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Optimization of low-loss and wide-band sharp photonic crystal waveguide bends using the genetic algorithm

Liyong Jiang[a,*], Hong Wu[a], Wei Jia[a,b], Xiangyin Li[a]

[a] Department of Physics, Nanjing University of Science and Technology, Nanjing 210094, China
[b] Clarendon Laboratory, Department of Physics, University of Oxford, Parks Road, Oxford OX1 3PU, United Kingdom

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ABSTRACT

This work discusses a robust genetic-algorithm based hybrid optimization scheme which was applied to handle the transmission problem in planar photonic crystal waveguide bend. For test purpose, two objective functions were proposed to characterize the transmission property of bend working at a special frequency or even over an entire frequency range. Optimization results for different 90° and 120° sharp bends have shown that, with the assistant of genetic-algorithm, random sizes of the cylinders surrounding the bend corner which correspond the maximum value of test functions are able to be rapidly obtained and obvious improvement of transmission property can be observed from each optimal bend structure, especially remarkable for the case of 120-I type bend.

1. Introduction

Photonic crystals (PCs) [1,2] are metamaterials based on a strong periodic modulation of the refractive index within the scale of the wavelength in one, two, or three dimensions. Due to the existence of photonic band gaps in PCs, the flow of photons can be controlled and the properties of light can be dramatically changed when it travels inside the PCs. One of the most fascinating applications of PCs is their ability to guide electromagnetic waves in narrow waveguides created by a sequence of line defects, including light propagation through extremely sharp waveguide bends with ultra-low loss transmission. This application is so important and is believed to be most promising for building low cost, highly functional optical chips where bending light path with arbitrary angles with minimum loss is highly desired [3]. In contrast to full three-dimensional (3D) PCs, two-dimensional (2D) planar PC waveguide bends are relatively easy to fabricate with conventional semiconductor processing technology. Recent studies addressed the issue of an improved design of sharp waveguide bends in 2D PCs and suggested that the transmission loss is very sensitive to the property of the band corner. Indeed, the physical mechanism which results in the transmission loss is mainly due to the impendence mismatch between the guiding mode propagating in the straight waveguide and that in bend corner. In other words, this means that if the impendence of old mode is in agreement with the new corner mode at the same frequency, there will be a coupling effect between them with no transmission loss taken place in the bend corner, or vice versa. In generally, only one of the old modes is allowed to propagate with no coupling loss, while the remaining ones are with different degrees of transmission loss or even under cut-off.

As a result, in order to improve the transmission performance in sharp waveguide bends based on 2D planar PCs, most of the designers have focused their attentions on the modification of the structure in the vicinity of the bend corner. The typical strategies include changing the refractive indexes [4], sizes [5,6], positions and lattice constant [7] of dielectric rods surrounding the corner, and removing or adding new rods [8–11] in the vicinity of the corner to form super defect. Unfortunately, to the present time, there is still no analytical way reported to reveal the relationships between bend corner structure and the best transmission performance. This will bring us a tough and time-consuming task to optimize all possible structure parameters in the bend corner concerning the use of a traditional step-by-step analytical routine which is only based on many usual numerical techniques, such as the finite-difference time-domain (FDTD) technique, the Green's tensor approach (GTA), the finite element method (FEM), and the multiple-scattering technique (MST).

To overcome this drawback, recently, some researchers made efforts to the use of inverse-design routine to fast searching the best design of bend corner with the help of effective global optimization tools, like topology optimization technique and genetic optimization technique. For instances, in many previous works [12–15], topology optimization technique was successfully applied in the

* Corresponding author at: Department of Physics, Nanjing University of Science and Technology, Street Xiao Linwei 200, Nanjing 210094, China.
Tel.: +86 25 84318547; fax: +86 25 84318547.
E-mail address: jly@mail.njust.edu.cn (L. Jiang).

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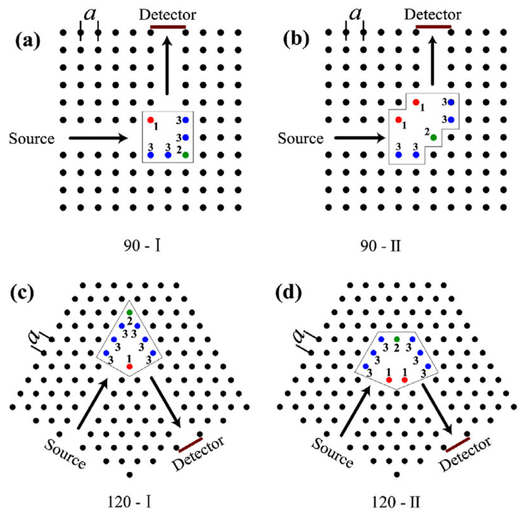

Fig. 1. Scheme of PC waveguide bend models studied in this paper: (a) and (b) represent 90° bends with different corner geometries, (c) and (d) represent 120° bends with different corner geometries.

