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# Quantitative analysis of bending efficiency in photonic-crystal waveguide bends at $\lambda$=1.55$\mu$m wavelengths

**Edmond Chow, S.Y. Lin, and J.R. Wendt**

*MS 0603, Sandia National Laboratories, P.O. Box 5800, Albuquerque, NM 87185*

**S.G. Johnson and J.D. Joannopoulos**

*Dept. of Physics, Massachusetts Institute of Technology, Cambridge, MA 02139*

**Abstract**

Based on a photonic-crystal slab structure, a 60-degree photonic-crystal waveguide bend has been successfully fabricated. Intrinsic bending efficiency ($\eta$) within the photonic band gap was measured, and a near 100% efficiency was observed at certain frequencies near the valence band edge. The bending radius was ~1$\mu$m at a wavelength of $\lambda$~1.55$\mu$m. The measured $\eta$ spectrum also agreed well with a finite difference time domain simulation.

# DISCLAIMER

The compact and low-loss optical waveguide bend is a key component for building future integrated photonic circuits. The conventional dielectric waveguide bend is limited by the critical angle of total internal reflection. Therefore, the typical curvature radius of a conventional waveguide bend operating at $\lambda$~1.55μm has to be about 1mm [1] to avoid significant bending loss. Photonic crystal [2], on the other hand, can in principle [3,4]offer a much more compact way (with ~1μm curvature radius) to bend light efficiently. By introducing a properly designed line defect in a photonic-crystal structure, the guiding band can be created within the photonic band gap. Light will therefore be forced to propagate along the line defect by the photonic band gap (PBG) effect.

An early experiment [5] showed that the compact, low-loss bending of light in the millimeter $\lambda$ is possible using a two-dimensional (2D) post array. The 2D post has a large aspect ratio (e.g., 1:50) in the third direction and thus approximates an ideal 2D system. At optical $\lambda$, however, such an ideal 2D structure is more difficult to fabricate [6]. Recently, a new type of photonic crystal slab structure was proposed [7] and experimentally [8] realized in the optical $\lambda$. The slab structure requires only the fabrication of shallow 2D pillars or holes, yet it confines light in the 2D plane by a photonic band gap and vertically by index guiding. As a result, it is ideal for realizing PBG-bends in the optical $\lambda$. Previous experimental work [9,10] has qualitatively indicated that light may be guided around a PBG-bend. In this letter, we report a quantitative analysis of light bending at $\lambda$~1.55μm using a PBG-bend. A near 100% intrinsic bending efficiency is experimentally observed at certain frequencies near the valence band edge. The corresponding bending radius is as small as ~1μm.

The photonic-crystal sample consists of a triangular array of cylindrical air holes etched through a thin GaAs slab. The GaAs slab is sandwiched between a 2μm $Al_xO_y$ and a 0.1μm $SiO_2$

as shown in Fig. 1. The $Al_xO_y$ is converted from $Al_{0.9}Ga_{0.1}As$ by using wet oxidation. The depth of etched holes is ~0.6μm, and their sidewalls are straight to within 5 degree. The photonic crystal is designed to have the hole diameter $d$=0.6$a$ and the slab thickness $t$=0.5$a$, where $a$ is the lattice constant. Previous measurement [8,11] and calculation [7] have shown that such photonic-crystal structure has a large TE photonic band gap. For this reason, all the data reported here is measured with TE polarization input light. To obtain a photonic band gap around λ~1.55μm, a set of samples with $a$=410-460nm is fabricated using direct write electron beam lithography (with nominal resolution of 2.5nm) and reactive ion beam etching.

A 60-degree photonic-crystal waveguide bend is created by removing one row of holes along two ΓK symmetry directions as shown in Fig. 2a. We have made two 60-degree bends to form a double-bend device such that the input and output light are parallel to each other to simplify the measurement setup. Two 60-degree bends are separated by 16 periods of photonic-crystal waveguide to ensure that there is no coupling effect between each individual bend. A 0.5mm-long conventional ridge waveguide on each side is used for coupling light in and out of the photonic-crystal waveguide. The ridge waveguides are designed to have a lateral width of $\sqrt{3}a$ to match the modal extend of photonic-crystal waveguide.

