Optimized planar photonic crystal waveguide 60° bend with more than 200 nm wide 1-dB transmission bandwidth

Kristensen, Martin; Borel, Peter Ingo; Frandsen, Lars Hagedorn; Harpøth, Anders; Jensen, Jakob Søndergaard; Sigmund, Ole

Published in:
Optical Fiber Communication Conference, 2005. Technical Digest. OFC/NFOEC

Publication date:
2005

Document Version
Publisher's PDF, also known as Version of record

Citation (APA):
Kristensen, M., Borel, P. I., Frandsen, L. H., Harpøth, A., Jensen, J. S., & Sigmund, O. (2005). Optimized planar photonic crystal waveguide 60° bend with more than 200 nm wide 1-dB transmission bandwidth. In *Optical Fiber Communication Conference, 2005. Technical Digest. OFC/NFOEC* IEEE.

Optimized planar photonic crystal waveguide 60° bend with more than 200nm wide 1-dB transmission bandwidth

M. Kristensen*, P.I. Borel, L.H. Frandsen, A. Harpøth
Research Center COM, Technical University of Denmark, Building 345 west, DK-2800, Kgs. Lyngby, Denmark
mk@com.dtu.dk, pib@com.dtu.dk, lhf@com.dtu.dk, harpoeth@com.dtu.dk
**Future address: Department of Physics and Astronomy, Aarhus University, DK-8000, Aarhus C, Denmark*

J.S. Jensen, O. Sigmund
Department of Mechanical Engineering, Technical University of Denmark, DK-2800 Kgs. Lyngby, Denmark
jsj@mek.dtu.dk, sigmund@mek.dtu.dk

Abstract: Topology optimization was used to design a planar photonic crystal waveguide 60° bend leading to a record-breaking transmission bandwidth of more than 200nm. The experimental results agree well with 3D finite-difference-time-domain simulations.

OCIS codes: (230.7390) Planar waveguides; (220.4630) Optical systems design; (230.3990) Microstructures devices; (220.4610) Optical fabrication; (230.5440) Polarization-sensitive devices; (999.9999) Photonic crystals

1. Introduction

The recent progress in the design of planar photonic crystal waveguides (PCWs) has paved the way for exploitation of low-loss propagation in 2D-patterned PCWs and devices [1,2]. Often, the holes in the planar photonic crystal (PC) are arranged in a triangular pattern as this arrangement may provide a large photonic bandgap for TE polarized light [3]. However, the useful bandwidth (~30nm) of practical waveguide devices is usually at least one order of magnitude smaller than the bandgap. Thus careful designing, tolerant to fabrication deviations, is very important to utilize the full bandgap of the PC. In our previous work [2], we have used topology optimization based on 2D finite-element calculations to optimize the performance of two consecutive 120° bends. Here, we show that the same method is applicable to the much more important and commonly used 60° bend and we have realized an experimental 1-dB transmission bandwidth of more than 200nm. Experimental transmission spectra are also compared to spectra obtained from three-dimensional finite-difference-time-domain (3D FDTD) calculations [4] and good agreement is found.

2. Fabrication and characterization

The PC structures have been fabricated in a Silicon-On-Insulator (SOI) material by arranging air holes with diameter D = 275nm in triangular arrays with lattice constants around Λ = 400nm. E-beam lithography was used for the patterning and reactive ion etching transferred the pattern to the 340nm thick top silicon layer of the SOI wafer. The PCWs were defined by removing single rows of holes in the nearest-neighbor direction of the photonic crystal as shown in Fig. 1.

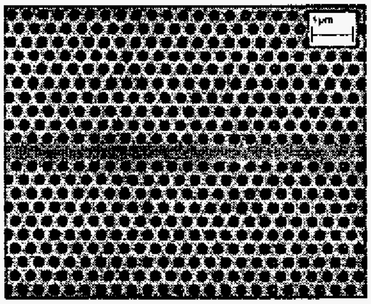

Fig. 1. Scanning electron micrograph of a straight PCW.

