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Unit cell topology optimization of line defect photonic crystal waveguide

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Abstract

In this paper we utilize a systematic method to optimize the topology of a line defect Photonic Crystal Wave guide (PCW), a very popular and effective optical device for realizing optical buffer in room temperate operation. In order to do this, we divide the unit cell PCW to 25 squares and utilize a Binary Particle Swarm Optimization (BPSO) algorithm to find the optimum topology. During the optimization process, we apply some constraints to avoid band mixing as well. Calculation results show that Normalized Delay-Bandwidth Product (NDBP) for the structure optimized is 0.27. This structure optimized possesses a high bandwidth (20.9 nm) with group index of 21.7 as well.

Keywords: Slow light; Optimization; BPSO; Binary Particle Swarm Optimization; PCW;

1. Introduction

Photonic Crystals (PC) have become very popular mostly due to their wide range of applications. One of the applications is the realization of slow light which is done by Photonic Crystal Waveguide (PCW) [1]. The PCW have been employed in different fields such as nonlinear optics [2], time-domain signal processing [3], and all-optical buffers [3, 4]. Fig. 1 illustrates the structure of a basic PCW. As may be seen in this figure, PCW is a triangle lattice

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PC slab with missing a row of holes. There are many theoretical and experimental studies in the literature concentrating on slow light in line defect PCWs [5-8]. To the best of our knowledge, however, there is no mechanism to optimize unit cell in PC lattice in the literature with considering the behaviour of all bands. In this work we propose and optimize a new unit cell in PC lattice by using Binary Particle swarm Optimization (BPSO) to make a PCW with high buffering capabilities. The rest of the paper is organized as follows:

Section 2 describes the PCW design problem. Section 3 formulates the problem for BPSO. The results and discussion are provided in Section 4. Eventually, Section 5 concludes the work and suggests some direction for future studies.

2. Photonic Crystal Waveguide Structure Design Problem

There are some preliminary concepts and definitions in slow light regime as follows:

The optical buffering performance of slow light devices with different lengths and operating frequencies are defined by normalized delay-Bandwidth Product (NDBP) as follows [8]:

$$NDBP = \overline{n_g}.\Delta\omega / \omega_0 \tag{1}$$

where $\overline{n_g}$ is the average of group index, $\Delta\omega$ is the normalized bandwidth, and ω_0 is the normalized central frequency of light wave.

The dispersion relations diagram is usually calculated by a 2-D plane wave expansion (PWE) with slab equivalent index method [9]. The background refractive index is the effective refractive index of the guided Transverse Electric (TE) polarized mode in silicon-on-insulator (SOI) slab. Note that a slab equivalent index is 3.18 for 400 *nm* thick silicon slab in silicon dioxide which is used [10].

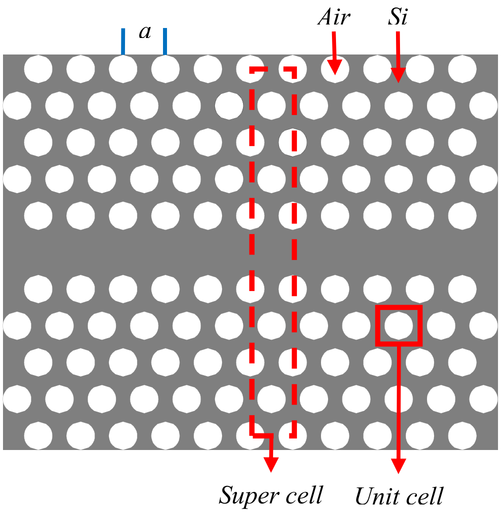


Fig. 1. PCW structure with super cell and unit cell

Fig. 2(a) shows the calculated dispersion relation of PCW. As may be observed in this figure, the PC slab waveguide supports one even and one odd mode in the photonic band gap. The modes which lie bellow the light line belongs to SiO_2 are intrinsically lossless in the vertical direction [8]. Apparently, both of these two modes are located below the light line of SiO_2. The even mode is chosen as the main propagation mode since its linear dispersion curve lays at large wave vectors. The group index n_g is defined as follows [11]:

$$n_g = \frac{C}{v_g} = C\frac{dk}{d\omega} \tag{2}$$

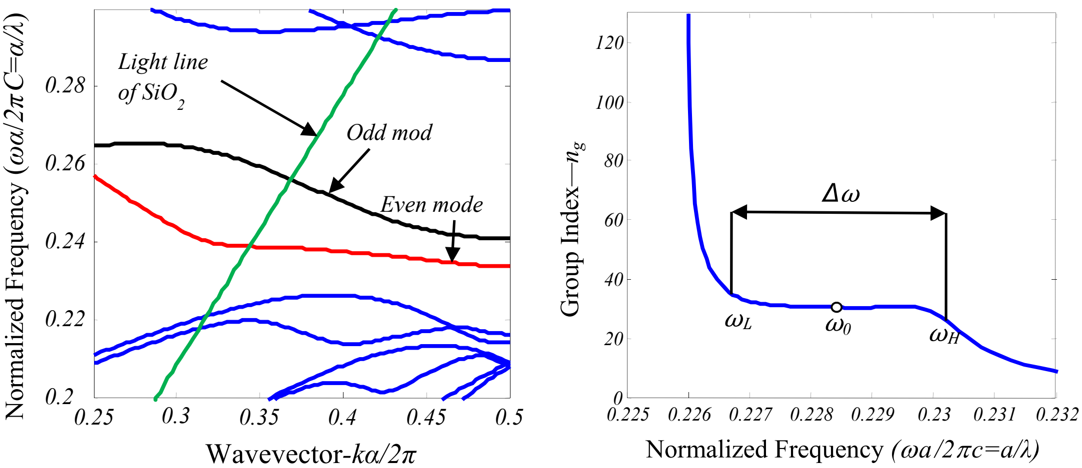
where ω is the dispersion, k indicates the wave vector, C is the velocity of light in free space, and n_g shows group index. The n_g parameter is changing in bandwidth range, so we have to average it as follows [11]:

$$\overline{n_g} = \int_{\omega_L}^{\omega_H} n_g(\omega)\frac{d\omega}{\Delta\omega} \tag{3}$$

The presence of slow light usually coincides with huge group velocity dispersion (GVD) [12]. Generally speaking, low group velocity has high GVD which reduces the bandwidth of guided mode. Therefore, the acceptable range of GVD (β_2) is in $|\beta_2|<10^6\ a/2\pi C^2$ [11, 13], and the final structure must satisfy this constraint. The parameter β_2 is defined as follows [11]:

$$\beta_2 = \frac{d^2k}{d\omega^2} = \frac{dn_g}{d\omega}\frac{1}{C} \tag{4}$$

According to Zhai *et al.* [8], the first five rows of cells next to the defect have much effect on slow light. Consequently, the slow light and control dispersion can be achieved by designing the shape of these rows.



(a) (b)

Fig. 2. (a) Photonic band structure of PCW; (b) Group index (n_g) diagram of even mode and the bandwidth region considering 10% fluctuation for n_g

The normalized bandwidth in PCW is a region of normalized frequency that the group index n_g is considered as a constant with $n_g \pm 10$ % range [8]. Fig. 2(b) shows the bandwidth region of n_g.

In this work we divide the unit cell of the PCW into 25 squares. Each square is known as an independent bit. Zero value for a bit means that the square should be empty (air), and one indicates that the square should not to be empty (filled by silicon). We want to find the binary unit cell with highest buffering capabilities (maximize NDBP). Moreover, the parameters of problems are in binary format. This is the reason of employing a binary algorithm called BPSO [14] to find the optimum shape for this problem. Please note that other binary algorithms such as Binary Bat Algorithm (BBA) [15] and Binary Magnetic Optimization Algorithm (BMOA) [16] can be utilized here as well. The

PCW super cell and binary unit cell is shown in Fig. 3. As can be seen in this figure, there are 25 binary cells (parameters) to be optimized.

3. Problem Formulation

The problem is mathematically formulated for BPSO as follows:

$$
\begin{aligned}
&\textit{Consider}: && \vec{x} = [Bit\,24, \ldots, Bit\,00], \\
&\textit{Maximize}: && f(\vec{x}) = NDBP = \frac{\overline{n_g}\Delta\omega}{\omega_0}, \\
&\textit{Subject to}: && \max(|\beta_2(\omega)|) < 10^6 a / (2\pi C^2), \\
& && \omega_H < \min(\omega_{up\ band}), \\
& && \omega_L > \max(\omega_{down\ band}), \\
&\textit{where}: && \omega_H = \max(\omega_{Guided\ mode}), \\
& && \omega_L = \min(\omega_{Guided\ mode}), \\
& && \Delta\omega = \omega_H - \omega_L, \\
& && a = \omega_0 * 1550(nm)
\end{aligned}
\qquad (5)
$$

Note that the second and third constraints of this problem are for avoiding band mixing. As the infeasibility handling method, we assign small negative objective function values (-100) to those candidate solutions that violate the constraints. The *a* parameter is lattice constant which is designed for bandwidth with 1550 *nm* central wave length.