To obtain the intrinsic bending efficiency (η), we perform an in-plane transmission measurement on samples with $a$=410, 430, 440, 450, and 460nm. Three diode laser modules with tuning range λ=1.29-1.35μm, λ=1.525-1.595μm, and λ=1.625-1.68μm are used. This combination allows for a complete mapping of η within the whole photonic band gap. Transmission is measured by focusing a TE polarized collimated laser beam into the input ridge waveguide with a microscope objective lens. A calibrated InGaAs detector is then used to measure the transmitted power from the output ridge waveguide. An infrared camera is also used to monitor the modal profile of the output light to ensure that only the signal of waveguiding mode is fed into the detector. A more detailed measurement setup has been described in Refs. [8]. Two transmission spectra are taken with (1) a double-bend device ($T_1$ shown in Fig.2a) and (2) a straight photonic-crystal waveguide of the same length (42 periods) as the double-bend device ($T_2$ shown in Fig2b). The raw data are first digitally smoothed to remove the periodic Fabry-Perot resonance peaks with wavelength spacing $\Delta\lambda$~0.5nm, which can be readily attributed to the resonance between the end facet and the photonic crystal. From the smoothed data, the intrinsic bending efficiency of a single bend is then given by $\eta = \sqrt{T_1 / T_2}$ .

In Fig. 3, the measured $\eta$ is plotted as function of frequency $\omega$ in reduced unit $a/\lambda$. Different color symbols represent data taken from samples with five different $a$'s, as labeled in Fig. 3. The two dashed lines represent valence band (VB) edge at $\omega$=0.255 and conduction band (CB) edge at $\omega$=0.325, respectively. The band-edge positions are obtained from previous measurements [11] on the same photonic-crystal structure without line defect. The slight mismatch among data taken with different $a$'s is within our ±10% experimental error because of the uncertainty in free-space to ridge waveguide coupling efficiency. The measured $\eta$ shows a clear maximum value of ~100% at $\omega^{max}$=0.272, which is near the VB edge. This $\omega$ (=a/$\lambda$) corresponds to a $\lambda$= 1585nm and a=430nm. The bending efficiency has a narrow bandwidth, i.e. $\Delta\omega$~0.05 for $\eta$ > 80%. To the best of our knowledge, this is the first experimental observation of a near perfect PBG-bend at $\lambda$~1.55μm.

Also shown in Fig. 3 is the calculated $\eta$ (black curve) obtained by finite difference time domain (FDTD) simulation on the same structures shown in Fig. 2. The numerical simulation consisted of sending a Gaussian input pulse (with center $\omega$=0.3) into the input waveguide and measuring the flux in the output waveguide. The computed $\eta$ is obtained with the same normalization procedure as in the experimental measurement described above. The calculated peak position, with no adjustable parameters, is at $\omega$=0.277, which agrees with the observed value to within 3%. The simulation also correctly predicts the detail $\eta$ spectral line shape. In particular, the predicted bending band-width for $\eta > 80\%$ is also $\Delta\omega \sim 0.05$.

The observed high bending efficiency at $\omega^{max}=0.272$ may be associated with one of the guiding modes of the straight PBG-guide. Fig. 4 shows the computed guiding mode dispersion ($\omega$ versus k) along ΓK direction, obtained by a full 3D calculation [7,12]. The CB, VB, and lightcone regions are indicated with shaded lines. The three guiding modes are labeled [13]as $p_x$ (red circles), $p_y$ (blue squares), and $d_{xy}$ (black triangles). The $p_x$ mode has a even symmetry, and the $p_y$, and $d_{xy}$ modes have an odd symmetry with respect to the *x-z* mirror plane (defined in Fig. 1) bisecting the PBG-guide. It is noted that the $p_x$ mode is at $\omega \sim 0.275$, which agrees well with $\omega^{max}$. The predicted flat dispersion, with a bandwidth of $\Delta\omega \sim 0.05$, is also consistent with the observed narrow bandwidth. These agreements indicate that it is the $p_x$ guiding mode that gives a high bending efficiency around the 60-degree bending corner.

