# Topology optimization and fabrication of photonic crystal structures

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**Abstract:** Topology optimization is used to design a planar photonic crystal waveguide component resulting in significantly enhanced functionality. Exceptional transmission through a photonic crystal waveguide Z-bend is obtained using this inverse design strategy. The design has been realized in a silicon-on-insulator based photonic crystal waveguide. A large low loss bandwidth of more than 200 nm for the TE polarization is experimentally confirmed.



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## 1. Introduction

The planar photonic crystal (PhC) is an optical nano-material with periodic modulation of the refractive index. The modulation is designed to forbid propagation of light in certain wavelength ranges, so-called photonic bandgaps (PBGs) [1-3]. Breaking the crystal symmetry by introducing line defects and other discontinuities allows control of the light on a sub-wavelength scale in the PhCs. Therefore, photonic devices based on the PBG effect may be up to one million times smaller than traditional integrated optical devices. PhC structures with 20-40 nm useful optical bandwidths have previously been demonstrated [4-6]. Until now, however, no bandgap-based PhC components have been demonstrated with satisfactory performance in a broad wavelength range. A major reason for this has been the lack of efficient inverse design tools that can be applied irrespectively of the device under consideration. Therefore, most PhC design structures today are obtained either by intuition or by varying one or two design parameters—typically the position or size of a PhC element—using the trial-and-error method.

In this paper we show exceptional transmission through a Z-bend consisting of two successive 120° PhC waveguide bends. The design of the bends is obtained using an efficient inverse design strategy called *topology optimization*. The optimized design is experimentally realized in a silicon-based PhC. Measurements have confirmed a large low-loss bandwidth of more than 200 nm for TE polarized light.

## 2. Topology optimization

The systematic design method based on topology optimization allows creation of improved PhC components with previously unseen low transmission losses and high operational bandwidths, or with wavelength selective functionalities. The method was originally developed for structural optimization problems [7], but has recently been extended to a range of other design problems [8]. The method is based on repeated finite element analyses where the distribution of material in a given design area is iteratively modified in order to improve a chosen performance measure. The resulting designs are inherently free from geometrical restrictions such as the number of holes, hole shapes etc., thereby allowing the large potentials of PhC components to be exploited to hitherto unseen levels. Previously reported optimization tools for such components have all been restricted to deal with circular holes [9-11].

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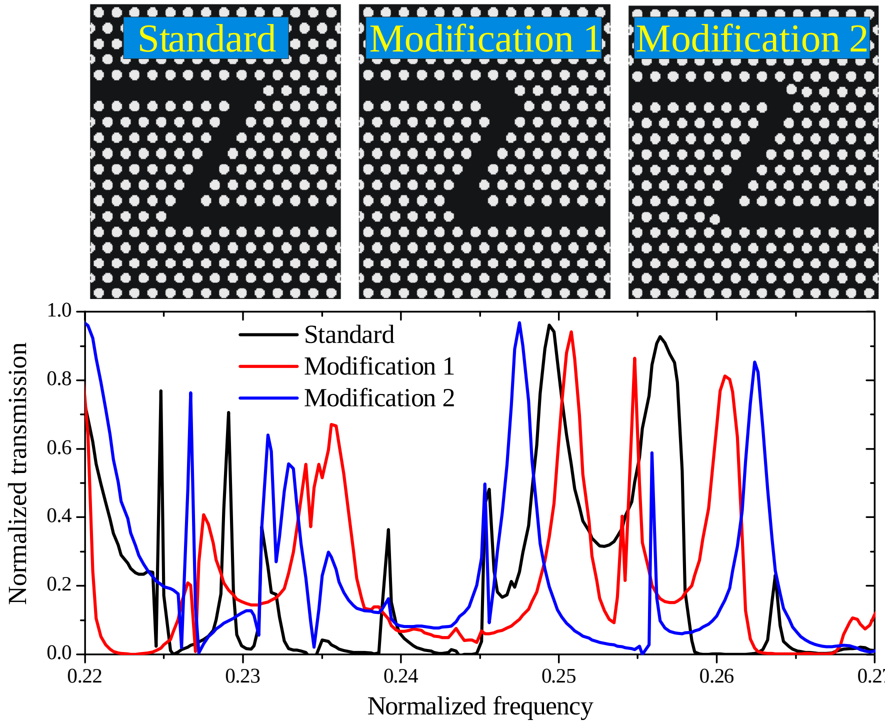


Fig. 1. Top: Standard and two modified Z-bend waveguides. Bottom: Transmission through the bends calculated using a 2D frequency domain finite element model.

