Design approach for side-coupled photonic crystal nanobeams: Enabling reliable measurement of a high contrast fundamental resonance

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Abstract: We present a design method for realizing side-coupled photonic crystal nanobeam (PCN) cavities with high contrast, low order resonances, which are often difficult to measure using traditional, in-line coupled PCNs. Using a straight bus waveguide adjacent to the PCN, we show in both simulation and experiment that near critical coupling can be achieved by properly adjusting the overlap in k-space between the bus waveguide and PCN cavity resonance modes. In experiment, greater than 100 times improvement in on-resonance peak amplitude is demonstrated for the fundamental optical resonance mode of a side-coupled PCN compared to an early identical PCN measured using in-line coupling. The straightforward design of PCNs with high contrast resonances opens the door to the practical implementation of multiplexed ultra-high quality factor, low mode volume on-chip photonic devices.

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1. Introduction

Optically resonant nanophotonic structures hold great promise in applications including optical signal processing [1–3], nanomanipulation [4–6], photovoltaics [7], imaging [8], and sensing [9, 10]. On-resonance, these structures support high, localized optical field intensities that can be leveraged for enhancing various types of interactions between light and matter. Resonant field enhancements in photonic and plasmonic devices result directly from the confinement of light both spatially, as characterized by the mode volume (V), and temporally, as characterized by the quality factor (Q). Most resonant nanophotonic structures have the ability to attain either high Q or low V, but lack the ability to simultaneously demonstrate significant spatial and temporal confinement (i.e., high Q/V) [4, 11–13]. Photonic crystal nanobeam (PCN) cavities are the exception [14–19]. PCN cavities have the design flexibility necessary to achieve low V while maintaining ultra-high Q, and they have the highest Q/V metrics reported to date [16–19]. Hence, PCNs are one of the most promising nanophotonic building blocks for realizing on-chip photonic...
devices with improved performance metrics, lower power consumption, and smaller footprint.

There are three primary challenges that have inhibited more widespread utilization of PCNs in integrated photonic applications. First, the sub-micron feature sizes in PCNs have predominantly been achieved using electron beam lithography, which is not a scalable fabrication approach. However, over the past few years, high Q photonic crystals have been fabricated in CMOS foundries that can reproducibly achieve features with sizes of order 100 nm [20, 21]. Therefore, scalable on-chip fabrication of PCNs is now attainable with the possible exception of the smallest incorporated slots or bowtie features. Second, in the traditional in-line coupling configuration, detailed in Section 3, the highest Q fundamental resonance of PCNs is typically transmitted through the nanobeam with very low intensity or is completely suppressed, limiting downstream on-chip applications before signal amplification is required [22, 23]. Third, using the in-line coupling configuration, the photonic bandgap of the PCN severely restricts which wavelengths of light are transmitted through the nanobeam, which limits wavelength division multiplexing opportunities [22–25]. For the latter two challenges, evanescent coupling to PCN cavities using a side-coupled bus waveguide (e.g., similar to the approach used for ring resonators) provides a solution [23, 26–34]. By coupling light into and out from the central cavity region of the PCN using the bus waveguide, light does not need to pass through highly reflecting mirror regions of the PCN. Moreover, use of a bus waveguide ensures a high baseline of transmitted intensity for all wavelengths within the bandwidth of the bus waveguide except for the resonant wavelengths. Thus, side-coupled PCNs are a promising building block for integrated photonic applications.

While there are several reports of the utilization of a simple side-coupled bus waveguide for PCN cavities, little attention has been given to understanding design rules for the bus waveguide [26, 27]. Most prior work implementing simple bus waveguides for side-coupling into PCN cavities has either briefly mentioned basic design concepts without detailed study or employed experimental trial and error approaches and parameter sweeps in fabrication to achieve the desired evanescent coupling that results in high contrast transmission resonances. We note that design analysis of PCN cavities laterally coupled to either a waveguide Fabry-Perot resonator or a PCN to excite Fano-resonances has been previously reported [31–33]. In this work, we show through simulation and experiment how tuning the overlap in k-space between a simple bus waveguide mode and PCN cavity resonances can be carried out as a straightforward approach to reliably achieve high contrast, high Q PCN resonances in transmission and improve device performance compared to in-line coupling.