While we have demonstrated that a PBG-bend can bend light efficiently in a very compact way, two important unsolved issues need to be addressed. First, the flat $p_x$ dispersion creates a large modal dispersion mismatch between a ridge waveguide and a PBG-guide [14]. This mismatch, in turn, reduces the light input coupling efficiency. Second, the flat dispersion has also caused a very narrow guiding bandwidth for the PBG-bend. We would like to point out that a much wider bandwidth is observed for the straight PBG-guide in our experimental measurement and FDTD simulation. In both cases, we found that the guiding bandwidth for the straight PBG-guide almost covers the entire band gap. The exact reason for it is not known. Since both $p_y$ and $d_{xy}$ modes have an odd symmetry, they should not couple to the incoming laser light, which has a Gaussian-like even symmetry. However, it is possible that light can be guided by the $p_x$ guiding modes above the lightcone boundary, which extend much further into the gap. Such leaky guiding modes may be more susceptible to the radiation loss and therefore cannot be guided in the PBG-bend.

In summary, we report experimental demonstration of high bending efficiency ($\eta$~100%) in a compact PBG-bend at $\lambda$~1.55μm. This work demonstrates the great potential of using photonic-crystal waveguide to connect different optical components in a much more compact way than the conventional dielectric waveguide.

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13. The guiding modes are labeled as $p_x$, $p_y$, and $d_{xy}$ because the field distributions around the line-defect are very similar to the corresponding electronic states in atomic orbitals. See Ref. [12] for more detailed analysis of the field distribution.
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**Figure Caption**

Figure1. A cross-section SEM view of a photonic crystal waveguide integrated with a ridge waveguide.

Figure 2a. A top view of a double-bend device with two 60-degree bends indicated by two circles.

Figure 2b. A top view of a 42-periods straight PBG waveguide.

Figure 3. Intrinsic bending efficiency ($\eta$), plotted as function of $\omega(a/\lambda)$ within the photon band gap. Different symbol colors represent data taken with different $a$'s

Figure 4. Computed dispersion of the photonic-crystal waveguide. Three guiding modes are represented by different symbols. The conduction band (CB), valence band (VB), and lightcone regions are indicated as shaded lines.

