Calculating the coupling efficiency between single mode fiber to photonic crystal fiber using the FDTD method

Jiazong Zhang and Michal Bodovsky,
Optiwave Corporation, 7 Capella Court, Ottawa, ON, Canada K2E 7X1

ABSTRACT

With advances in photonic crystal and photonic band gap research, the interest in interconnecting traditional guided wave devices to the new photonic crystal layout has greatly increased in EMC community. However in order to take complex electromagnetic effects such as radiation, reflection, and coupling into account, full-wave numerical modeling must be considered. This paper investigates the wave coupling performance of a photonic crystal fiber (PCF) and photonic band gap (PBG) structure using the finite-difference time-domain (FDTD) method. We also illustrate the application potential for using the FDTD method for the estimating the coupling efficiency.

Key words: *Photonic band gap (PBG), Photonic Crystal Fiber (PCF), Coupling efficiency, Finite-difference time-domain (FDTD) method*

I. INTRODUCTION

Photonic crystal fiber (PCF) and photonic band gap (PBG) structures are new components that add a unique dimension to optic and photonic design possibilities. Such structures achieve previously unthinkable performance in different application areas. In past several years, research work on mode field analysis and band-gap effect analysis had proven the advantages of the PCF and PBG layout [1]-[3]. When applied to traditional waveguide devices, the important issue to consider is how a signal can be coupled from the traditional layout to this new type layout. Consequently, numerical analysis can greatly facilitate the practical design work.

The interconnection is a discontinuity for the wave traveling. All the wave effects such as propagation, reflection, radiation, and polarization in the discontinuity must be taken into account for the design. Among all photonics numerical methods, the FDTD is the best way to address this task. The FDTD method is a very general method for calculating electromagnetic field distributions in structures of arbitrary geometry. It can be very accurate since the method is based on a direct discretization of Maxwell's equations, making no assumptions on the kind of solution or the propagation direction of waves. Starting from a given field distribution, driven by sources at given locations, the time-evolution of the electromagnetic field is calculated over a given spatial domain. This makes FDTD a tool that is suitable for investigating complicated wave phenomena. Another advantage of the FDTD method is that it provides results for a large range of frequencies in a single run, by applying a pulsed start field and Fourier transforming the response. For these reasons, the FDTD method is well suited for modeling photonic crystal discontinuities.

II. FDTD method and coupling efficiency analysis

A very detailed and practical overview of the FDTD method is given in the book by Prof. Taflove [4]. There are several technical points for the FDTD method which should be mentioned here: (1) The conventional FDTD algorithm is based on the Yee's cell, where the electric and magnetic field components are evaluated at different grids having the same pitch, but which have been shifted over half a grid spacing, both in space and in time. The Central Finite-difference technique is applied to Maxwell's equation, as the method in general has the 2nd-order accuracy refer to the mesh in space domain and time domain. (2) To achieve convergence results, the maximum mesh size should be at least 10 percent of the interested minimum wavelength. (3) To keep the method stable, the time domain step should follow the Courant-Friedrichs-Levy CFL condition:

$$\Delta t \leq \frac{1}{v\sqrt{\frac{1}{\Delta x^2}+\frac{1}{\Delta y^2}+\frac{1}{\Delta z^2}}} \qquad (1)$$

where $\Delta x, \Delta y, \Delta z$ is the space domain step in three direction respectively, and v is the speed of light in the layout. The above two points limit FDTD both in terms of CPU time and memory. (4) The FDTD computational space is truncated, where the numerical absorbing boundary conditions (ABC) are necessary to keep outgoing waves from being reflected back. Among all the different boundary conditions, the perfectly matched layer (PML) boundary condition is being widely used [4].

The FDTD method in regards to the coupling efficiency analysis: Of importance, the input wave should be fully launched to one direction in order for the transmittance and refection to be observed. Therefore two considerations should take place: (1) The total field/scattering field (TF/SF) technique for the input wave [4] and (2) observation areas to extract the coupled power or reflect power beyond the input wave. The observation area should be set in the waveguide, then Fourier transform based on the simulated time domain response for each field components at all the meshes should be performed so that the Poynting vector can be calculated.

III. SIMULATION RESULTS

1. 2D-Photonic Band gap Waveguide Coupler.

