Optik 126 (2015) 421–425

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

A novel reliable optimization method for output beam forming of photonic crystal waveguide terminated with surface CROW

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ARTICLE INFO

Article history:
Received 17 August 2013
Accepted 28 October 2014

Keywords:
Photonic crystal waveguide (PCW)
CROW
FDTD
Beam shaping
Optimization algorithm

ABSTRACT

In this paper, in order to achieve more coupling between photonic crystal waveguide (PCW) and photonic devices, we have used a new optimization method to create output focused beams. The PCW terminated with coupled resonator optical waveguide (CROW) is analyzed by the finite difference time domain (FDTD) method. We have optimized the rods of CROW one by one in a special sequence. Our proposed method is more reliable and much faster than other optimization methods such as particle swarm optimization (PSO) and genetic algorithms. The optimized structure compared to the non-optimized one has a factor of 4.73 times improvement in the intensity of the PCW output main lobe.

1. Introduction

In recent years, photonic crystals (PCs) [1,2] are known as one of the best structures for design and fabrication of optical devices and photonic integrated circuits (PICs), because of their special characteristics, wavelength-scalesize and low mismatch losses [3–5]. Generally photonic crystal (PC) with periodic refractive index creates some stop bands in specific frequency spectrum and lightwave incident directions [6]. Photonic crystals are similar to the semiconductors from many prospects, and their effects on photons are the same as those of semiconductors on electrons. Hence the photonic band gaps are dual of the electron band gaps in semiconductors [6].

However, the most significant weakness of photonic crystal waveguides is their non-directive beam emission from their output port, which causes losses and low connection efficiency to other telecommunication devices in PICs [7,8]. Output beam of photonic crystal waveguides (PCWs) can be shaped by various methods [9–26], all with intention of coping with the non-intensive emission of the PC structures. In one of these methods, to access the non-radiative surface modes, radii of the output rods of photonic crystal layer are reduced, and the rods of this layer are periodically modulated [9].

In another approach, the radii of the rods of two PC terminative layers are reduced down to half of the PC rods. These layers create a surface mode at the output of the waveguide to split the output beam which can easily be connected to a multi-input device [23].

Efficient focusing the PCW output beam can also be achieved by adding coupled resonator optical waveguide (CROW) to terminate the PCW [18]. CROW resonators produce resonant modes. The radiations of CROW are propagated in free space and will be vectorially added up to the output beam of the PCW to create a more focused intensive beam. The radiations must be constructively interfered in desired region, and destructively interfered in other regions. This effect is a consequence of lower Q factor of the CROW resonators at the termination surface of the PCW and its radiation to the free space [18,24].

By utilizing some special structures, the output beam can be shaped in more special ways. For instance, the output focused beam can be directed to a desired angle or can be divided into different sections with desired angles, intensities and full width at half maximums (FWHMs) [12,24]. These designed structures can be considered for launching the waveguide output beam to multi-input or several parallel optical devices.

By utilizing a proper optimization method, appropriate parameters can be achieved to attain more focused and intensive beams with lossless connection to other devices can be achieved. Two of the most efficient optimization methods are the particle swarm optimization (PSO) [27] and genetic algorithm (GA) that have been vastly used in related scopes of PCs and their optimizations [27–38]. One of the significant advantages of these algorithms is their prompt solution of the optimization problems, whereas, due

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http://dx.doi.org/10.1016/j.ijleo.2014.10.002
0030-4026/

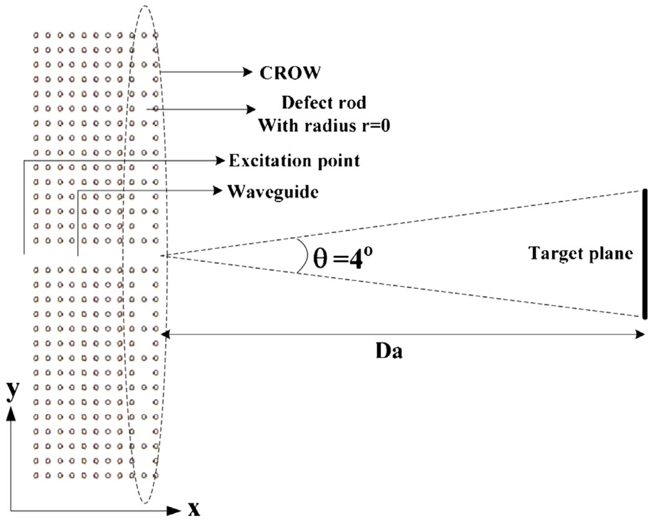

Fig. 1. PCW structure, CROW with defect rods radii of $r = 0$ at surface, target plane and excitation point are shown [24].

to the stochastic search behavior of these algorithms, the optimum solutions are not trustworthy, which is a disadvantages of them.