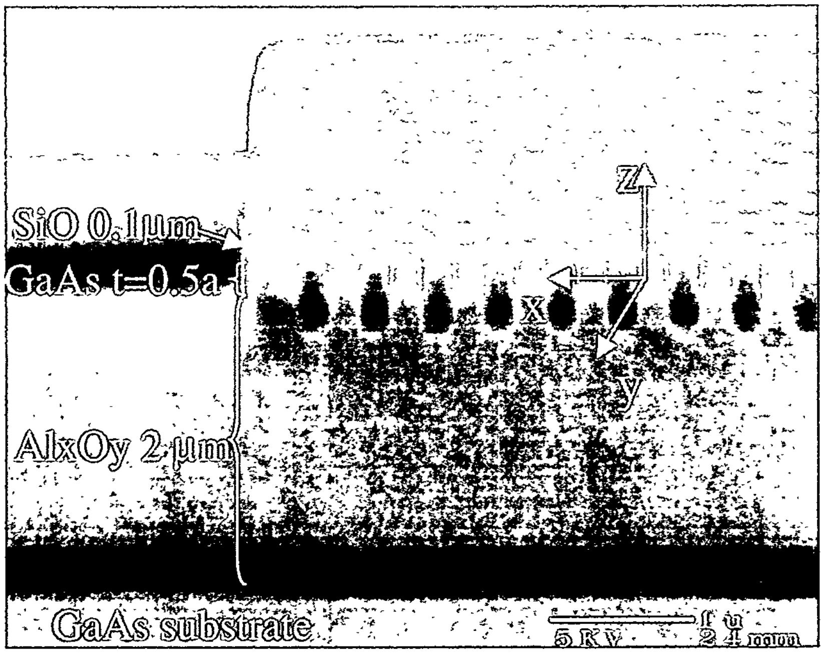



Fig.1

