Ultra-low loss photonic integrated circuit with membrane-type photonic crystal waveguides

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Abstract: We report the design and testing of an SOI-based photonic integrated circuit containing two-dimensional membrane-type photonic crystal waveguides. The circuit comprises spot-size converters to efficiently couple light from a fiber into single-mode strip waveguides and butt-couplers to couple from strip waveguides to photonic crystal waveguides. Each optical interface was optimized to minimize back-reflections and reduce the Fabry-Perot noise. The transmission characteristics of each component are measured and record low propagation losses in photonic crystal waveguides of 24dB/cm are reported. The combination of an efficient two-stage coupling scheme and utilization of ultra-long (up to 2mm) photonic crystal waveguides reduces the uncertainty in determining the loss figure to 3dB/cm.

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1. Introduction

Realization of an optical equivalent to the silicon integrated circuits (IC) will reap large rewards in terms of packaging density, improved functionality and cost effectiveness. Silicon-on-insulator (SOI) is an attractive platform as it allows miniaturization of waveguide cross-sectional area to sub-micron scales while maintaining single-mode operation due to the high refractive index contrast. SOI is also the material of choice for high performance complementary metal oxide semiconductor (CMOS) ICs which makes it potentially compatible for on-chip opto-electronic integration. Two dimensional slab-type photonic crystals (PhCs) on SOI [1-6] may be a technology that can provide high density integration of optical components leveraging its unique properties such as strong light confinement and tailorabe dispersion. In this system the light is confined in the silicon slab by index guiding, while waveguiding within the slab plane is dictated by the photonic crystal, made of a periodic array of holes etched through the slab. However large losses in coupling into the SOI PhC device and scattering losses in the PhC waveguide itself due to structural irregularities have been identified as the main obstacles that hinder their further exploration. Large coupling losses are a direct result of the small geometric overlap and poor impedance matching of the optical modes between the launching fiber and PhC waveguide. Typically silicon strip waveguides are used to facilitate the coupling into the PhC waveguide. However multiple poorly matched interfaces in the optical circuit result in strong Fabry-Perot oscillations in the transmission spectra, which can easily reach over 50% of the signal amplitude [7]. As a result intrinsic spectral features arising from the underlying photonic band structure are hidden in this Fabry-Perot noise, severely complicating interpretation of experimental results.

In this paper we report the design and fabrication of a photonic integrated circuit consisting of efficient spot-size converters for coupling the light from the launching fiber to the single-mode silicon strip access waveguide, butt-couplers that butt-couple the strip waveguide to the PhC waveguide and the PhC waveguide itself. Section 2 describes the circuit design utilized to optimize coupling and minimize the effects of Fabry-Perot noise and Section 3 its fabrication. In Section 4 optical characterization of individual components and the circuit as a whole is presented.

2. Circuit design

2.1 Photonic crystal waveguides

It has been shown that the width of the photonic band gap (PBG) in a triangular lattice photonic crystal is optimized for a slab thickness around $0.5a$ (where $a$ is the lattice constant)
and a hole radius of ~ 0.35a [8]. To position the TE-like (electric field in the slab plane) waveguiding mode at the telecommunications wavelength of 1.5µm, a lattice constant of 445 nm was chosen. The PhC waveguide is formed by removing one row of holes along the Γ-K direction in the photonic lattice (so-called W1 waveguide). In the SOI structure the bandwidth of the W1 waveguiding mode is limited by the oxide light cone [5]. To increase the bandwidth and reduce mode-mixing [8] we adopted the membrane type PhC waveguide geometry, where the buried oxide (BOX) layer is removed leaving a free-standing silicon membrane with perforated holes.

