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Topology Design and Fabrication of an Efficient Double 90° Photonic Crystal Waveguide Bend

J. S. Jensen, O. Sigmund, L. H. Frandsen, P. I. Borel, A. Harpøth, and M. Kristensen

***Abstract*—We have designed and fabricated a novel 90° bend in a photonic crystal waveguide. The design was obtained using topology optimization and the fabricated waveguide displays a bend loss for transverse-electric-polarized light of less than 1 dB per bend in a 200-nm wavelength range.**

***Index Terms*—Planar photonic crystals (PhCs), topology optimization, waveguide bends.**

I. INTRODUCTION

IN THIS letter, we report on the performance of a fabricated planar photonic crystal (PhC) waveguide with a new type of double 90° bend that we have designed using topology optimization.

Topology optimization is an inverse design method that allows for manipulating the distribution of material in a structure so that a quantified performance is systematically improved. The method was originally developed to obtain the layout of a limited amount of elastic material that gives the stiffest possible structure [1]. Since then, the method has been extended to a variety of applications, such as design of mechanical mechanisms, electrothermomechanical actuators, materials with prescribed properties, conduction problems, and many others [2].

PhCs based on a triangular pattern of holes in a high refractive index material, such as silicon or GaAs, display large photonic bandgaps (PBGs) for transverse-electric (TE)-polarized light [3] and are regarded as possible candidates for components in photonic integrated circuits (PICs) [4]. Thus, the possibility for improving the performance of PhCW bends and splitters has recently received a lot of attention, e.g., [5]–[8]. We have previously reported on topology optimized components, such as a 120° bend [9], a 60° bend [10], and a Y-splitter [11]. All components displayed the important characteristics of low loss and a broad-band performance.

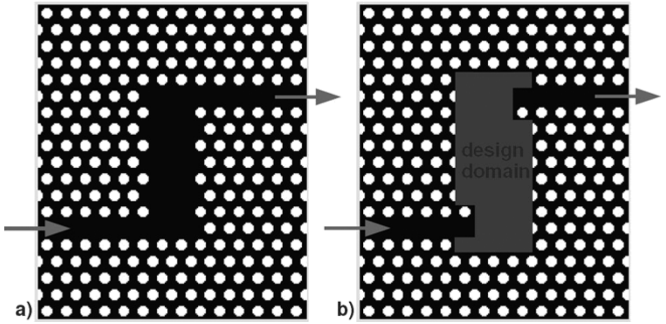

Fig. 1. (a) Initial configuration of the double 90° bend and (b) indication of the design domain where the material distribution is to be modified by the optimization algorithm.

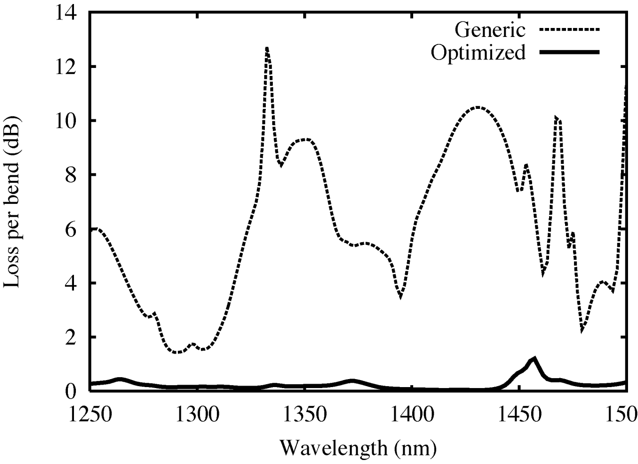

Fig. 2. Loss per bend for the initial structure (dotted) and for the final optimized structure (solid) calculated with the 2-D frequency-domain finite element solver.

Here, we report on a new type of double 90° waveguide bend, which may be used to provide an offset transition to a waveguide over a very short distance. Such a type of bend is unnatural with a triangular hole configuration due to the inherent lack of 90° symmetry and a satisfactory performance is difficult to obtain. Nevertheless, the component may be a useful supplement to the standard 60° bends if its performance can be improved. We use the initial structure shown in Fig. 1(a) as a basis for the optimization procedure. This generic structure has, as expected, a poor transmission for most wavelengths, as shown in Fig. 2. The key advantage of the topology design method is, however, that there is no geometrical restrictions on the design so the specific performance of the initial structure is of little importance. In order to improve the performance sufficiently, we must allow for the entire bend region to be modified, as indicated by the shaded area in Fig. 1(b). This approach is different from the previous applications of the method [9]–[11], where there was only a need to modify a small part of the waveguide structure. Consequently, the design that we obtain here has a very different appearance compared to conventional PhC waveguide (PhCW) structures.