To demonstrate the method, we have designed and fabricated an optimized PhC Z-bend consisting of two successive 120° waveguide bends [12]. The un-optimized Z-bend displays high bend losses except in narrow frequency bands. Although a Z-bend PhC may have limited practical applicability, it is a difficult and challenging design problem that serves as an excellent benchmark for our method. Intuitive attempts to improve the design by removing or displacing single holes in the bends do usually not lead to significant reduction of the bend loss as indicated in Fig. 1. Larger bandwidth with high transmission has previously been predicted for two 120° bends by displacing a larger number of holes [13], but this procedure is very time-consuming and does not guarantee acceptable solutions.

We base our optimization procedure on a 2D frequency domain finite element model of the waveguide [14] and choose the outer parts of the two bend regions as design areas wherein the material distribution should be modified (see Fig. 2, Left).

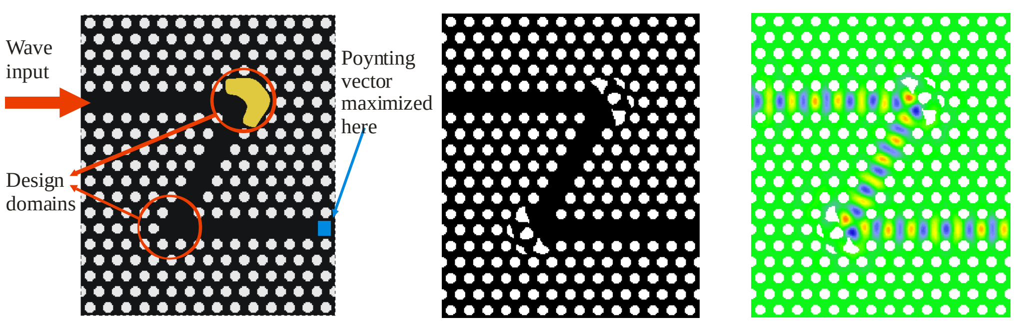


Fig. 2. Left: Schematic illustration of the topology optimization procedure. The yellow area sketches the design domain of one bend. Middle: (149 kB) Movie of how the material is redistributed in the design domain in the optimization procedure. In about 600 iteration steps a final design is obtained that has optimized transmission properties. Right: (482 kB) Movie of TE polarized light propagating through the topology optimized Z-bend.

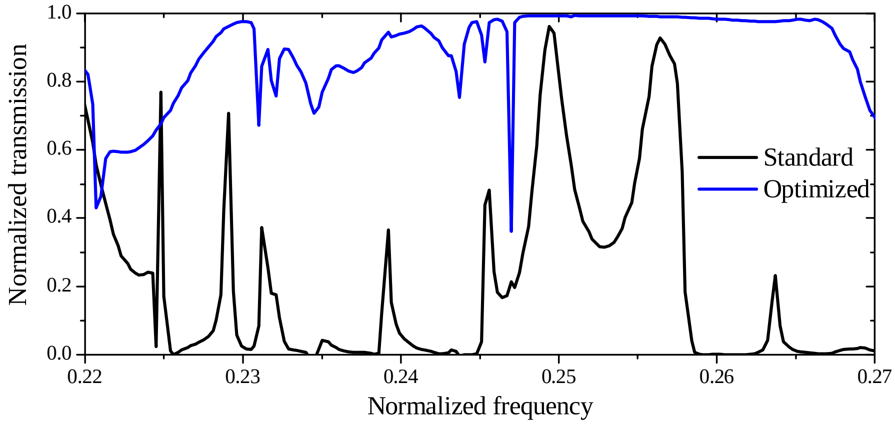


Fig. 3. The transmission for TE polarized light through the un-optimized (standard) design (black) and the optimized design (blue). The transmission spectra are based on a 2D frequency domain finite element model.