2.2 Spot-size converter for fiber-to-strip waveguide (F-S) coupling

An advantage of the SOI platform is the potential for strong optical confinement of the waveguiding mode, which is crucial for miniaturization of the photonic IC. However it also creates a major challenge in coupling light on and off-chip via fiber. Direct coupling from standard telecom fiber to a W1 silicon PhC waveguide is inefficient owing to the large differences in effective refractive index, geometric size and profile of the optical modes. At least 30 dB coupling loss can be expected from the poor geometric overlap (~0.2 %) alone, as the cross-section of the optical mode in the fiber is in the order of 65µm² (for single mode fiber (SMF)) while in the photonic crystal waveguide it can be as small as 0.1µm². To address the issue of coupling from fiber to a PhC waveguide we divide the problem into two stages: first we address coupling from the fiber to the single-mode silicon strip waveguide (F-S) by designing a spot-size converter. Secondly we optimize the coupling from a strip waveguide to the photonic crystal waveguide using butt-coupling (S-PhC). The optical circuit consisting of these three components is illustrated in Figure 1(a).

Fig. 1. (a), Schematic of the photonic IC. It consists of a fiber-to-strip waveguide (F-S) spot-size converter and strip-to-photonic crystal (S-PhC) waveguide butt-coupler making up the input and output to the photonic crystal waveguide. (b). Reference optical circuit with 450nm wide strip waveguide and central section with 700nm wide waveguide coupled via adiabatic tapers (same as S-PhC coupler as in 1a). (c). Schematic of the F-S spot-size converter optimized for the PhC-based circuit.

Single-mode operation of the silicon strip waveguide at wavelengths around 1.5 µm requires the thickness of the silicon slab to be below 300nm and the width of the strip waveguide to be below 500nm. The small cross-sectional area and high effective refractive index of the waveguiding mode prohibit efficient direct coupling from the fiber. An intuitively simple solution for the fiber-to-strip waveguide F-S coupler is to increase considerably the thickness and width of the silicon slab in the coupling region to a cross-section equivalent to the fiber and then adiabatically taper the silicon layer both laterally and vertically to the desired single-mode strip waveguide dimensions [9]. Another approach is to introduce a surface grating to couple light from a fiber perpendicular to the surface into the planar waveguide [10]. However
most of these schemes require a number of additional processing steps that complicates the fabrication.

Instead we adopted the approach based on an inverted lateral taper [11-13]. It was first proposed to convert the confined mode in a SiN waveguide to a mode in the silica waveguide to facilitate laser to fiber coupling [11] and this was recently extended to couple to single-mode silicon strip waveguides [12, 13]. On the input facet the silicon waveguide is tapered to a width well below that required to support a propagating mode. The fiber mode is coupled evanescently to the silicon taper and becomes progressively more confined as the taper adiabatically widens to the final single-mode strip waveguide. The effective refractive index at the input facet is initially small then gradually increases along the taper, this gradual refractive index change helps to minimize back-reflections. In addition to providing low-loss coupling the taper is defined in the same processing level as the other waveguides, thus simplifying the fabrication. The F-S coupler proposed in [12] requires the end tip of the taper to be positioned exactly at the edge of the chip to avoid large leakage of the evanescent mode to the substrate. By instead overlaying the silicon taper with a polymer waveguide this problem can be mitigated by confining the light in the polymer waveguide [13]. The design proposed in Ref. 13 is optimized for strip waveguide-based planar lightwave systems, which requires efficient coupling of both TE and TM polarizations from the SMF fiber into a 300x300 nm strip waveguide with small polarization dependent losses (PDL). In contrast, for the PhC-based circuit the thickness of the slab is fixed at 220 nm and PDL are not very important as the band gap waveguiding occurs for only the TE polarization. We optimized the parameters of the F-S coupler for efficient coupling of only TE polarized light into the strip waveguide with 450nm width. These requirements allow increasing the width of the end taper tip up to 75nm, decreasing the length of the taper to 150 µm, and minimizing the cross-section of the overlaying polymer to 2x2µm², thus providing more relaxed fabrication tolerances without significant compromise of the coupling efficiency. Figure 1(c) shows a schematic of the resulting F-S coupler.