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II. OPTIMIZATION

The method of topology optimization is used to modify the distribution between the dielectric and air in the designated design area shown in Fig. 1(b). The optimization algorithm is based on a two-dimensional (2-D) frequency-domain solver based on a finite element discretization that yields the following equations for TE-polarized light:

$$\mathbf{S}\left(\varepsilon^{-1}(\mathbf{r}),\omega\right)\mathbf{u}=\mathbf{f}(\omega) \tag{1}$$

in which $\mathbf{f}$ is a wave input vector, $\mathbf{u}$ is a vector containing the discretized nodal values of the out-of-plane magnetic field H_z, and $\mathbf{S}$ is the system matrix with an explicit dependence on the wave frequency ω, and the position-dependent dielectric constant $\varepsilon(\mathbf{r})$. Here, $\mathbf{r}$ is the plane position vector.

Each unit cell is discretized using 14 × 12 four-noded quadrilateral elements. This discretization is sufficient for describing the geometry satisfactorily, and for capturing the dynamic behavior with adequate accuracy. The full computational model consists of the domain shown in Fig. 1(a) as well as additional perfectly matching layers [12] and comprises in total about 115 000 elements of which 6720 are within the design domain.

A single design variable x_e is now introduced in each finite element within the design domain, and ε is assumed to be element-wise constant and to depend explicitly on x_e as follows:

$$\varepsilon_e^{-1}=1+x_e\left(\varepsilon_d^{-1}-1\right) \tag{2}$$

where

$$x_e\in R,\qquad 0<x_e<1. \tag{3}$$

Thus, we let the design variable in each element govern the material properties of the element, in such a way that if $x_e=0$, the dielectric constant of that element is one, and with $x_e=1$ it takes the value ε_d.

We use continuous design variables to allow for using a gradient-based optimization strategy. The optimization method is described in detail in [2] and [13] and will only be briefly outlined here; as the goal for the optimization algorithm, we wish to find the material distribution that maximizes the transmitted power evaluated at the output port P_{out}, which is computed based on the solution to (1). Based on the sensitivities $\partial P_{\text{out}}/\partial x_e$, computed analytically, a mathematical programming tool MMA [14] is then used to change the material distribution in an iterative process until P_{out} cannot be further improved.

Since the design variables are continuous and not discrete, the possibility for elements in the final design with values between zero and one, so-called "gray" elements, is present. This corresponds to an intermediate "porous" material which is not feasible from a fabrication point of view. Several techniques have been developed to remedy this problem [2], but here we use a method specially designed for photonic waveguides [13], in that we artificially make design variables between zero and one induce additional conduction σ_e, in the following form:

$$\sigma_e\sim\alpha x_e(1-x_e) \tag{4}$$

which enters (1) as an additional imaginary term in the system matrix $\mathbf{S}$ and causes dissipation of energy. In this way, gray elements will be "un-economical" and will, thus, be forced toward either white or black ($x_e=0$ or $x_e=1$), if the conduction parameter α is sufficiently large.

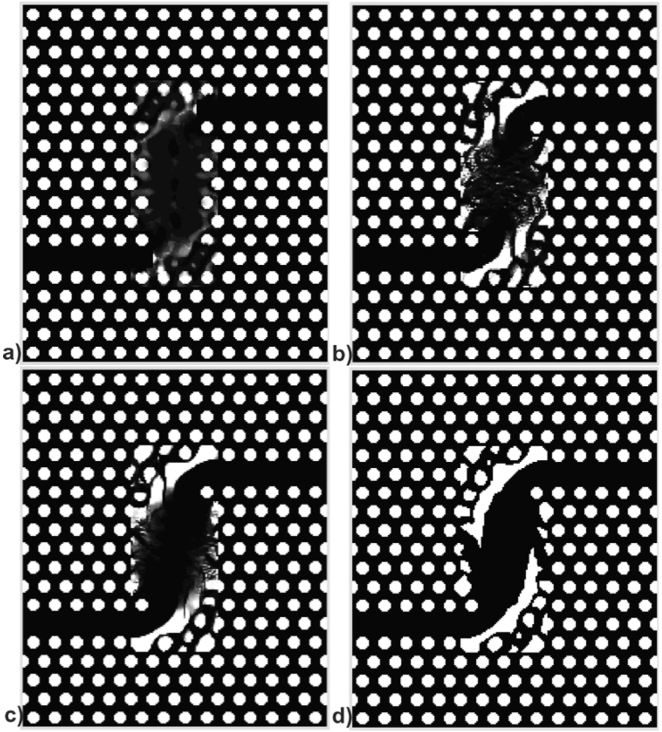

Fig. 3. Snapshots of the material distribution during the optimization process at (a) 25, (b) 1000, and (c) 2300 iterations, and (d) the final design after about 2500 iterations.

The effect is seen in Fig. 3 that shows four snapshots of the optimization iteration process. After about 1000 iterations with $\alpha=0$, the basic structure is formed [Fig. 3(b)] but many gray elements appear in the design. Then α is slowly increased and the gray elements gradually disappear as the final structure is reached in about 2500 iterations. The computation time per iteration is less than 10 s on a standard PC.