Although we could have chosen much larger design areas, the numerical experiments showed that relatively small design areas were enough to yield the wanted improvement in efficiency. Had the efficiency been unsatisfactory, the design areas could have been enlarged in order to introduce more freedom in the design. In order to reduce the bend loss we choose the transmitted energy flow (Poynting vector) through the Z bent waveguide to be maximized (see Fig. 2, left). Relatively short inlet, 120 degree and outlet channels were chosen for CPU time reasons. However, the results have been numerically verified to be insensitive to larger channel lengths.

During the iterative optimization procedure the material distribution is changed based on analytical sensitivity analysis combined with the use of a mathematical programming tool [15]. For more information regarding the procedure we refer to Ref. [16] dealing with optimization of a 90° bend in a pillar-based waveguide. More details regarding sensitivity analysis etc. can be found in Ref. [17] where *phononic* bandgap materials and structures are optimized.

The optimization can be performed for any number of frequencies simultaneously, also with min-max (or max-min) formulations. In the case of the Z-bend we find that the use of a single frequency in the optimization is sufficient to produce a large bandwidth with low loss. The algorithm is run on a personal computer requiring about 5 s per iteration and around 600 iteration steps to reach a converged design.

Figure 2 shows the optimized design along with the iterative material re-distribution in the design domains (middle) and the resulting wave propagation through the optimized waveguide (right). In Fig. 3 the transmission through an un-optimized (black) and an optimized (blue) Z-bend is shown. It is noticed how the operational bandwidth is dramatically improved by applying topology optimization to the design.

## 3. Fabrication and characterization

The PhC Z-bend has been fabricated in silicon-on-insulator material utilizing e-beam lithography (JEOL JBX-9300FS). The written patterns were transferred into the approximately 300 nm thick top silicon layer employing standard anisotropic reactive-ion etch as described in Ref. [18]. The Z-bend waveguide is realized in a triangular lattice of holes by removing rows of nearest-neighbor holes. The lattice constant Λ=430 nm and the diameter of the holes D=260 nm. A scanning electron micrograph of the fabricated Z-bend is shown in Fig. 4.


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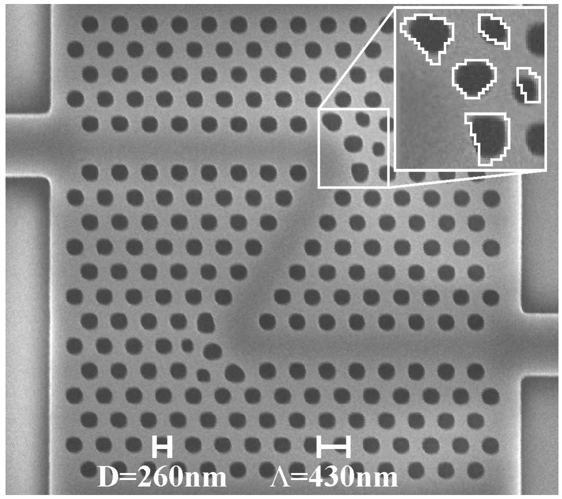


Fig. 4. Scanning electron micrograph of the fabricated Z-bend. The number, shape and size of the holes at each bend are designed using topology optimization. The inset shows a magnified view of the optimized holes as designed (white contour) and actually fabricated.

The e-beam was slightly defocused during the lithography process due to imperfect filament conditions. Corrections to compensate for this deficiency were undertaken by appropriate modifications of the design files. Due to the finite e-beam spot-size, the fabricated structure is slightly different from the optimized design as shown in the inset. No special proximity corrections were applied for the irregular shaped holes.

The fabricated components were characterized using the setup sketched in Fig. 5. Tapered lensed fibers were used to couple light in and out of the ridge waveguides connected to the PhC waveguides. The light sources were broadband light emitting diodes. Three polarization controllers and two polarizer crystals with extinction ratios better than 35 dB were used to control the polarization of the in-coupled light and to analyze the transmitted light from the device under test. The optical spectra for the transmitted light are recorded using an optical spectrum analyzer with a 10 nm resolution (ANDO AQ6315E).