2.3. Strip waveguide to PhC waveguide (S-PhC) butt-coupler

Once the light is coupled into the strip waveguide the next problem is to efficiently couple it into the PhC waveguide. The small group velocity of the TE mode in the W1 PhC waveguide results in large impedance mismatch with the mode in the strip waveguide. To solve this problem a number of different coupling schemes have been theoretically extensively studied [14-18]. Typically some kind of adiabatic tapering is proposed, for example introducing the periodicity of the crystal gradually by using smaller hole diameters in the coupler section [14], or by tapering the strip waveguide deep inside the PhC waveguide [15,16], or introducing additional holes at the interface to better match the impedances [17,18]. The resulting coupling efficiency relies heavily on precise control over the holes diameter and position in the coupler section. Fabrication-wise the easiest although counterintuitive solution is to simply butt couple the strip waveguide into the W1 PhC waveguide. The mode impedances will still be unmatched, however the modes geometrical overlap can be tailored by changing the width of the access strip waveguide. Recently this approach was tested numerically using 3D FDTD simulations for W1 PhC waveguides with a triangular lattice in an SOI based system [19] and a membrane-type silicon system [20]. Surprisingly small reflection losses for both structures were predicted, below 1 dB per interface for optimized widths of the strip waveguide. We adopted a strip waveguide width of 1.6a from Ref. [19] which is approximately the distance between the center of the holes adjacent to the W1 waveguide (V3a). The strip waveguide with these dimensions (700x220nm cross section) becomes multimoded at 1.5 µm with two TE and one TM modes. In order to excite predominantly the fundamental TE mode adiabatic tapers are introduced into the circuit design that connect 450 nm wide access strip waveguides from the F-S couplers to the S-PhC coupler sections as shown in Fig. 1(a).
3. Fabrication

Devices were patterned on 200 mm SOI Unibond wafers manufactured by SOITEC with 220 nm of lightly p-doped Si on a 2 \( \mu \)m BOX layer. The thick oxide serves to optically isolate the circuit from the substrate, reducing losses due to substrate leakage. A 50 nm thick oxide was deposited on the wafers via low pressure chemical vapor deposition to act as a hard mask for subsequent etching. The PhC waveguides, strip waveguides and silicon taper of the F-S coupler were defined in one step by electron beam lithography using Leica’s VB6-HR commercial 100 keV system.

Fig. 2. SEM micrographs of a) PhC membrane waveguide with strip access waveguide. b) sidewall profile showing ~90 angle sidewalls. c) F-S coupler, end of the silicon taper tip is visible overlaid by thick (3 \( \mu \)m in this case) polymer waveguide.
The length of the whole circuit with F-S couplers on both ends was 4.6 mm. As some of the PhC waveguides span a number of writing fields, minimization of field stitch error was essential. The photonic crystal patterns were routinely over-exposed to smooth out the effects of fracturing circles into polygons for pattern writing. The exposed wafers containing over one thousand devices were etched in a standard 200mm CMOS line at IBM Watson Research Center. The resist pattern was transferred to the oxide hard mask using a CF$_4$/CHF$_3$/Ar chemistry. The resist was then removed and the patterned oxide mask transferred to the Si layer with an HBr-based etch. Sidewall angles close to 90° were obtained and sidewall roughness is estimated to be below 5nm (see Figs. 2(a) and (b)). A second lithography step is required to mask the strip waveguides and coupler regions to protect them from being under-etched during BOE etching of the BOX layer for definition of the PhC membranes (see Fig. 2(a)). A final lithography step defined the epoxy polymer for the F-S coupler (see Fig. 2(c)). Individual samples containing ~ 40 devices were then cleaved on each side to enable edge-coupling. Since the refractive index (~1.58) of the epoxy polymer we used is higher than the underlying oxide the polymer waveguide by itself can support waveguiding. Extending the polymer waveguide lengthwise past the vertex of the taper provides significantly relaxed cleaving tolerances.