As we investigate the coupling efficiency, we first consider a simplified model as shown in figure 1, where it is a 2D Photonic crystal slab, with two line defect waveguide. The slab waveguide dielectric constant is $\varepsilon = 13$. The hexagonal lattice array has a circular atom with lattice constant $d = 1.0\mu m$, material as air and radius as 0.4µm. The structure is assumed to be uniform in the y-direction. Light is excited at one port (P1) of the defect line. At the other three defect line ports, the output power is monitored so that the coupling efficiency can be obtained. Figure 2 shows the band diagram that is obtained by plane wave expansion (PWE) method. It tells us that the band gap happens in the wavelength range of 2.46µm-4.16 µm. But the line defect might break the bad-gap effects. We set input pulse in port 1 with center wavelength of 3.0µm. Figure 4 is the power transmittance spectrum in port 2-port 4 calculated from FDTD method. When we set the input wavelength range to 1.45 µm-1.65µm, no coupling is found through the FDTD simulation.

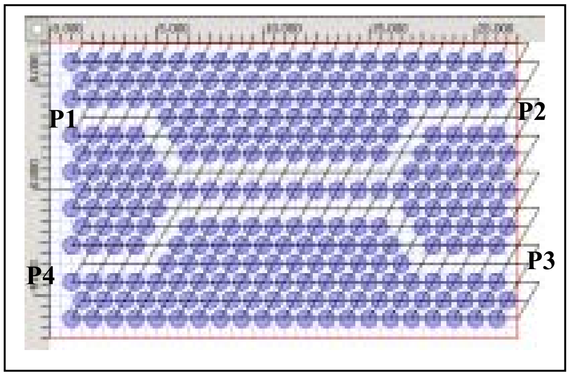

Figure 1. 2D Photonic Crystal waveguide Coupler.

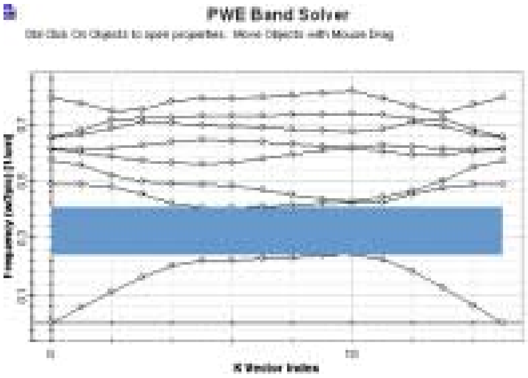

Figure 2. Band diagram

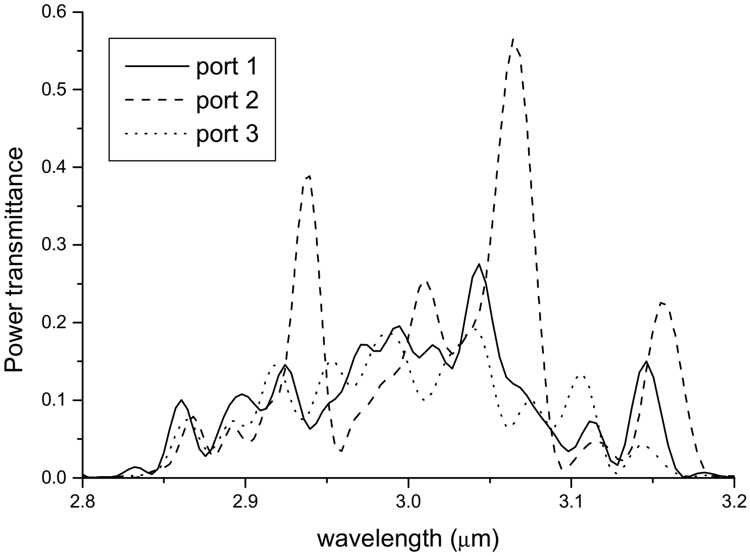

Figure 3. Power transmittance spectrum in output port

2. Fiber to Photonic Crystal Fiber Coupler

A traditional fiber coupled to a photonic crystal fiber is shown in Figure 4. The core radius is 4.07 μm with refractive index of 1.45205. The cladding index is 1.44681. Photonic crystal fiber consists of hexagonal air cylinders with radius of 0.25μm and a background material with refractive index of 1.45. Because the wave is mainly confined in the center region of the waveguide, the FDTD simulation consequently takes 12μm*12um cross-section only as the transverse simulation window. The simulated length is set as 15μm. For the input wavelength of 1.5um, FDTD calculation shows that the coupling efficiency is 92.21% at the beginning of the interconnection. When the wave travels along the PCF after the discontinuity, it couples to a PCF mode. This will lead to some leakage. The FDTD simulation shows 3.24% percent leakage when the PCF fiber mode is excited. The FCF mode field pattern can be observed after a certain distance from the discontinuity as shown in Figure 5. Figure 6 is the far field pattern as transformed from the near field. One important concern for this connection is the polarization state. The initial field is polarized in y-direction. The FDTD shows that the excited x-polarized wave is only take about 0.0022% of the total input power, which means such a connection will not change the polarization.