2. Design Considerations

Evanescent coupling between two optical devices, such as waveguides and resonance cavities, occurs when energy is transferred from a photonic mode in one device to a photonic mode in the other device by means of the evanescent tails of the electric field distributions. The efficacy of evanescent coupling, or extent of energy exchange between optical devices, is dependent on the overlap of the two modes in both physical and state-space (e.g., k-space, ω-space). In physical space, the overlap of the modes is controlled by adjusting the size of the physical gap separating the evanescently coupled optical devices. In k-space, the modal overlap may be adjusted by wave-vector matching between the optical devices. In the case of an optical device with discontinuous values allowed in state-space, such as a resonator where limited combinations of optical frequencies and wave-vectors are supported, coupling between the resonant device and a feeding device, such as a waveguide, may only occur when the mode of the feeding device is similar to an allowed mode in the resonator. Considering one of the most common evanescently coupled photonic components, a ring resonator, coupling between a straight bus waveguide and a resonant ring occurs when the bus waveguide mode is of the same frequency as the resonant mode in the ring. Since the wave-vectors of the bus waveguide mode and resonant mode in the ring are very similar when the bus and ring waveguides have similar widths, the rate of energy
exchange between the bus waveguide and resonant ring is almost entirely determined by the gap spacing between them. Hence, to achieve near critical coupling for ring resonator devices, usually a small parameter sweep of coupling gap sizes is sufficient. However, for evanescent coupling between a bus waveguide and a PCN cavity, it cannot be assumed that the wave-vectors of the bus waveguide and PCN cavity are similar. Therefore, additional design considerations are necessary to ensure that the modes of the bus waveguide and PCN cavity are sufficiently close in both physical and k-space. We note that prior work examined design rules for efficient evanescent coupling between two-dimensional photonic crystals and out-of-plane optical fiber tapers [35].

As a first step toward developing design rules to tune the degree of k-space overlap between a PCN cavity mode and bus waveguide mode, we define the wave-vectors of these modes. Assuming the PCN cavity mode is designed to be at the edge of the Brillouin zone, the wave-vector of the resonant cavity mode is given by

\[ k_{cav} = \frac{0.5}{a} \left( \frac{1}{\text{nm}} \right), \]  

(1)

where \( a \) is the period of the air holes comprising the PCN. In this work, the PCN cavity mode is a dielectric mode. The band structure of the PCN, which depends on the dimensions of the unit cell, determines the dielectric band edge frequency and, thus, the dielectric cavity mode resonance frequency, as discussed in Section 3. In order to couple light from a bus waveguide to the PCN cavity mode, there must exist a bus waveguide mode that has the same frequency as the PCN cavity mode. The wave-vector of such a bus waveguide mode is given by

\[ k_{wg} = n_{\text{eff-wg}} \cdot \frac{1}{\lambda_{\text{res}}} \left( \frac{1}{\text{nm}} \right), \]  

(2)

where \( n_{\text{eff-wg}} \) and \( \lambda_{\text{res}} \) are the effective index of the propagating waveguide mode and the free-space wavelength corresponding to the PCN cavity resonance frequency, respectively. The condition necessary for wave-vector matching between the bus waveguide and PCN cavity modes can be obtained by setting \( k_{cav} = k_{wg} \), as shown in Eq. (3).

\[ n_{\text{eff-wg}} = \frac{0.5}{a} \cdot \lambda_{\text{res}} \]  

(3)

Therefore, in order to efficiently couple light into a particularly designed PCN cavity, the only requirements are to (1) properly design the bus waveguide to have a guided mode with the appropriate effective index and (2) tune the coupling gap separating the bus waveguide and PCN cavity to achieve critical coupling. The former requirement can be satisfied by simply adjusting the waveguide width and the latter requirement can be satisfied in the usual way for evanescently coupled optical devices, by using a small parameter sweep of gap sizes.