4. Optical measurements

4.1 Optical setup

The device under test (DUT) was mounted on a XYZ translational stage. The intensity of vertically scattered light was observed with a NIR microscope equipped with a NIR camera. Transmission measurements were made using tapered fibers at the input and output ports of the DUT. Four LEDs were combined to obtain a bandwidth spanning 1200 to 1700nm. Light from the source was coupled to a polarization maintaining (PM) fiber and directed through a polarization controller before being coupled to the DUT via a tapered and microlensed PM fiber. The fiber tip produces a spot with a beam waist of 2.1µm with minimal mixing of TE-TM modes (rejection ratio of over 30-40dB). After passing through the DUT the light was collected by a tapered SMF fiber with beam waist of 1.85 µm and the transmission analyzed by an optical spectrum analyzer. The input and output fibers are mounted on XYZ micrometer piezo-stages for precision alignment with respect to the DUT. The presented spectra are normalized to the measured spectrum obtained by maximizing the signal with the input and output fiber tips separated by their combined focal distances. No further normalization is performed unless explicitly stated.

4.2 Losses in single-mode Si/SiO2 strip waveguides

Careful determination of losses in the strip waveguides is of crucial importance for characterization of all other components of the integrated circuit. Two separate LEDs with central wavelengths of 1550nm and 1330nm and bandwidth of 70nm were used. The light from the LED source is coupled into a reference optical circuit without a PhC waveguide section (see Fig.1(b)). A small portion of this light is scattered vertically from the sample due to imperfections and sidewall roughness. This vertically scattered light was captured by an IR camera attached to the microscope as the DUT was translated along the direction of the strip waveguide producing an image as the one shown on the top panel of Fig.3. By averaging several such images the transverse profile of the scattering intensity as a function of the waveguide length was produced as presented in Fig. 3. It can be seen that for the 1330nm central wavelength (black trace) the slope gives the loss value of 12.5+/-1 dB/cm. The scattering at 1550nm is much reduced owing to lower losses. The linear fit to the blue trace gives an upper estimate of losses of 3.5dB/cm with an error of the order of 2dB/cm. The larger error is a result of the lower signal to noise ratio. These loss numbers are among the lowest reported to date for Si/SiO2 single-mode strip waveguides [21] and are consistent with the magnitude of sidewall roughness below 5nm estimated from SEM inspection.
Fig. 3. Intensity of light scattered vertically from the reference optical circuit of Fig. 1(b) with a 450nm wide strip waveguide for TE polarized light. Blue curve corresponds to the wavelength of 1550nm and black to 1330nm. Inset: Image of the vertically scattered light acquired by the IR camera. Several of such images were averaged to produce the traces in the main figure.

4.3 Characterization of the F-S spot-size converter

Figure 4 represents transmission spectra of the reference circuit of Fig. 1(b). As can be seen the insertion losses for the whole circuit for the TE polarization are minimal with attenuation of 2.5dB at a wavelength of 1.55µm. The loss spectrum is relatively broadband with a 3dB bandwidth of about 340nm. Loss measurements of strip waveguides discussed above have shown losses of 3.5+/-2dB/cm for TE polarized light. Hence most of the losses (~ 1.5dB) seen in Fig.4 are coming from the strip waveguide itself. The F-S coupler section provides excellent coupling efficiency with losses below 1dB. The estimated uncertainty of the coupling efficiency between different devices is minimized to below 0.2dB owing to good repeatability of coupling into the F-S spot-size converter. The spot-size converter is not as efficient for TM polarized light as is evident in Fig. 4. The bandwidth is much narrower partly due to the strip waveguide’s TM mode cutoff at 1.55 µm. Fabry-Perot oscillations are more pronounced and the highest transmission is 4.5dB despite lower losses in the strip waveguide for the TM mode below 3dB/cm. This gives an upper estimate of the combined input/output TM coupler losses of approximately 2dB.