For each component and reference waveguide we used ridge waveguides, gradually tapered from a width of 4μm at the sample facet to 1μm at the PC interface for routing the light to and from the PCWs.

The fabricated PCWs have been characterized using the setup sketched in Fig. 2. To cover the full bandwidth of the fabricated components we used three different broadband light emitting diodes centrered around 1310nm, 1414nm, and 1538nm. Tapered lensed fibers are used to couple light in and out of the ridge waveguides connected to the PCWs. Two polarization controllers and a polarizer with an extinction ration better than 35 dB are used to control the polarization of the light sent into the device under test. The optical spectra for the transmitted light are recorded with a spectral resolution of 10nm using an optical spectrum analyzer.

Fig. 2. Experimental setup used to characterize the photonic crystal waveguide components.

3. Topology optimization

In the field of planar photonic crystals, research has within the last decade relied on an Edisonian design approach where human inspiration has been followed by experimental verification. Further optimizations have typically been done in an iterative trial-and-error procedure to improve a chosen performance measure of the PhC component [5]. Such an approach is very time-consuming and does not guarantee acceptable solutions. In contrast, the integrated electronic circuits have undergone an evolutionary development during the last couple of decades and design problems are, today, addressed as mathematical inverse problems that secure optimized and functional designs. A systematic design method based on topology optimization has been developed and allows creation of improved PC components with previously unseen low transmission losses and high operational bandwidths. The method was originally developed for structural optimization problems but has recently been extended to a range of other design problems [2,6]. The method is based on repeated 2D finite-element analyzes where the distribution of material is iteratively modified in order to improve a chosen performance measure. The resulting designs are inherently free from geometrical restrictions, thereby allowing the large potentials of PC components to be exploited to hitherto unseen levels. The topology-optimized components can freely be used as individual building blocks to assemble integrated photonic circuits.

4. Results and discussion

Fig. 3 shows scanning electron micrographs (SEMs) of fabricated PCWs containing two consecutive un-optimized (left) and topology-optimized (right) 60° bends. Fig. 4 shows the measured loss of TE polarized light for the un-optimized (gray curve) and the topology-optimized (black curve) 60° bend.

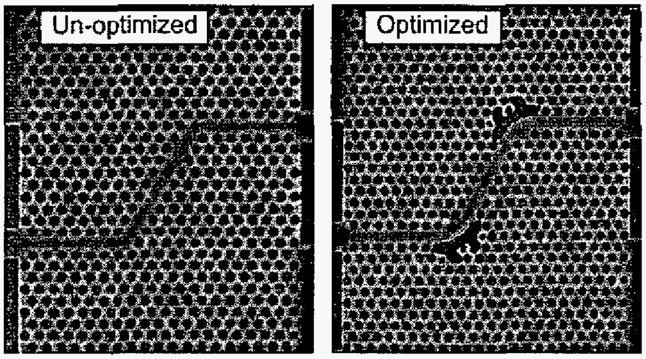

Fig. 3. Scanning electron micrograph of a photonic crystal waveguide with two un-optimized 60° bends (left) and two topology-optimized 60° bends (right).

The optimized bend displays a more than 200nm bandwidth with a bend loss below 1 dB, thus the performance of the optimized bend compares favorably to the transmission through an un-optimized 60° bend consisting of two butt-coupled PCWs.

Fig. 5 shows a detailed comparison between the measured and calculated loss of the optimized bend. A good agreement is found between the experimental and theoretical results. The 3D FDTD spectrum has been shifted 1.2% in absolute wavelength and slightly undershoots the experimental values. These deviations are partly due to uncertainties in the experimental hole diameters, but more importantly due to the limited grid resolution in the calculations [4].

