency domain have been developed using both integral and differential equation formulations [3–7]. Yet, because of efficiency and stability problems of early time-domain-integral-equation (TDIE)-based solvers [8–12], the analysis of periodic structures such as photonic crystals was limited until recently to the use of techniques based on differential equation formulations [13–16]. However, continued effort to improve TDIE solution techniques has paved the way to the recent development of TDIE solvers for periodic structures [17,18].

Motivated by this development, this paper utilizes for the first time, as far as the authors are aware, a TDIE solver for the analysis of a photonic-crystal structure. When the scattering problem consists of a wide-band excitation, such as a short-time pulse, the use of a direct time-domain solver will be highly advantageous compared with applying a Fourier transform over a multitude of frequency-domain solutions. Moreover, relying on the advantages inherent to integral-equation-based techniques, it is expected that the basic TDIE solver described here, when coupled with state-of-the-art acceleration methods for integral equation solvers [19,20], will become much more efficient than other available time-domain solvers.

The TDIE solver that is used in this paper for the analysis of a photonic crystal structure is based on a time-domain (TD) source-model technique (SMT). The SMT has been used extensively in frequency-domain solutions of scattering by both finite size bodies and periodic structures [21–26] and has been found to be a viable alternative to integral-equation-based techniques in which ordinary surface formulations amenable to conventional moment-method solutions are used. A discussion of the advantages of the SMT can be found in [22]. Recently, a time-domain SMT (TD-SMT) solver for calculating electromagnetic transient scattering by a conducting cylinder has been proposed [27], and has subsequently been extended to solve a periodic array of perfectly conducting cylinders [18].

The present paper further extends the TD-SMT solution method suggested in [18] to treat electromagnetic scattering by a periodic array of dielectric cylinders illuminated by a transient plane wave. This solution method is then utilized to study the energy transmitted through a finite photonic-crystal slab by pulses of different bandwidths impinging at different incidence angles.

The remainder of the paper is organized as follows. The scattering problem under study is specified in Section 2. In Section 3, a general formulation of the TD-SMT for a