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Review

Coupling light in photonic crystal waveguides: A review

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Abstract

Submicron scale structures with high index contrast are key to compact structures for realizing photonic integrated structures. Ultra-compact optical devices in silicon-on-insulator (SOI) substrates serve compatibility with semiconductor fabrication technology leading to reduction of cost and mass production. Photonic crystal structures possess immense potential for realizing various compact optical devices. However, coupling light to photonic crystal waveguide structures is crucial in order to achieve strong transmission and wider bandwidth of signal. Widening of bandwidth will increase potential for various applications and high transmission will make easy signal detection at the output. In this paper, the techniques reported so far for coupling light in photonic crystal waveguides have been reviewed and analyzed so that a comprehensive guide for an efficient coupling to photonic crystal waveguides can be made possible.

Keywords: Photonic crystal waveguides; Nanophotonic waveguides; On-chip coupling; Off-chip coupling

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1. Introduction

Integration of photonic functions in a chip is the key for advancements in technology and functionality as it has done in the field of microelectronics. Moreover, its compatibility to CMOS technology reduces the cost as well as size of implementation. Scaling down devices and functions has led significant progress in photonic integrated circuits (PICs). Miniaturization of device dimension can be done using high index contrast material technology such as silicon-on-insulator (SOI). The high index contrast of 0.412 in SOI allows submicron waveguides and ultra-compact bends enabling high-density packaging in PICs. In order to use SOI waveguides for optical communication, the propagation loss must be smaller and single mode condition must be fulfilled [1,2]. Higher order modes are weakly confined and becomes leaky in the bends thus increases propagation loss. Careful design can lead to high quality silicon waveguide suitable for optical communication.

Controlling propagation of light on small scale using photonic band gap (PBG) effect is gaining attention exponentially in recent years [3–5]. The intricate confinement of light in photonic crystal waveguide (PhCW) enables realizing complex PICs. PhCW provides strong dispersion, which facilitates slow light effect in the vicinity of PBG edge [6,7]. Slow light provides strong light–matter interaction, which enhances absorption, non-linearity and gain per unit length [8]. Slow light effect enables miniaturization of various optical devices like amplifiers, lasers, detectors, sensors and wavelength modulators. PhCW offers a promising approach for the on-chip integration of slow-light structures. Implementation of this kind of waveguide faces several problems. Conventionally designed PhCWs have been constructed as an air-membrane structure for reducing the off-plane leakage of the waveguide modes [9]. However, fragility of air-membrane structure makes it unsuitable for large-scale integration of PICs. For improving the physical strength, PhC slab is realized on the Si film of the SOI substrate retaining the underlying oxide layer. Efficient coupling of light from silica fibers to PhCW has been an important issue [10–12]. The modal mismatch of more than a hundred times results in a very poor coupling efficiency. Typically silicon strip waveguides are used for coupling PhCWs. However, there occurs a huge group index mismatch at the interface. Poorly matched interfaces generate Fabry–Perot oscillations, which severely complicates the interpretation of experimental results [13].

In this paper, we review various techniques for efficient coupling of light from silica fibers to PhCWs for on-chip integration of slow light devices. Various issues like propagation losses, index mismatch, modal mismatch, etc. in coupling PhCWs have been studied and comparative study of the existing literature has been done. The paper is organized as follows: Section 2 describes the design constraints of PhCW structures; Section 3 describes the applications of PhCs; Section 4 focuses on nanophotonic components required for on-chip coupling in PhCWs; Section 5 presents the fiber-to-chip coupling technique and finally conclusions are drawn in Section 6.

2. Photonic crystal structures: design issues

In last decades, strong effort has been carried out in controlling and manipulating the propagation of light. The components based on total internal reflection like optical fibers have already transformed communication industry. The propagation of light in periodic material has been a topic of research for a large span of time [14]. Yablonovitch [15] and John [16] independently proposed the concept of photonic crystal in 1987 using the concept of semiconductor crystal with the analogy of electronic band gap. Photonic crystal can be defined as a periodic dielectric material with periodicity in one, two or all three orthogonal directions (namely 1D PhC, 2D PhC and 3D PhC). Out of the three, 2D PhC combines most of the interesting optical properties with accessible and available means of fabrication and thus has a wider research value. 2D PhC can be of two types: air holes in high dielectric material, high dielectric rod in air. Air hole type 2D PhC can be easily fabricated by etching holes periodically in high dielectric materials like Si, GaAs, Ge, etc. Due to the periodic variation of refractive index, PhC possesses a photonic band gap (PBG) defined as a range of frequencies, which is prohibited to propagate inside the crystal This unique property has been exploited to form waveguide by inducing line defects in PhC structure [17]. The line defect introduces a guided mode in PBG and hence can be utilized in guiding light from one point to another. The frequencies in PBG are guided through the defect and out-of-plane confinement