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Particle swarm optimized ultra-compact polarization beam splitter on silicon-on-insulator

Qichao Lu[a], Wei Wei[b,*], Xin Yan[a], Bing Shen[c], Yanbin Luo[a], Xia Zhang[a,*], Xiaomin Ren[a]

[a] State Key Laboratory of Information Photonics and Optical Communications, Beijing University of Posts and Telecommunications, Beijing, 100876, China
[b] School of Mechanical and Electric Engineering, Guangzhou University, Guangzhou, 510006, China
[c] 4catalyzer Inc., Guilford, 06437, USA

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ABSTRACT

We have designed an ultra-compact polarization beam splitter on silicon-on-insulator (SOI). The device is designed by a Particle swarm optimized (PSO) inverse-design method with a quite small footprint of $2 \times 2\,\mu m^2$. Simulation results shows that the transmission is 61% for TE mode and 52% for TM mode at designed wavelength 1550 nm. The extinction ratio of our device is greater than 10dB within a bandwidth of 40 nm (1528–1567 nm). Benefiting from the global optimization of our inverse-design method, the transmission and extinction ratio can keep greater than 40% and 10 dB separately for both polarizations when the designed pixel side length varies from 100 to 130 nm. Besides, we demonstrate that the design method could have tolerance for input waveguide width, in this case, the device could maintain functionality while the width of input waveguide ranges from 300 to 350 nm.

1. Introduction

Recently, photonic-integrated circuits (PICs) fabricated on the silicon-on-insulator (SOI) platform have attracted substantial attention due to the low power consumption, high transmit efficiency, small footprint, as well as the compatibility with complementary metal-oxide-semiconductor (CMOS) fabrication process [1–5]. The high refractive index contrast of SOI permits sharp waveguide bends and ultra-small device sizes allowing for such high density integration. However, the high refractive index contrast results in strong birefringence, leading to polarization-sensitive performance, which has bad influence on photonic integrated circuits (PICs). Because polarization states can change randomly in optical fibers, the polarization sensitivity is a problem for compatibility between on-chip PICs and optical fibers [6]. Therefore, the polarization control in the process of optical transmission in PICs is essential. In PICs, the polarization beamsplitter (PBS), which splits or combines the orthogonal TE and TM modes, is a fundamental component for polarization control. In consequence, a PBS compact in size, easy to fabricate and low loss should be designed to fit the require of PICs.

Various kinds of waveguide-type PBSs have been reported such as multimode interference (MMI) structures [7–9], Mach–Zehnder interferometers [10–12], and directional couplers(DCs) [13–20] based PBSs. Among them, smaller footprint PBS devices who could be integrated are preferred. Therefore, different methods are used to decrease the size of PBSs on PIC. In 2013, a DC-based PBS composed of a hybrid plasmonic waveguide and a silicon nanowire was reported by Guan and colleagues [21]. Their device has dimensions of $1.9 \times 3.7 = 7.03\ \mu m^2$, but the incorporation of metal creates significant parasitic absorption losses and renders the process complementary metal–oxide–semiconductor (CMOS) incompatible. While in 2015, B Shen and his colleagues proposed a free-form metamaterial based PBS with an ultra-small footprint $2.4 \times 2.4 = 5.76\,\mu m^2$ [22]. The free-form metamaterial based PBS has a small footprint and is CMOS compatible, but the device size could still be decreased.

In contrast to previous device designs, we demonstrate the use of an inverse design method that explores the full design space and allows us to design devices with previously unattainable functionality, higher performance and robustness, and smaller footprints than conventional devices [23]. Previously in [23], an alternating directions method of multipliers (ADMM) algorithm was used to optimize the inverse design method. Their optical simulation was based on a home-built finite-difference frequency-domain (FDFD) solver. Various ultra-compact devices including, sub-wavelength optical gratings [24], wavelength de-multiplexing grating coupler [25], and wavelength splitters [26] were created by the ADMM based method. Here we proposed a Particle swarm optimized (PSO) algorithm based inverse design method. The optical simulation was supported by a finite-difference time-domain

* Corresponding authors.
E-mail addresses: wei@gzhu.edu.cn (W. Wei), xzhang@bupt.edu.cn (X. Zhang).

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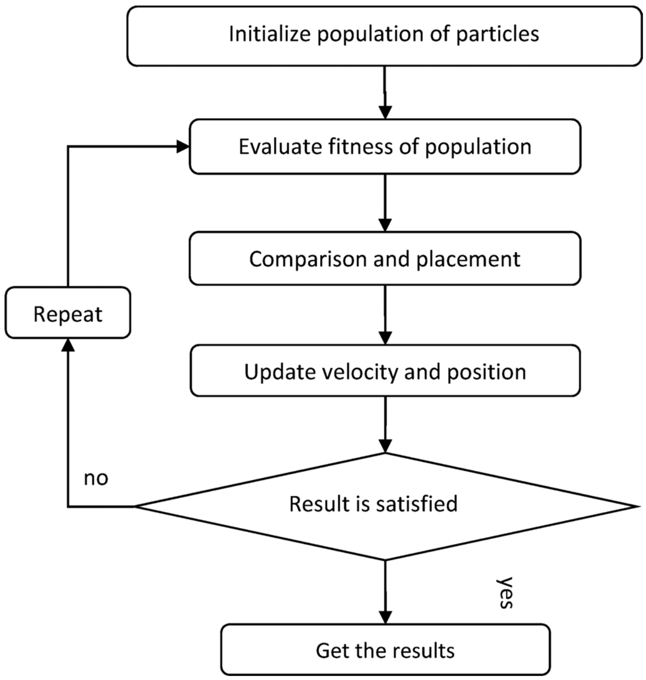

Fig. 1. Flow chart of PSO algorithm.