The inset in Fig. 4 shows measurements of the fiber misalignment tolerances for the TE polarization. As can be seen the 3dB cutoff is reached when the fiber is displaced in either the vertical (Y-axis) or horizontal (X-axis) direction by only 1 µm from the optimal position. The slight asymmetry of the curve for negative vertical displacement is due to the underlying...
buried oxide layer. The misalignment tolerance is a direct result of the 2x2µm cross-section of the core of a polymer waveguide.

4.4 Characterization of the photonic IC by the cut-back method

Several methods were proposed in the literature to estimate the propagation losses in PhC waveguides – observation of the intensity of light scattered in vertical direction [3,4], visibility of the Fabry-Perot interference fringes [14], and the cut-back method [5]. The first method can give reliable results for low-coherent light sources, but these typically also have a relatively broad bandwidth compared to the PhC waveguiding bandwidth. The Fabry-Perot fringe method is also unsuitable here as Fabry-Perot fringes are weak owing to the well-matched interfaces in our optical circuit.

We use the cut-back method that compares the transmitted power \( P_1, P_2, P_3, \ldots \) in dB measured for devices with PhC waveguides of different lengths \( l_1, l_2, l_3, \ldots \) and infer losses from the slope of the \( P(l) \) dependence. The losses in each circuit can be described by Eqn. 1 where \( P_n \) is the transmitted power collected in dB for a PhC waveguide of length \( l_n \), \( \alpha_{\text{PhC}} \) is the transmission loss in PhC waveguides, \( \alpha_{\text{strip}} \) is the transmission loss in the strip waveguide, \( L \) is a constant that is the combined length of the strip and PhC waveguides and \( b \) is a constant.

\[
\text{Fig. 4. Fiber-to-fiber transmission through the reference optical circuit of Fig.1(b) with a 450nm wide strip waveguide. Inset shows insertion loss due to horizontal (X-axis) and vertical (Y-axis) misalignment.}
\]
encompassing fixed losses from additional circuit components common to all devices, namely the S-PhC butt-couplers and F-S spot-size converters.

\[ P_n = -\alpha_{\text{PhC}} l_n - \alpha_{\text{strip}} (L - l_n) - b \]  

(1)

By comparing two devices with different PhC waveguide lengths \( \alpha_{\text{PhC}} \) can be calculated according to Eq. (2).

\[ \alpha_{\text{PhC}} = \frac{P_2 - P_1}{l_1 - l_2} + \alpha_{\text{strip}} \]  

(2)

Uncertainties in the measurement of the loss figure arise from inconsistencies in coupling and uncertainty in the strip waveguide loss figure. Compared to other loss measurement methods the cut-back method is more susceptible to inconsistencies in device coupling, particularly when PhC waveguides with small \( \Delta l \) are being measured as in previous publications. When the light is coupled directly to the cleaved edge of a PhC waveguide typical variation of the coupling is about 1 dB, which gives an estimate of the error for 350\( \mu \)m long PhC waveguides.
of the order of 1dB/0.35mm=30dB/cm. With F-S spot-size converters the measured uncertainty in coupling efficiency between different devices was measured to be below 0.2dB. By fabricating and measuring devices with lengths ranging from 29 µm to 2 mm (i.e., 66 to 4572 lattice periods) we were able to reduce this error to an estimated 0.2dB/2mm=1dB/cm.