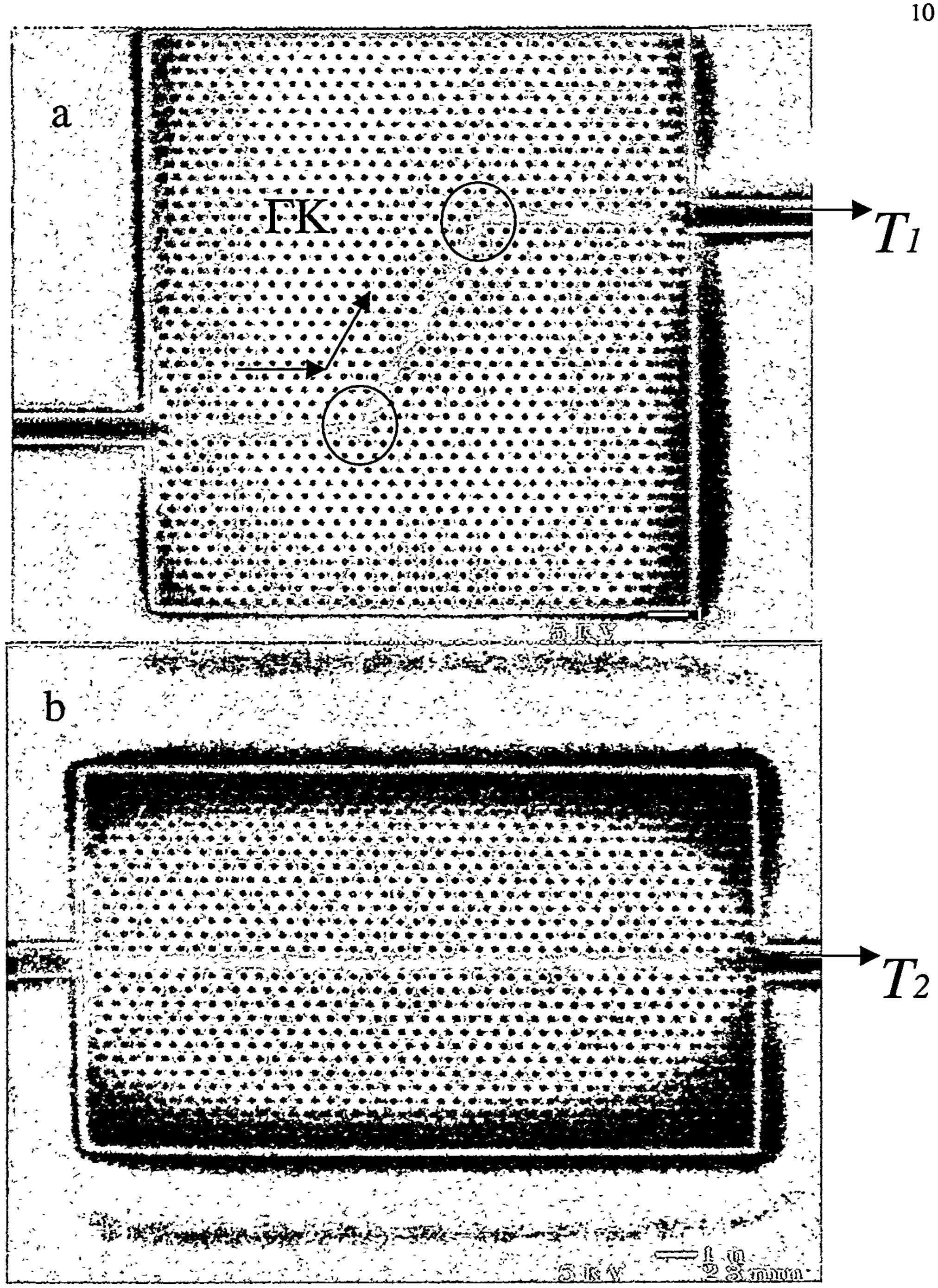
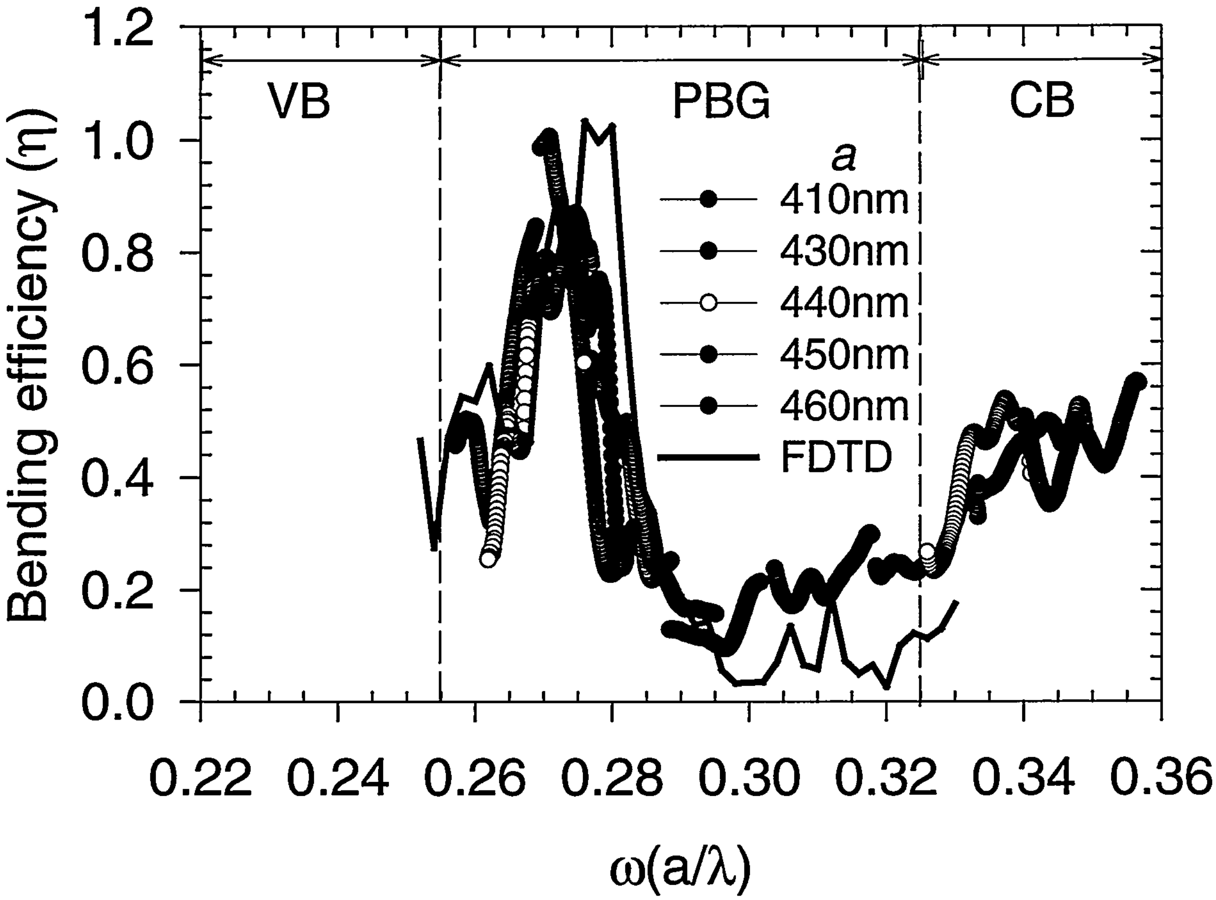