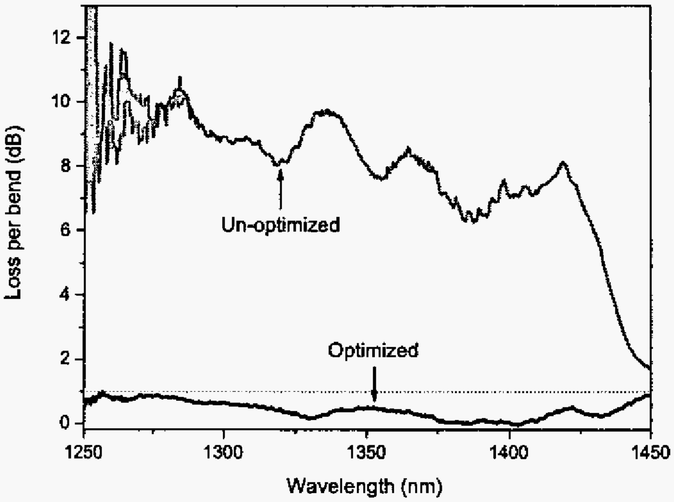

Fig. 4. Measured loss per bend for the un-optimized 60° bends (gray) and the optimized 60° bends (black). Both spectra have been normalized to the transmission through straight PCWs to eliminate coupling and propagation loss in straight waveguides. Dotted line marks a bend loss of 1dB.

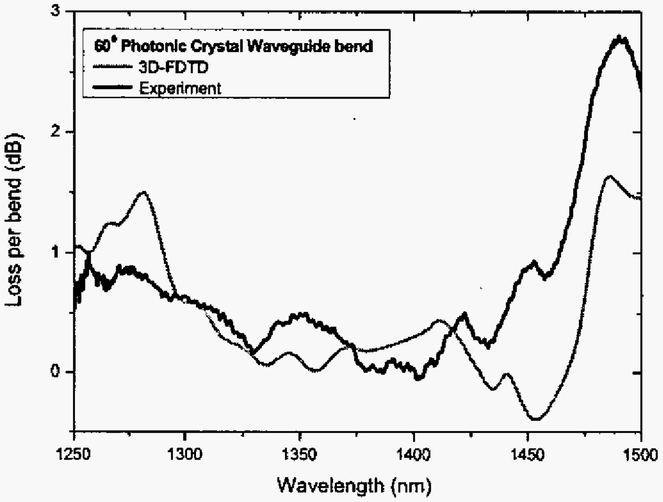

Fig. 5. Experimental bend loss (black) compared to 3D FDTD calculated loss (gray, shifted 1.2% in absolute wavelength).

5. Summary

We have optimized the performance of 60° planar photonic crystal waveguide bends using topology-optimization and obtained a record high 1-dB transmission bandwidth exceeding 200nm. The experimental transmission properties have been investigated and compared to 3D FDTD calculations. The experimental results agree well with the numerical simulations.

6. References

[1] S.J. McNab, N. Moll and Y.A. Vlasov, "Ultra-low loss photonic integrated circuit with membrane-type photonic crystal waveguides", Optics Express **11**, 2927-2939 (2003).

[2] P.I. Borel, A. Harpøth, L.H. Frandsen, M. Kristensen, P. Shi, J.S. Jensen and O. Sigmund, "Topology Optimization and fabrication of photonic crystal structures", Optics Express **12**, 1996–2001 (2004).

[3] T. Søndergaard, J. Arentoft and M. Kristensen, "Theoretical analysis of Finite-height semiconductor-on-insulator-based planar photonic crystal waveguides,"J. Lightwave Technol. **20**, 1619-1626 (2002).

[4] A. Lavrinenko, P.I. Borel, L.H. Frandsen, M. Thorhauge, A. Harpøth, M. Kristensen and T. Niemi, "Comprehensive FDTD Modelling of Photonic Crystal Waveguide Components", Optics Express **12**, 234-248 (2004).

[5] P.I. Borel, L.H. Frandsen, A. Harpøth, J.B. Leon, H. Liu, M. Kristensen, W. Bogaerts, P. Dumon, R. Baets, W. Wiaux, J. Wouters, S. Beckx, "Bandwidth tuning of photonic crystal waveguide bends", To appear in *Electron. Lett.* (2004).

[6] M. P. Bendsøe and O. Sigmund, Topology optimization — Theory, Methods and Applications (Springer-Verlag, 2003).