Two-dimensional (2D) finite-difference time-domain (FDTD) simulations were carried out in Lumerical to design and characterize the PCN cavities studied in this work. Two-dimensional analysis was chosen due to the significant computational resources required to simulate parameter sweeps for high Q cavities, and because the trends in PCN cavity resonance depth as a function of excitation source location (Section 3.1), and bus waveguide width and coupling gap size (Section 3.2), are expected to be similar for 2D and 3D analysis. The deterministic design approach for PCN cavities was followed in order to reduce scattering losses and increase the quality factor of the PCN cavities [36]. The specific dimensions utilized for the PCN cavities are as follows. The width of the nanobeam was selected to be \( n_{w} = 600\text{nm} \) and the period was set to \( a = 300\text{nm} \) with deterministic hole tapering from a radius of 103nm in the mirror segments to a radius of 130nm in the cavity region. We chose \( n_{w} = 600\text{nm} \) for tailoring the lateral confinement of the optical mode to better mimic the performance of 3D devices. To maintain the cavity resonance frequency near 1550nm with this \( n_{w} \), a relatively short period of \( a = 300\text{nm} \) was employed. A taper length of 20 unit cells was utilized along with 10 identical unit cells in the end mirror regions to yield
a well-confined resonance mode. The band structure of the unit cells comprising the PCN and a schematic of the PCN are shown in Fig. 1(a,b). By gradually modifying the unit cell band structure from the ends of the mirror region to the cavity center, a locally allowed state is created at the edge of the Brillouin zone. Figure 1(a) shows that in a PCN designed for a dielectric cavity resonance mode, the resonance frequency is determined by the dielectric band edge frequency for unit cells in the cavity center, where the cavity resonance wave-vector is $k_x = \frac{0.5}{a}$ (i.e., at the edge of the Brillouin zone). The profile of the fundamental cavity resonance mode of the designed PCN cavity is shown in Fig. 1(c) and has a simulated $Q^{intrinsic} = 1.7 \times 10^8$.

Fig. 1. a) Band diagram of TE modes associated with end mirror (red), taper (green), and cavity (blue) regions of the photonic crystal cavity shown in b). These bands were calculated via 2D FDTD simulations. b) Schematic illustration of deterministically designed PCN with cavity resonance state within the band gap of the end mirror segments. c) Mode profile (electric power) of fundamental resonance of designed PCN cavity.

3. Simulations

3.1. Challenges In-Line

To illustrate the implementation challenges associated with utilizing PCN cavities in an in-line coupling configuration, resonance excitation in the PCN cavity was first simulated with a TE mode source at one end of the PCN (Fig. 2(a), red), mimicking the traditional in-line coupling configuration, and subsequently with a dipole source near the center of the PCN cavity (Fig. 2(a), blue). The transmission spectrum for in-line coupling was computationally measured using a power monitor at the end of the cavity opposite to the mode source. The dipole power spectrum, enhanced from interaction with the cavity, was measured by a field monitor at the dipole location. Ideally, both source locations would be suitable for exciting the fundamental resonance mode of the PCN cavity, which in general has the highest Q/V metrics. However, as shown in Fig. 2(b,c), this is not the case. The positioning of the dipole source in the center of the cavity allows it to excite both the lowest order resonance mode as well as other odd order resonant modes. The lowest order resonance excited by the dipole source is located at $\lambda_i = 1536\text{nm}$ (labeled (i) in the figure) while the lowest order resonance with intensity above the baseline level excited using the in-line coupling configuration is located at $\lambda_{ii} = 1705\text{nm}$ (labeled (ii) in the figure). Figure 2(c) shows the electric field profile for the resonances labeled (i) and (ii). Resonance (i) is indeed the fundamental mode while resonance (ii) is a much higher order mode. Hence, the in-line coupling configuration precludes measurement of low order modes in transmission, including the fundamental mode. Here, we define the peak amplitude of a resonance in the transmission
spectrum to be the fractional resonance peak size relative to unity transmission where the intensity of the band edge is normalized to one. For example, the relative peak amplitude of resonance (ii) is 0.045 compared to unity transmission of 1 at the band edge of the PCN. A peak amplitude cannot be assigned if the intensity of the resonance is less than that of the local variance in the transmitted intensity of light, as is the case for the lower order modes of the PCN cavity excited in the in-line coupling configuration. To reiterate, Fig. 2 highlights two key challenges of in-line coupled PCN cavities – suppression of resonance modes and intra-bandgap signal loss – which limit both the ability of PCN devices to exploit light-matter interaction using low order resonant modes and the feasibility of serial integration with other photonic components.