In this paper, we have proposed a new optimization algorithm for directive emission of PCWs with CROW termination. First, we have determined the most effective defect rods in output beam shaping. Then the optimum radii of the defect rods in order of their higher effects on output beam shaping are derived one by one. The refractive indices of the PCW-CROW rods can also be optimized by this method, but there is no guarantee for the feasibility of the resulted materials. This novel method is faster and more reliable compared to other optimization algorithms.

The paper is organized as follows: after introduction of Section 1 the details of structure and simulation space will be described in Section 2. In Section 3, effects of different CROW defect rods will be perused. In Section 4, the optimized radii of different CROW defect rods will be derived by our proposed reliable sequence optimization method (SOM) to attain the most directive PCW output. In Section 5, the FWHM and polar radiation diagram of each structure will be demonstrated and compared. The paper is concluded in Section 6.

2. Details of structure and simulation space

The square lattice PCW under study, shown in Fig. 1, is exactly the same as that of Ref. [24]. The dielectric rods have relative dielectric constant of 11.56 corresponding to that of InGaAsPInP at 1.55 μm wavelength [18].

Cross-section diameters of the PC rods are 0.36a, where a is the structure lattice constant. The stop band of this PC structure is in the normalized frequency ($\omega a/2\pi c$) range of 0.306–0.439, where ω and c are the angular frequency and the free space speed of light, respectively [18,24]. This stop band is for TM polarization with electrical field component, E_z parallel and magnetic field components, H_x and H_y perpendicular to the rods' axes. In the simulations we have used 31 × 11 dielectric rods. The output CROW is created by means of making defects with regular distances of 2a at the termination of the PC waveguide by changing the diameter of the central rod of the CROW resonators.

In our FDTD analysis, space steps are assumed to be $\Delta x = \Delta y = d/10$, where d is the cross section diameter of the rods. Target plane distance is Da ($D = 35$) from the PCW termination, within an angle of $\theta = 4°$, as shown in Fig. 1. Applied lightwave signal is a modulated Gaussian pulse:

$$S = \cos(2\pi f_0 t)\, e^{-4(t-T_0)^2/\sigma^2} \tag{1}$$

where f_0 is the resonance frequency of the resonators with defect rod diameter of $d = 0$, t is time, T_0 is the peak time and σ is the width controller of the Gaussian pulse [24].

The prepared software for the simulations in C++ and MATLAB environments have been executed on a Pentium IV PC, with quad core CPU, processing capacity of 2.48 GHz and RAM of 3.25 Gb.

Table 1
Optimized diameters of the defect rods of the CROW structure of Fig. 4.

Defect no.	1	2	3	4	5	6	7
Defect diameter (×a)	0.144	0.949	1.012	1.008	1.049	1.024	1.064

3. Effects of crow different defect rods

Applications of PSO, genetic algorithm and other similar optimization algorithms in photonic crystal structures are useful, but have some disadvantages. All PC rods do not have the same role in structure performance. The effects of defect rods of the CROW on output beam shaping are decreased by moving away from the PCW.

Primarily, we have examined this effect. At the beginning, we assumed a PCW terminated with a CROW which its defect rods have the same diameters as those of the PC rods. By changing the diameter of the first defect rod, from zero to the maximum allowed value of 1.64a, we obtained the maximum power transferred to the target plane, the results of which are illustrated in Fig. 2(a).

Then, the diameters of all defect rods are randomly chosen, except the first one which is changed from zero to the maximum allowed value. The results are shown in Fig. 2(b). In the next step, the second CROW defect rod is optimized, whereas all other defect rods have random diameters. The power transferred to the target plane versus the CROW second defect rod diameter is depicted in Fig. 3. These simulations have been repeated several times to confirm that, as depicted in Figs. 2 and 3, the diameter of the CROW first defect rod has the main effect on the transferred power to the target plane; and that during optimization of each rod, better results are derived, if higher number defect rods diameters are kept the same as those of PC, compared to the case that higher number rods have random diameters. Therefore, as we go far from the PCW, the effect of variation of diameter of the CROW defect rods on transferred power is decreased. This also approves that the performance of a PCW structure is complete when 5–6 PC periods are considered on both sides of the waveguide.

The fact that effects of defect rods in forming the output beam are different reveals another weakness of the previous mentioned optimization algorithms. As a solution, the sequence of the defect rods effects must be taken into account in optimization, otherwise obtaining a local optimum is quite probable.

4. Reliable sequence optimization method for PCW output shaping

To optimize the output directional emission of PCW of Fig. 1, due to our proposed sequence optimization method (SOM) in previous Section, we optimized the diameters of CROW defect rods from rod 1 to 7, shown in Fig. 4, whereas in each step higher number rods diameters are kept the same as those of the PC, the results of which are respectively demonstrated in Figs. 5(a–f).

The normalized diameters of the CROW defect rods derived by our proposed SOM are summarized in Table 1. Therefore, as it can