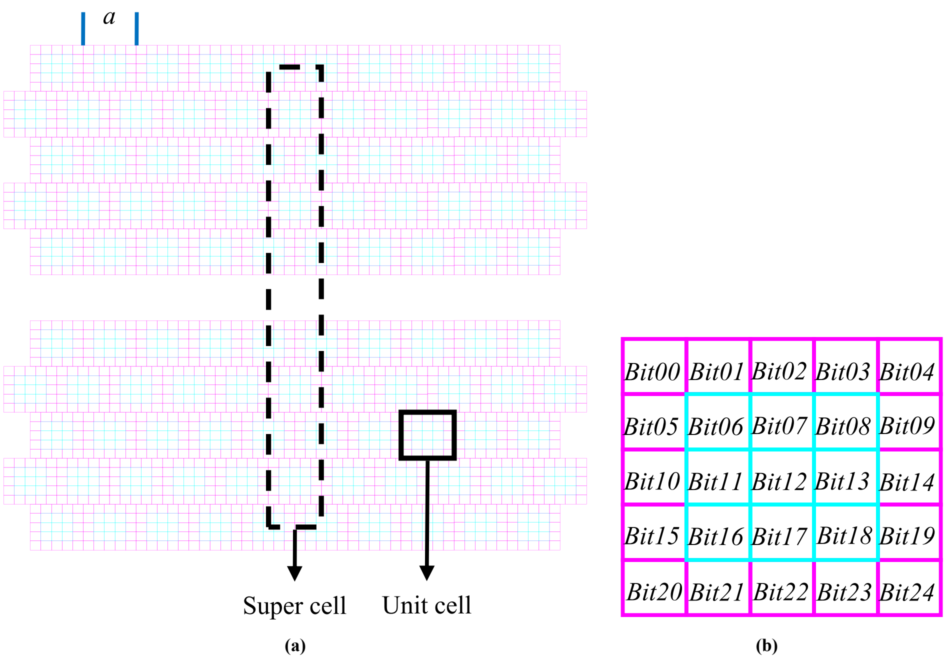


Fig. 3. (a) Proposed binary PCW with super cell and unit cell (b) Binary unit cell.

4. Results

We solved this problem by BPSO 10 times over 200 iterations and provide the best results in this section. The optimized binary unit cell and the corresponding group index are shown in Fig. 4. The slow light properties of the best binary unit cell obtained are presented in Table 1. The highest NDBP shows that the optimized binary unit cell has a good optical buffer capability due to high bandwidth operation. The BPSO algorithm proved its merit in optical buffer design in this study. It is worth mentioning that the optimized structure has a symmetric bandwidth around $\lambda_0=1550\ nm$ with no overlaps with other bands in the bandwidth region. This is the outcome of utilizing the BPSO optimizer with considering constraints which allow us to confidently state that the obtained design is a feasible optimized design.

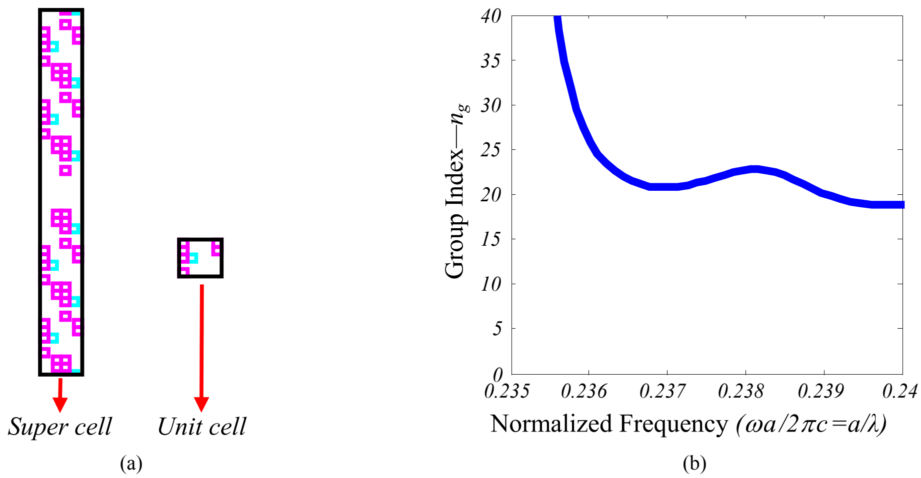


Fig. 4. (*a*) Optimized binary super cell and unit cell correspond to $\vec{x}$=[1000110001110000000010000] (*b*) Group index of the optimized binary PCW.

To sum up, it seems that the optimized structure is suitable for making optical buffer. Moreover, the obtained design is totally feasible with considering constraints.

Table 1. Slow light properties of the optimized binary unit cell ($\vec{x} = [1000110001110000000010000]$)

a (nm)	ω_0	$\overline{n_g}$	$\Delta\omega$	$\Delta\lambda(nm)$	*NDBP*	$GVD(a/(2\pi C^2))$
368	0.2376	21.7	0.0032	20.9	0.2931	4.14e+03

5. Conclusion

This paper was dedicated to find the optimum shape for a line defect PCW. The optimizer employed was the BPSO algorithm. The problem was formulated with constraints for the BPSO algorithm. The results showed that the BPSO algorithm was able to find an optimum structure with very promising optical properties. Moreover, the structure optimized was completely feasible without any band mixing due to the constraints applied. The structure optimized had NDBP=0.2931 which is considered as a very high bandwidth. Meanwhile, the structure optimized show good group index as well.

For future works, we are planning to optimize the structures of different PCW such as Bragg slot PCW and Ring-Hole-shaped PCW.

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