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A tri-objective Particle Swarm Optimizer for designing line defect Photonic Crystal Waveguides

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Abstract

This paper proposes a novel tri-objective approach for optimizing the structure of line defect Photonic Crystal Waveguides (PCW). A nature-inspired algorithm called Multi-Objective Particle Swarm Optimization (MOPSO) is employed as the optimizer. The three objectives considered are maximization of group index, maximization of bandwidth, and minimization of Group Velocity Dispersion (GVD). In addition, the optimization process is subject to five constraints in order to guarantee the feasibility of the structures obtained and prevent bad mixing in the final optimized structures. The results show that the tri-objective MOPSO is able to find 20 optimized structures for line defect PCW. The comparative study verifies the significant improvement of the optimized structures compared to current structures. Moreover, post analysis of the results reveals the importance of holes and their possible physical behaviours in line defect PCW. Finally, the implementation considerations and investigations show that the optimized structures are feasible for manufacturing with a resolution of 1 nm.

Keywords: Photonic Crystal; Line defect Photonic Crystal Waveguides; Slow light; MOPSO; Multi-objective Particle Swarm Optimization

1. Introduction

Recently, there has been a growing interest in utilizing Photonic Crystals Waveguide (PCW) for buffering optical packets. Optical buffers are considered as one of the key common components of all optical processors. This component is responsible for storing optical packets and adjust Central Processing Unit (CPU) timing. In order to build an optical buffer, there are two options for designers: long transmission line and slow light regime. However, the former method is infeasible due to the size of CPUs. The common methods to achieve slow light regime are PCW, resonator, material dispersion, optical fibre, and quantum dot.

PCW is one of the most popular methods. This popularity is due their easy integration on chips, operation at room temperature, wide bandwidth, and low dispersion. Some of the structures proposed so far are Slot PCW (SPCW) [1,2], line defect PCW [3,4], Ring-shape Hole PCW (RHPCW) [5,6], and Brag Slot PCW (BSPCW) [7]. Regardless of the differences, these structures are compared based on three factors: group

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index (n_g), bandwidth ($\Delta\omega$), and Group Velocity Dispersion (GVD). The ultimate goal here is to build a PCW to achieve the highest group index, highest bandwidth, and lowest GVD. Building a PCW for achieving the ultimate goal is very challenging since these criteria are in conflict [41]. To the best of our knowledge, there is no mechanism to optimize these criteria simultaneously in the literature. This is the motivation of this study wherein we optimize the structure of a line defect PCW using a tri-objective optimization algorithm called Multi-Objective Particle Swarm Optimization (MOPSO). The rest of the paper is organized as follows.

Section 2 discusses the problem of optical buffer design, relevant preliminaries, and problem formulation. Section 3 provides the concepts and definitions of multi-objective optimization followed by the principles of MOPSO. The numerical results and discussion are then provided in Section 4. Implementation issues and time domain simulations are discussed in Section 5. Finally, Section 6 concludes the work and suggests some directions for future research.

2. Photonic Crystal Waveguide structure design problem

In this section the basic concepts and structure of the PCW-based optical buffer with relevant literature review are first provided. The problem of Photonic Crystal Waveguide (PCW) structure design is then formulated for MOPSO in a tri-objective way for the first time.

Over the last decade, there has been a growing interest in utilizing Photonic Crystal (PC) due to its wide range of applications. The slow light in PCW is one of the attractive methods for realizing slow light at room temperature [8]. PCW has been used in nonlinear optics [9], time-domain signal processing [8], and all-optical buffers [10,11]. There are many theoretical and experimental studies in the literature focusing on slow light in line defect PCWs [12,13,3,6]. The presence of slow light usually coincides with a huge Group Velocity Dispersion (GVD) [14]. Generally speaking, low group velocity has high GVD, which reduces the bandwidth of the guided mode. Therefore, it is very important to find a method to maximize the bandwidth and minimize GVD in slow light structures [42].

There are two factors in comparing the performance of slow light devices: Delay-Bandwidth Product (DBP) and Normalized DBP (NDBP), which are defined as follows [15]:

$$\mathrm{DBP} = \Delta t \cdot \Delta f \tag{1}$$

where Δt indicates delay and Δf is the bandwidth of slow light device.

Obviously, Δt should be increased in order to increase DBP. This happens by increasing the length of device (L). So normalized DBP (NDBP) is a better choice to compare devices with different lengths and operating frequencies as follows [6,16,17]:

$$\mathrm{NDBP} = \overline{n_g}.\Delta\omega/\omega_0 \tag{2}$$

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.

As may be inferred from Eq. 2, NDBP increases as $\Delta\omega$ rises. However, the bandwidth and group index are in conflict. So, we need to increase both of them in order to maximize NDBP. Finding the optimum values for these two factors is considered a challenging task as the literature shows [18,17,6,3,12,19,20].

The structure utilized is shown in Fig. 1. The waveguide is a single line defect of a triangle lattice PC slab with lattice constant along x at the length of a in a dielectric silicon. So, $a = 1.06d$ where d is the lattice constant of the normal triangle PC lattice. The radii R_1 to R_5 are modified in this study. The other parameters are fixed during the optimization process.

The dispersion relations are calculated by a 2D Plane Wave Expansion (PWE) with the slab equivalent index method [21]. 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 [5].

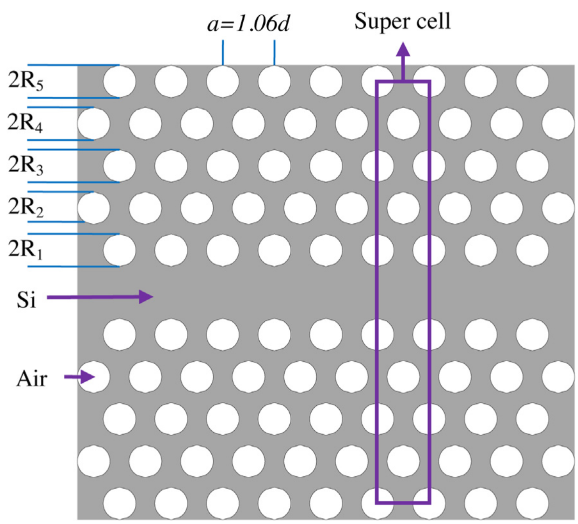

Fig. 1. Line defect PCW structure with super cell.