Figure 5(a) shows a set of typical TE transmission spectra of devices with W1 membrane-type PhC waveguides of different lengths together with the spectrum from a reference strip waveguide. Comparing the spectrum in red for a 29 µm length PhC waveguide with that of the reference strip waveguide it can be seen that the transmission characteristics of the PhC dominate the spectrum. To interpret the spectra the photonic band structure of the W1 PhC waveguide was calculated by the planewave method using the MIT Photonics Band code [22]. The PhC parameters used in the calculations were measured directly from SEM images: lattice constant $a$ of 445 nm, slab thickness of 0.5$a$ and hole radius 0.37$a$. The dielectric constant $\varepsilon$ of the silicon slab was taken as 12.13. A number of the spectral features in the transmission spectra of the 29 µm device of Fig. 5(a) can be directly mapped to features in the photonic band diagram in Fig.5(b). At a normalized frequency of 0.294 the onset of the propagating waveguide mode can be seen, which explains the sharp cutoff at 1512nm wavelength. At lower frequencies a set of slab modes at the photonic band edge can be directly traced to the small resonances in the transmission spectrum around 1550 nm. Folding of the waveguide mode at 0.365$c/a$ opens a stopband, which explains the strong dip in the transmission spectra around 1230nm.

### 4.5. Measurements of losses in the PhC waveguides

Comparing the spectra with different lengths of PhC waveguides it is clear that there are two different loss regimes. For wavelengths shorter than 1500 nm the transmission is strongly attenuated with increasing length while the transmission remains high around 1505nm. These two regimes can be explained by referring to the band structure. It can be seen that around 0.297$c/a$ frequency the waveguiding mode is crossing the light-line. The first regime is the region above the light-line (shaded region in Fig. 5(b)) where the mode is not longer a true propagating mode but suffers radiative losses as a result of out-of-plane diffraction. The second regime is for the region below the light-line cut-off (unshaded region in Fig. 5(b)) where the waveguiding mode propagates as a Bloch wave with no intrinsic losses.

#### 4.5.A. Losses above the light-line in W1 PhC waveguides

As can be seen from Fig. 5(a) the propagation losses above the light-line cutoff at wavelength shorter than 1500nm are very high due to diffraction of light out of the slab plane. There is a distinct spectral dependence of the diffraction losses with a maximum of 1300 dB/cm at 1370nm lowering to 400dB/cm about 1250nm in the proximity of the stop-band. The loss magnitude as well as its spectral dependence is consistent with numerous recent theoretical calculations and experimental results [4,19,23]. It was argued [4] that near the stopband edge radiation losses are suppressed due to strong distributed feedback. However it should be pointed out that even in this spectral region the losses are very high, making it questionable whether efficient waveguiding can be utilized above the light-line. Detailed analysis of radiation losses above the light-line will be published elsewhere [22].

#### 4.5.B. Losses below the light-line in W1 PhC waveguides

Waveguiding at frequencies below the light-line cutoff at 0.297$c/a$ is intrinsically lossless since the light is guided in the PhC waveguide as a Bloch wave. However in practice surface roughness, variations in hole diameter, lattice constant, etc. disrupt the perfect periodicity required for Bloch-wave propagation. This results in leakage of the mode out of the slab plane, contributing to significant scattering losses typically measured to be of the order of 60-100 dB/cm [3,5]. In order to quantify scattering losses in this spectral region, high resolution (0.5 nm) spectra were measured.
The high resolution spectra presented in Fig. 6 are normalized on the spectrum from the reference optical circuit (Fig. 1(b)). Note that Fabry-Perot oscillations are virtually absent indicating good impedance matching at all interfaces in the optical circuit. Above the light-line around $0.297c/a$ exponential decay is evident with the slope increasing with the length. At frequencies below the light-line the attenuation is much smaller. For the circuit with a 2mm PhC waveguide it reaches 5.6dB. The inset of Fig. 6 plots the transmission versus PhC waveguide length for a number of devices measured at a wavelength of 1505nm. The red open circles plot the transmission normalized on the strip waveguide transmission with the slope of the fitted line giving a propagation losses of $20.7\pm2.4$dB/cm. This number however underestimates the losses $\alpha_{\text{PhC}}$ as it fails to take into account the reduction in the length of strip waveguide as the PhC waveguide becomes longer. A corrected figure of $24.2\pm2.4$ dB results from addition of $\alpha_{\text{strip}}$ as defined in Eq. (2). Corrected data is presented with red filled circles in Fig. 6.
4.6. Losses in the S-PhC butt-coupler