Fig.2



1.2
1.0
0.8
0.6
0.4
0.2
0.0
Bending efficiency (η)
VB
PBG
CB
a
410nm
430nm
440nm
450nm
460nm
FDTD
0.22 0.24 0.26 0.28 0.30 0.32 0.34 0.36
ω(a/λ)


Fig. 3

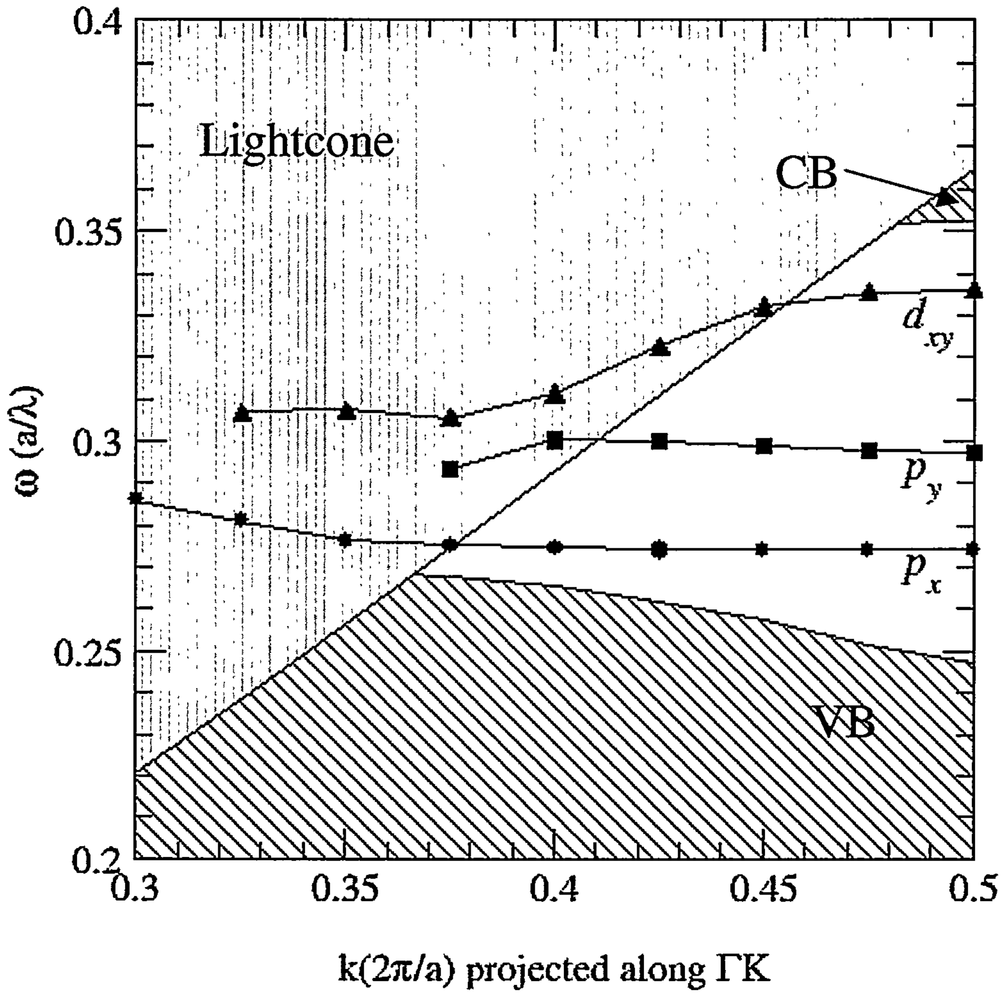

Lightcone
CB
$d_{xy}$
$p_y$
$p_x$
VB
0.4
0.35
0.3
0.25
0.2
ω (a/λ)
0.3
0.35
0.4
0.45
0.5
k(2π/a) projected along ΓK

Fig. 4