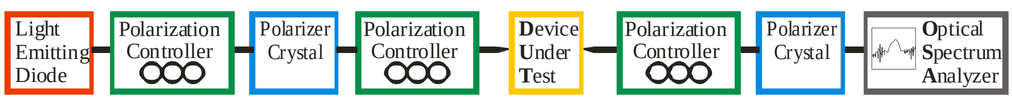


Fig. 5. Experimental setup used to characterize the waveguide samples.

## 4. Experimental results

The measured loss per bend for TE polarized light sent through the fabricated Z-bend is shown in Fig. 6. The measured transmission spectrum has been normalized to a transmission spectrum for a straight PhC waveguide of the same length. The polarization of the light transmitted through the device containing the Z-bend was analyzed and found to be purely TE polarized. Hence, no significant TE-TM coupling is introduced by the Z-bend.

Also shown in the figure are the calculated losses, obtained by employing 3D finite-difference time-domain (FDTD) calculations [19], for the fabricated and the un-optimized Z-bend. These spectra have also been normalized to spectra for straight PhC waveguides of the same length. The calculated FDTD spectra have been blue-shifted ~4% in wavelength.

The most prominent feature of the spectra is the extremely broad wavelength range of more than 200 nm having a low bend loss of just above ~1 dB. This is to the best of our knowledge by far the largest bandwidth with low bend loss demonstrated for the TE polarization in a PhC waveguide. Without topology optimization 3D FDTD calculations show up to ~10 dB higher loss per bend.

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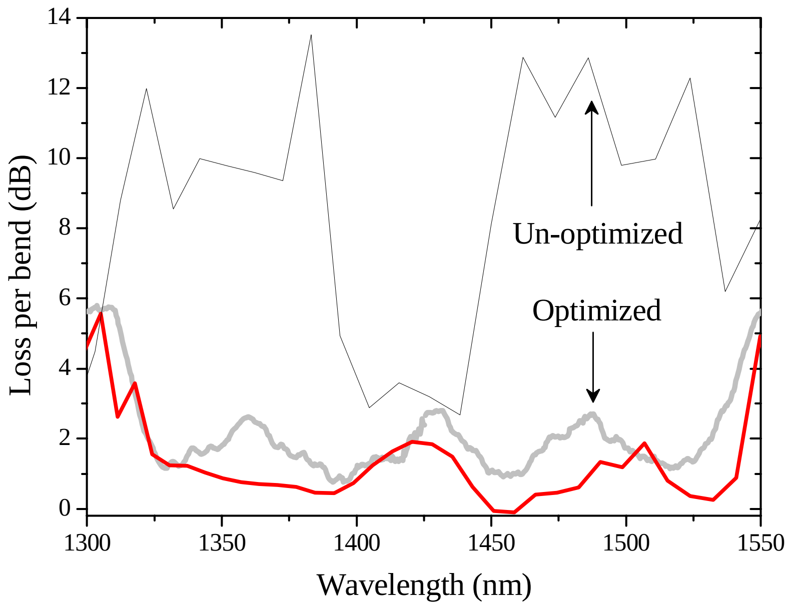


Fig. 6. The measured (gray) and 3D FDTD calculated (red) loss per bend for TE polarized light in the fabricated structure. Also shown is the 3D FDTD calculated bend loss for the un-optimized (black) Z-bend.

It is worth noting that the low bend loss is obtained experimentally even though the fabricated structure deviates slightly from the optimized design shown in Fig. 2 (middle). This fact proves the robustness of the design for experimental fabrication tolerances. Using the min-max formulation, this robustness may also hold for other applications.

**5. Conclusion**

We have reported the successful experimental realization of a planar photonic crystal component with functionalities that have been enhanced using the inverse design strategy *topology optimization*. As an example application of this new method we have chosen to design and fabricate a topology optimized photonic crystal bend consisting of two successive 120° waveguide bends.

The optimized photonic crystal waveguide Z-bend has experimentally been found to display a low bend loss of just more than ~1 dB in a broad wavelength range of more than 200 nm for the TE polarization. The design is proven robust regarding fabrication tolerances. We believe topology optimization can be used as a general inverse design tool to design a wide range of photonic crystal waveguide components irrespectively of the device under consideration.

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