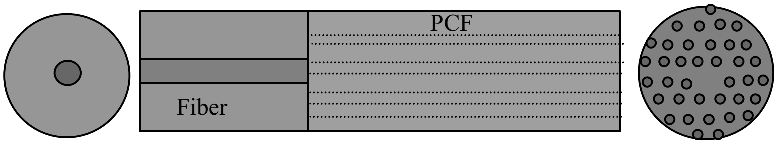

Figure 4 Fiber to PCF coupler

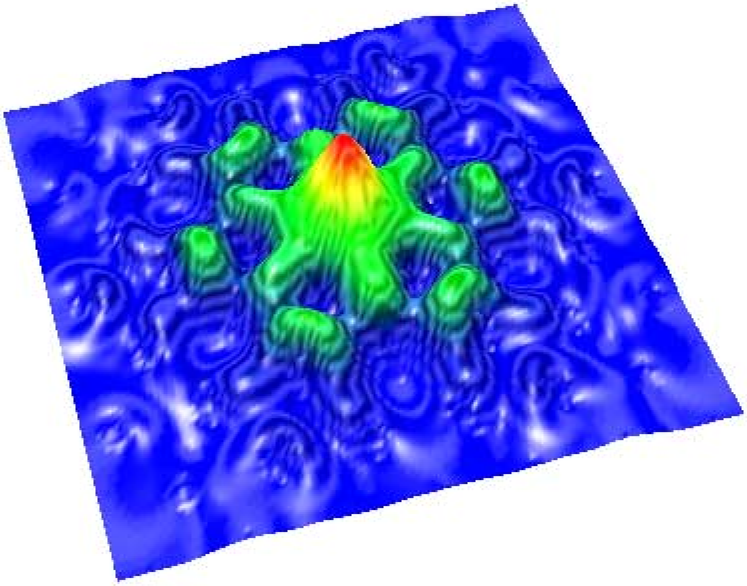

Figure 5 Calculated field pattern in PCF Fiber

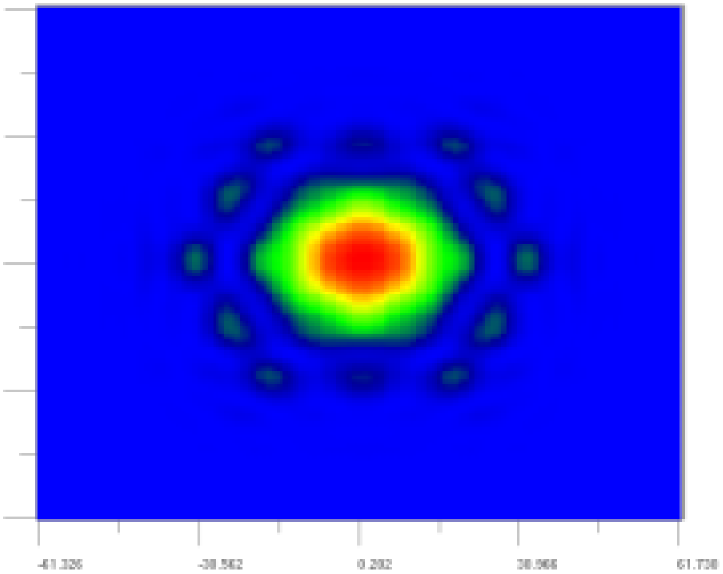

Figure 6   Far field pattern

IV. CONCLUSION

In this paper, we investigate the electromagnetic coupling phenomenon for PBG and PCF layouts using the FDTD method. Because PBG and PCF are typical band gap layouts, the band diagram solving using the PWE method is still necessary for the practical layout design. However, FDTD may provide more detailed information for the wave coupling effect. Deep insight into the electromagnetic mechanism is still acquired.

REFERENCE

[1]. R. Ghosh et al., ‘‘Modal characteristics of few-mode silica-based photonic crystal fibers,’’ *Opt. Quantum Electron.* **32**, 963–970 ~2000

[2]. M. Qiu, ‘‘Analysis of guided modes in photonic crystal fibers using the finite-difference time-domain method,’’ *Microwave Opt. Technol. Lett.* **30(**5), 2001

[3]. T. M. Monro, ‘‘Holey optical fibers: an effective modal method,’’ *J. Lightwave Technol.* **11**, 1093–1102 , 1999

[4]. A. Taflove. S. C Hagness. “Computational electrodynamics---the finite-difference time-domain method”, second edition, Artech House, Boston. 2000