With all these numbers at hand we can now estimate coupling losses at the two access strip waveguide - PhC waveguide interfaces. These losses in the S-PhC butt-coupler sections can be estimated from Fig. 4(a) by comparing the transmission spectra of the device with the 29µm length PhC waveguide with that of the spectra of the strip waveguide. Around 1505nm wavelength the difference in the two spectra is smallest with a loss of about 1dB. At shorter wavelengths the difference becomes more significant, of the order of 5dB at 1370nm and 3dB at 1250nm. As explained in Section 4.6a most of this loss results from intrinsic radiation in the PhC. Subtracting PhC radiation losses from the spectrum of the PhC of 29µm in Fig. 4(a) leaves at most 1.3dB for losses in the two S-PhC butt-couplers, with a relatively flat spectral response over a 300nm bandwidth.

5. Summary and conclusions

A photonic integrated circuit containing membrane-type W1 PhC waveguides was designed, fabricated and each component characterized. To our knowledge this is the first demonstration of a complete photonic IC incorporating a PhC waveguide that provides efficient fiber-to-fiber transmission with minimal back-reflections. The results of each individual component are summarized in Table 1.

Table 1. Summary of characterization of photonic IC components for TE polarization

| Component                              | Wavelength (nm) | Loss (dB or dB/cm) | Loss error (dB or dB/cm) |
|----------------------------------------|-----------------|--------------------|--------------------------|
| F-S spot-size converter (for pair)     | 1550            | 1                  | 0.8                      |
| S-PhC butt-coupler (for pair)          | 1500            | 1.3                | 0.4                      |
| Strip waveguide (450x220nm)           | 1550            | 3.5                | 2                        |
| W1 membrane-type PhC waveguide         | 1505            | 24                 | 2.4                      |

Insertion loss in the F-S spot-size converter was measured to be of the order of 1dB with a relatively broad bandwidth of 340nm for TE polarization. Losses in the butt-couplers are below 1dB with a nearly flat response over a bandwidth of over 300nm. Intrinsic diffraction losses in the PhC waveguide were measured to be very large reaching 1300dB/cm for frequencies above the light line and with a spectral dependence that correlates well with recent theoretical calculations. Due to these strong radiation losses the bandwidth of low-loss propagation is limited to only 12 nm for frequencies below the light-line. The low-loss propagation regime is characterized by scattering losses of 24dB/cm. This number is the lowest reported to date for PhC waveguides.

The results from Table 1 can be checked for consistency by comparing them for the case of the photonic IC containing the 2mm long PhC waveguide with the absolute measured transmission loss. The total fiber-to-fiber loss at 1505nm is measured from Fig. 5 as 7.9 dB. The loss budget can be estimated from Table 1 as 4.8 dB from the PhC waveguide, 0.8 dB from the access strip waveguides (two strip waveguides with a total length of 2 mm), 1 dB loss from the pair of S-PhC butt-couplers and 1 dB from a pair of F-S spot-size converters. This sums to a total loss of 7.6dB, a difference of only 0.3dB from the measured result and well within our experimental uncertainty.
Since the lattice period and hole diameters are well controlled even in the longest PhC waveguide of 2mm length, the main source of residual loss is scattering of the Bloch wave due to sidewall surface roughness of the order of 5nm. Further improvement of the loss figure should be possible by reducing the sidewall roughness, which can be pursued, for example, by oxidation smoothing of the sidewalls. In reality the length of PhC-based photonic ICs is expected to be of the order of hundreds of micrometers, which will result in only a few dB losses. With this level of losses PhC-based ultra-dense photonic ICs appear feasible.

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