Fig. 2. a) Schematic illustration of a PCN cavity being excited via dipole coupling (blue) and in-line coupling (red). b) Normalized intensity spectrum for both the dipole power enhanced by the cavity (blue) for dipole coupling and transmitted optical power through the cavity (red) from in-line coupling. The lowest order resonance with intensity above the baseline level excited via each excitation method is circled. c) Electric field profiles for resonances labeled (i) and (ii) in (b). It can be clearly seen that the fundamental resonance mode excited via dipole coupling does not match the lowest order mode observed from in-line coupling in mode profile.

3.2. Resonance Excitation with Side-Coupling

PCN cavities side-coupled to straight bus waveguides, as schematically illustrated in Fig. 3(b), are explored as a means to circumvent the implementation hurdles associated with in-line coupling. Following the design rules discussed in Section 2, we carried out simulations to demonstrate how wave-vector matching between modes of a straight bus waveguide and a PCN cavity can lead to the realization of high contrast PCN transmission resonances that are not achievable by in-line coupling. We first examined the Fourier transform of the electric field profile of the PCN cavity fundamental mode (Fig. 1(c)) to visualize the cavity resonance profile in k-space, as shown in Fig. 3(a). The wave-vectors are localized at $|k_x| = \frac{0.5}{a}$, as expected for a deterministically designed cavity. Next, in order to tune the wave-vector of light evanescently coupled from the bus waveguide, the effective index of the bus waveguide was altered by adjusting $w$, the width of the bus waveguide. Numerical MODE Solutions was used to calculate the effective index of the fundamental TE-mode in the bus waveguide for different values of $w$. Increasing $w$ leads to an increase in the wave-vector of the guided mode. Fig. 3(c) shows the Fourier transform of the electric field distribution in the bus waveguide for three different waveguide widths, $w = 250\text{nm}, 290\text{nm},$ and $400\text{nm}$, corresponding to wave-vectors that are less than, nearly equal to, and greater
Fig. 3. a) K-space plot of optical cavity resonance taken from the Fourier transform of the field profile shown in Fig. 1(c). b) Schematic illustration of side-coupling configuration for PCN cavity. c) K-space plots of bus waveguide modes of various waveguide widths ($w = 250\text{nm}, 290\text{nm}, \text{and} 400\text{nm}$). By increasing the waveguide width, it is possible to increase the k-vector of the waveguide mode due to an increase in the modal effective index.

than the wave-vector of the resonant PCN cavity mode, respectively. FDTD simulations of the waveguide mode profile in k-space were done with a 5000fs pulsed mode source at the resonant wavelength of the PCN cavity and measured by an electric field monitor extending through the waveguide. The long mode source was utilized to minimize transient effects and to ensure guided optical fields extended throughout the full waveguide region monitored.

In order to investigate the effect of wave-vector mismatch on the efficacy of resonance excitation in PCN cavities, 2D calculations in Lumerical FDTD Solutions were carried out to simulate the transmission spectrum of the PCN specified at the beginning of Section 3 when side-coupled with different bus waveguide and coupling gap dimensions. As discussed previously, we believe the results of the less computationally intensive 2D simulations will qualitatively agree with 3D simulations, and we show this to be the case in comparison to experimental results in Section 4. The three aforementioned bus waveguide widths were considered and the coupling gap size was varied between $100 \rightarrow 600\text{nm}$. The results of the simulations are shown in Fig. 4(a). The most pronounced resonances occur when the wave-vector of the bus waveguide mode closely matches that of the PCN cavity resonance (i.e., $w = 290\text{nm}$). The transition from over-coupled at small $g$ to near critically-coupled and then under-coupled for increasing $g$ is evident. For the side-coupled PCN with the narrowest bus waveguide width, the transmission features that appear for small coupling gap size are most likely Fabry-Perot fringes that result from the finite size of the bus waveguide used in the simulation and the large evanescent tail of the electric field that extends from the narrow waveguide. Two narrow, but rather shallow resonances appear in the transmission spectra of the side-coupled PCN with the widest bus waveguide width and smaller coupling gaps. Overall, the data in Fig. 4(a) suggest that the coupling efficiency between the PCN cavity and bus waveguide modes is very sensitive to the wave-vector mismatch between the bus waveguide and cavity resonance modes. It is important to note that in the case where the waveguide width, $w$, is narrowest ($w = 250\text{nm}$), the evanescent tail of the electric field extending from the bus waveguide is the largest due to the mode being more delocalized and having a lower effective index. However, despite the fact that the 250nm wide bus waveguide has the largest field overlap in physical space with the PCN cavity, coupling from the bus waveguide of width $w = 290\text{nm}$ is significantly improved. Although the spatial field overlap between the bus waveguide with $w = 290\text{nm}$ and the PCN cavity is not the largest of the three bus waveguides considered,
Increasing $w$ of the bus waveguide is the most closely matched to that of the PCN cavity resonance. Therefore, we conclude that the effect of modal overlap in k-space may, at times, dominate the effect of field overlap between devices in physical space.