(FDTD) solver. Our method allows the user to 'design by function', whereby the user could simply specify the desired functionality of the device, and the algorithm finds a structure that meets these requirements. In particular, our algorithm searches the full design space of devices with arbitrary topologies. Moreover, the convergence speed of our method is controllable to increase the computing efficiency. Due to the greatly expanded design space, the complex and aperiodic structure can provide previously unattainable functionality, higher performance or smaller footprints than traditional devices.

In general, we use a computationally inverse design to engineer the refractive index of a region of silicon to achieve a specific photonic function. In our case, the function is polarization beam splitter in a waveguide. Here, we have designed and characterized an ultra-compact PBS with a footprint of only $2 \times 2 = 4\,\mu m^2$ for a designed wavelength of 1550 nm in simulation. The PBS is patterned on an SOI substrate, in which the thicknesses of the silicon is 300 nm. The PBS is comprised of only silicon which is CMOS compatible and can be fabricated with a single lithography step [27]. The transmission efficiencies for TE and TM modes at 1550 nm are 61% and 52%, respectively. The operation bandwidth of the PBS, defined as the range extinction ratio greater than 10 dB, is 40 nm (1528–1567 nm). Since the inverse design method allows the geometry of the device to be freely optimized, our device not only exhibit a small footprint, but are also expected to be fairly tolerant to fabrication errors. Besides, our PBS could fit varied input waveguide of different width.

2. Design and simulation

Particle swarm optimization (PSO) was firstly proposed by Eberhart et al. through simulating the social behavior of flying birds [28]. Each individual, called a particle, adjusts its flight according to both its own and neighbor' flying experiences. The position of a particle is updated via the following equation,

$$x_{i,d} = x_{i,d} + \Delta t \tag{1}$$

$$v_{i,d} = \varpi_n \times v_{i,d} + c_1 \times rand() \times (p_{i,d} - x_{i,d}) + c_2 \times rand() \times (g_{i,d} - x_{i,d}) \tag{2}$$

Where $x_{i,d}$ is the ith particle's position in the dth dimension of the parameter space, and $v_{i,d}$ is the corresponding velocity. w_n is the inertial weight for nth iteration and determines how likely the particle stays on its old velocity. $p_{i,d}$ and $g_{i,d}$ are individual and global best positions, respectively. c_1 and c_2 are two positive constants, which determine how much a particle is influenced by the memory of its own best position and the global best position, respectively. In our case, a large inertial weight is used to traverse most of the design space and finally a smaller inertial weight is employed for convergence. The flow chart of PSO algorithm is shown in Fig. 1.

In this work, the objective of PSO is to obtain a design that splits a combined TE + TM signal transmitted from the input waveguide to two separate TE and TM modes. The design district is a square consisted of 20 × 20 pixels. Every pixel is in the shape of a square made of silicon or air with side length of 100 nm. Each pixel has two states "0″ and "1″, indicating the pixel's material: "0″ for air and "1″ for silicon. The pixels are seen as particles with identical states (instead of position) and velocity. A random initial state and velocity would be given to the particles, fitness for both single particle and the whole population would be calculated to find a best state during each iteration. The fitness in this

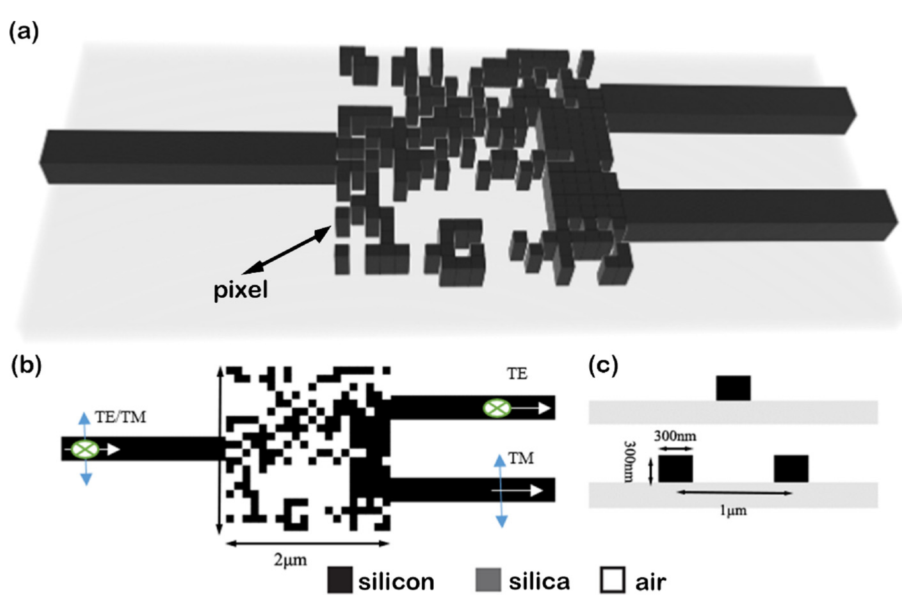

Fig. 2. Schematic diagram of the designed device. (a)3-d image of the device; cross section of the device from (b) up and (c) front and back sides.