A broad bandwidth operation is ensured by maximizing the transmission through the waveguide for several frequencies simultaneously. We use a technique based on active sets [13] in which we fix a number of target frequencies in the desired frequency interval. During the optimization, these target frequencies are repeatedly changed, according to the most critical frequencies with lowest transmission. The critical frequencies are found every 10th or 20th iteration by performing a fast frequency sweep [15].

The final optimized design is seen in Fig. 3(d). This design is quite different from traditional photonic crystal structures but, nevertheless, shows a very good broad-band performance, as shown in Fig. 2, computed using the 2-D frequency-domain finite element solver.

III. FABRICATION AND CHARACTERIZATION

We have fabricated the designed waveguide structure and tested its performance. Silicon-on-insulator (SOI) is an excellent choice of material with low optical propagation loss and with future possibilities for a monolithic integration of PhC-based PICs and electronic devices. We define the PhC structures in the top silicon layer of an SOI material using

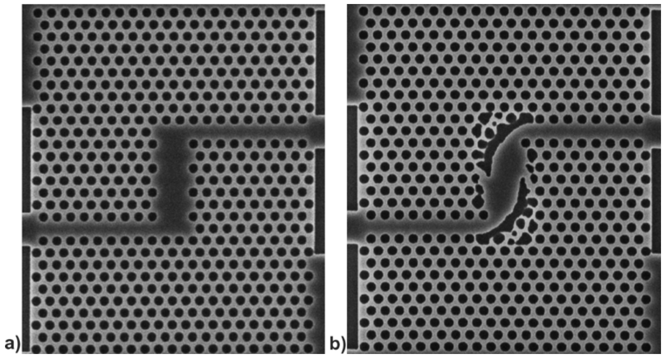

Fig. 4. (a) Fabricated generic structure and (b) the topology optimized double 90° waveguide bend.

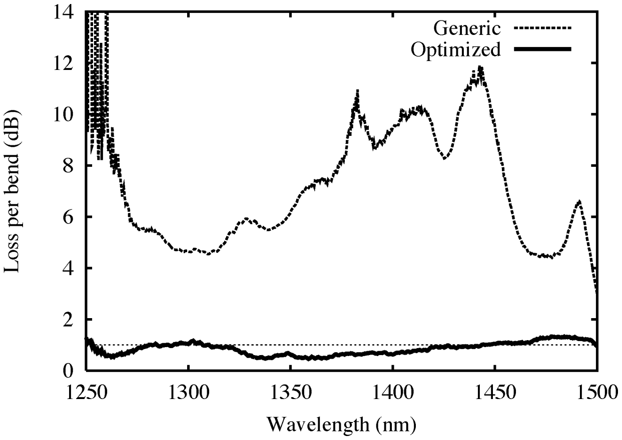

Fig. 5. Measured bend loss for the fabricated generic and optimized waveguide component.

e-beam lithography and standard anisotropic reactive-ion etch. The PhCs are defined as air holes in a triangular lattice and the PhCWs are carved out by removing a single row of holes in the nearest-neighbor direction of the crystal lattice. We use lattice pitch $\Gamma = 400$ nm, diameter of the holes $D = 275$ nm, and thickness of the Si–SiO$_2$ layers 340 nm/1 μm. This configuration displays a broad PBG below the silica-line from 0.2592 to 0.3436 (normalized frequency) and allows TE-polarized single-mode propagation in the PhCWs. The fabricated topology-optimized structure is shown in Fig. 4(b) and it nicely resembles the designed structure [Fig. 3(d)].

The fabricated PhCWs were optically characterized using broad-band light-emitting diodes (LEDs) as sources. Three different LEDs centered around 1310, 1414, and 1538 nm were used to cover the full bandwidth of the fabricated components and tapered lensed fibers were used to couple light in and out of the ridge waveguides connected to the PhCWs. Two polarization controllers and a polarizer with an extinction ratio better than 35 dB were used to control the polarization of the light sent into the device. The optical spectra for the transmitted light were recorded with a spectral resolution of 10 nm using an optical spectrum analyzer. To extract the bend loss, the transmission spectra have been normalized to the transmission spectrum for a straight PhCW of similar length. Fig. 5 shows the measured bend loss of TE-polarized light for the generic structure and the topology-optimized structure. A transmission loss of <1 dB/bend is obtained for the wavelength range 1250–1450 nm.

IV. CONCLUSION

We have used the method of topology optimization to design a double 90° bend in a photonic crystal waveguide based on a triangular configuration of air holes. The waveguide was fabricated in SOI and showed a very low bend loss for TE-polarized light of less than 1 dB per bend in a broad wavelength range of 200 nm.

The fabricated device adds to the existing collection of high-performance photonic crystal building blocks that display low-loss over a broad wavelength. The good performance makes these components natural parts of the realization of PICs based on photonic crystals.

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