Next, we simulated transmission spectra for side-coupled PCNs with constant $g = 150\text{nm}$ and variable $w$ between 240$\text{nm}$ – 350$\text{nm}$ to further explore the sensitivity of the wave-vector mismatch on the energy exchange rate between the bus waveguide and PCN cavity. Figure 4(b) shows that the width and depth of the fundamental transmission resonance is highly dependent on the bus waveguide width, and, hence, its supported wave-vector. We note that the slight change in resonance wavelength as a function of $w$ is likely due to the different levels of interaction between the bus waveguide mode and the PCN cavity mode, which affects the cavity resonance frequency. By increasing $w$, at a constant $g$, the modal overlap between the bus waveguide and PCN cavity is altered in k-space and, consequently, the coupling regime is correspondingly tuned to achieve under-coupling, critical coupling, and over-coupling. The critical coupling region is defined by zero transmission on resonance, or a peak amplitude of 1. Critical coupling occurs when the intrinsic and extrinsic losses of the resonator are matched. Due to the large coupling interface between the bus waveguide and PCN cavity in 2D FDTD simulations, the extrinsic and intrinsic losses of the resonator become entangled and result in critical coupling over a region of $w$ values. The under-coupled region is characterized by a simultaneous decrease in peak amplitude and resonance width compared to critical coupling while the over-coupled region is defined by a simultaneous decrease in peak amplitude and increase in resonance width compared to critical coupling. The over-coupled region is centered around $w = 290\text{nm}$, suggesting this is where $k_{\text{cav}} = k_{\text{wg}}$, in good agreement with data from Figure 3(c) and Figure 4(a). Slight differences between simulations in these figures are attributed to small meshing variation that marginally alters the waveguide and PCN cavity k-vectors.

It can be clearly seen in Figure 4(b) that the coupling regime is very sensitive to small changes in $w$ as the over-coupled region in this case occurs within 10$\text{nm}$ of waveguide width variation and the critical coupling regions occur within a combined 70$\text{nm}$ of waveguide width variation. It is important to emphasize that for the selected coupling gap size in simulation, a slight mismatch in wave-vector between the bus waveguide and PCN cavity is needed to prevent over-coupling. However, if a larger coupling gap size is utilized, thereby reducing the contribution of the

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Fig. 4. a) Simulated transmission from side-coupled PCN cavities with bus waveguide widths of 250nm (Bottom), 290nm (Middle) and 400nm (Top) and different coupling gap sizes. b) Simulated transmission from side-coupled PCN cavities with fixed coupling gap ($g = 150\text{nm}$) and various waveguide widths. Undercoupled, overcoupled and critically coupled regions are denoted by UC, OC and CC, respectively.
evanescent tail overlap to the energy exchange rate between the bus waveguide and the PCN cavity, closely matched wave-vectors will likely fulfill the critical coupling requirement.

4. Experiments

Side-coupled PCNs were fabricated to enable experimental verification of the simulated trends for coupling efficiency shown in Section 3 and to demonstrate excitation of high contrast resonance modes suppressed by in-line coupling. The devices were processed on a silicon-on-insulator (SOI) wafer with a 220nm thick silicon device layer and a 3µm thick buried oxide layer (SOITEC). Chips cleaved from these SOI wafers were coated with 300nm ZEP520A photoresist by spinning at 6000rpm for 45s. A JEOL93000FS tool was utilized to perform electron beam lithography. The photoresist was patterned with an electron beam at 100kV and 400 µC/cm² areal dosage. Patterns were developed after exposure with gentle agitation in xylenes for 30s followed by a rinse in isopropyl alcohol. The photoresist pattern was then transferred to the SOI device layer via reactive ion etching using an Oxford PlasmaLab100. Reactive ion etching was carried out with C₄F₈/SF₆/Ar gases. Samples were cleaved after fabrication to expose the edges of the feeding waveguides to enable characterization in an end-fire coupling setup.