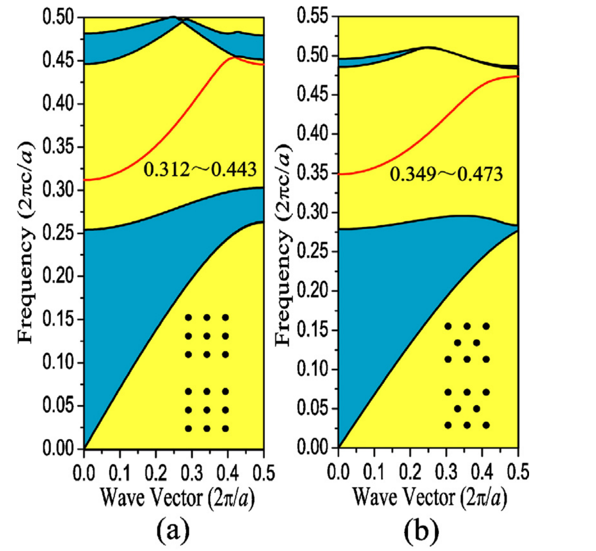

Fig. 2. TM band structure for different PC waveguides as shown in the inset (a) square-lattice GaAs PC waveguide and (b) triangular-lattice GaAs PC waveguide.

searching of several wide-band and flat-bandwidth 2D PC waveguide bend designs and improved transmission performance in the corresponding experiments was observed, even though the final optimal geometry of bend corner is more complex and difficult for fabrication than those using traditional analytical method. In Ref. [16], the genetic algorithm (GA) in conjunction with the MST technique was firstly used in the optimization of several 2D PC waveguide bends and numerical results have verified the effectiveness of such new method. In this study, we will continue to extend the GA based inverse-design routine to the optimization of 2D PC sharp waveguide bends for not only reducing the transmission loss at a single frequency [16] but also improving the transmission performance over a wide band. More importantly, we only consider modifying the sizes of rods surrounding the corner, from a practical point of view, which will make the designs relatively simple for further fabrication.

2. Models and methods

2.1. Models of sharp waveguide bends

As a model system, we consider two typical 2D PC sharp waveguide bends for optimization test as shown in Fig. 1. The first case is a 90° bend obtained by removing one line of rods from a 2D PC with infinitely long circular dielectric rods arranged in a square lattice and embedded in air on the *x*–*y* plane. In this framework, we consider two different typical corner geometries for comparison purpose: the standard sharp corner (90-I) and the relatively smooth corner (90-II) created by repositioning a single rod. Another case is a 120° bend obtained by removing one line of rods from a triangular-lattice 2D PC with infinitely long circular dielectric rods arranged in air on the *x*–*y* plane. Similarly, two different typical corner geometries are also considered in 120° bend (see 120-I and 120-II).

In all four bend models, the dielectric rod's refractive index is 3.4 and the radius of each rod is 0.18*a*, where *a* is the lattice constant. Fig. 2 shows the corresponding band structure of different lattice-type 2D PC waveguides for the TM polarization (i.e., with the electric field parallel to the dielectric rods), calculated by the MPB [17] which treats the Maxwell's wave equation as the Hermitian eigenvalue problem with the plane wave basis. The square lattice PC waveguide supports a guided mode within the frequency range of $0.312 < 2\pi c/a < 0.443$ and the triangular-lattice one exhibits a frequency range of $0.349 < 2\pi c/a < 0.473$ for fundamental defect waveguide mode.

Considering a light source located near the input of these bends, subsequently, a detector is placed in the vicinity of the bends' output in order to monitor the transmitted flux of the Poynting vector. Furthermore, the area need to be designed in each model is represented by an area with enclosed solid line and the to-be optimized variables are the radii of rods with number marked. We denote these variables as r_1, r_2, and r_3.

2.2. Problem description and design methods

If one needs to obtain a low-loss sharp bend working at a given normalized frequency ω, the optimization problem can be readily described by searching the maximum normalized transmission $T_{norm}(\omega)$, represented by the ratio between the flux of the Poynting vector on the detector near the outlet and that from input side. Hence, the objection function can be written as:

$$F_1 = \max\{T_{norm}(\omega)\} = \max\left\{\left|\frac{P_{out}(\omega)}{P_{in}(\omega)}\right|\right\} \quad (1)$$

Here, the FDTD technique is used to calculate the absolute value of $P_{out}(\omega)$ and $P_{in}(\omega)$. The FDTD is employed almost exclusively by all groups because of its simplicity in essence and ease of computational storage requirements.

For another condition, if one needs to design a sharp bend with high power transmission over almost the entire frequency range $(\omega_1, \omega_2, \ldots, \omega_i)$ in the photonic bandgap, i.e., an achromatic bend. The considered optimization problem can be described by maximizing the sum of the normalized transmission for all frequencies and the relative objection function is:

$$F_2 = \text{sum}\left\{T_{norm}(\omega_1), T_{norm}(\omega_2), \ldots T_{norm}(\omega_i)\right\} \quad (2)$$

In particular, in order to avoid time-consuming calculation for each $T_{norm}(\omega_i)$, an efficient technique [18] based on the pulse light source and fast-Fourier transform method is adopt to well tackling such dispersion problem.

Based upon these definitions, the problem can be further treated as searching the optimal variables r_1, r_2, and r_3 for maximum value of F_1 or F_2. In this study, the optimization procedure is implemented by utilizing a GA coupled to the FDTD with perfectly matched layer boundaries. This combined method has been successfully applied