Fig. 5(b) shows a scanning electron microscope (SEM) image of one of the side-coupled PCNs studied in this work. The large sensitivity of device performance to small variation in waveguide width demonstrated in Section 3 suggested the most practical way to measure the effects of k-vector mismatch and fabricate functional devices is to sweep the feeding bus waveguide width while maintaining a constant coupling gap size and PCN cavity geometry. In this way, our experiments are able to tolerate deviations in the PCN cavity resonance conditions that arise from fabrication variation by having several side-coupled devices, each with a bus waveguide supporting a mode with a slightly different k-vector. We chose to sweep the waveguide width in a range which would nominally capture the $k_{cav} = k_{wvg}$ condition. Accordingly, we fabricated identically designed PCN cavities with feeding bus waveguide widths ranging from $w = 380$nm to $w = 580$nm in 10nm increments, and a fixed coupling gap size of $g = 400$nm. The fabricated PCNs had a target width of $nw = 700$nm and period of $a = 350$nm with deterministic hole tapering from a radius of 105nm in the mirror segments to a radius of 127nm in the cavity region. The taper regions on either side of the cavity center consisted of 20 unit cells each, and the mirror regions consisted of 10 unit cells each.

Differences in the bus waveguide and PCN dimensions between the 2D FDTD simulations (Section 3) and fabricated structures were required to compensate for the different mode confinement in a 2D simulation compared to a fabricated (i.e., 3D) structure. As stated earlier, the PCN width was decreased in simulation to $nw = 600$nm to better mimic the modal confinement in a fabricated PCN cavity with a traditional $nw = 700$nm width. The period $a$ and radii of the PCN holes were accordingly adjusted in the fabricated PCN cavities to follow the deterministic design approach for a PCN with $nw = 700$nm in a 220nm thick SOI device layer [36]. The nominal bus waveguide width of $w = 480$nm was chosen to match $k_{cav}$ and $k_{wvg}$ in simulation, and the range of $w$ values fabricated ensured that different coupling regimes could be measured in experiment. A small, relatively quick (~ 10-15 minutes per simulation), parameter sweep of $g$ with $w = 480$nm was performed in 3D FDTD simulations to determine at which gap sizes the bus waveguide and PCN cavity were coupled. We determined the fundamental PCN cavity resonance was coupled to the bus waveguide if the $Q_{intrinsic}$ of the fundamental PCN cavity resonance mode dropped significantly when the bus waveguide was added to the simulation. Using dipole excitation (Fig. 2(a), blue), we calculated $Q_{intrinsic} = 1.0 \times 10^6$ for the fundamental PCN resonance mode without the bus waveguide present and $Q_{intrinsic} = 2.7 \times 10^5$ with the bus waveguide present at $g = 400$nm with $w = 480$nm. A non-uniform meshing parameter of 2 in Lumerical FDTD was used in these 3D calculations to reduce simulation resources. We note that a larger coupling gap could have been selected to reduce the drop in $Q_{intrinsic}$ caused by the
Fig. 5. a) Experimental data for peak depth and quality factor of the fundamental resonance in side-coupled PCN cavities. Blue and red data points represent data taken from two separately fabricated sample sets. The dashed grey lines are cubic spline interpolated fits to act as a guide to the eye. Undercoupled, overcoupled and near critically coupled regions are denoted by UC, OC and NCC, respectively. b) SEM image of device fabricated for experimental testing, illustrating the bus waveguide width, $w$, PCN width, $nw$, coupling gap, $g$, cavity period, $a$, and optical input and output of the bus waveguide. c) Experimental transmission spectra for in-line and side-coupled PCNs having the same PCN cavity design. The labels (i) and (ii) refer to the first measurable resonance mode in the side-coupled and in-line configurations, respectively. A magnified view of resonance (ii) is shown to the right with the corresponding Lorentzian fit.

The transmission spectra of the side-coupled PCN cavities were measured by coupling near-infrared light from a tunable laser (1500 to 1630nm, Santec TSL-510) into and out from the bus waveguides using polarization-maintaining lensed fibers (OZ Optics Ltd.), and detecting the output light intensity with a fiber-coupled avalanche photodiode photoreceiver (Newport 2936-C). TE optical polarization was utilized for resonance excitation and to acquire measured transmission spectra. In order to verify that the fundamental resonance of the PCN cavities was measurable in the transmission spectra, a separate PCN structure was fabricated to determine the approximate location of the band edge corresponding to the central cavity unit cell of the PCN cavities. This separate PCN comprised an array of air holes possessing the same unit cell geometry as that of the central cavity unit cell of the PCN cavities under test. The band edge of this PCN was located near 1521nm (not shown). According to the deterministic design method, the fundamental resonance of a PCN cavity is located near the band edge wavelength corresponding to its central cavity unit cell. Experimental measurement of this band edge allows us to predict and verify the fundamental resonance position despite deviation in fabricated PCN geometry from simulated design.

The metrics of resonance depth and width of the side-coupled PCN cavities with different bus waveguide widths are summarized in Fig. 5(a). The depth of the resonance was characterized by the transmission intensity of the resonance compared to the local baseline transmission intensity, which was normalized to a maximum of 1. The resonance width was characterized by the measured $Q$; we note that the fundamental resonance wavelength was similar for all measured
PCN cavities fabricated on the same chip, varying from 1513nm − 1521nm and 1518nm − 1530nm for the devices represented by the red and blue data points, respectively, in Fig. 5(a). These slight resonance wavelength variations are due to minor fabrication variations between devices, but all resonance wavelengths are near the expected band edge position. In order to highlight the importance of wave-vectoring matching, the relative resonance depth and Q of each of the measured side-coupled PCN cavities was plotted against the ratio of $k_{cav}$ to $k_{wvg}$. Following Eqs. (1) and (2), $k_{cav}$ was calculated from the PCN period, $a$, and $k_{wvg}$ was calculated from the measured resonance wavelength and the effective index estimated from Lumerical MODE Solutions simulations that considered bus waveguides with the designed widths, $w$. The data in Fig. 5(a) show that tuning of the bus waveguide wave-vector via a change in $w$ enables control of the coupling regime of the side-coupled PCN cavity independent of coupling gap. As expected, large wave-vector mismatch, $k_{cav}/k_{wvg} \gg 1$ or $k_{cav}/k_{wvg} \ll 1$, leads to low energy exchange and under-coupling of the resonator, as characterized by a low relative resonance depth and high Q of the measured fundamental transmission resonance. Close wave-vector matching, $k_{cav}/k_{wvg} \approx 1$, leads to drastically increased energy exchange; however, the lowered Q and small relative resonance depth are indicative of the over-coupled regime. A slight mismatch between $k_{cav}$ and $k_{wav}$ is necessary in this case to achieve near-critical coupling conditions for which the relative resonance depth is large and the Q is relatively high (peak depth $= 0.45$ and $Q = 2.6 \times 10^4$ demonstrated in Fig. 5(a)). The experimental trends shown in Fig. 5(a) are in excellent agreement with the simulated data in Fig. 4(b).

The transmission spectrum of a near-critically coupled, side-coupled PCN cavity ($k_{cav}/k_{wvg} = 0.98$, $w = 410$nm) with multiple high contrast resonances is shown in Fig. 5(c). The resonance labeled (i) corresponds to the fundamental mode of the PCN cavity with measured $Q = 2.6 \times 10^4$. In order to provide direct experimental evidence of the benefit of using the evanescent coupling into the PCN cavity, we fabricated a nearly identical in-line coupled PCN cavity with the same geometry but without a side-coupled bus waveguide present. A feeding waveguide extending from the edges of the cavity was utilized to couple light into the device. Figure 5(c) shows that the fundamental resonance is not measurable for the in-line coupled PCN cavity, indicating that its peak amplitude is lower than the measurement noise. The first resonance peak that can be observed in the in-line coupling configuration, labeled (ii), occurs at a much longer wavelength than (i), suggesting that (ii) is a much higher order resonance mode than (i), and mode orders lower than (ii) are significantly suppressed in the in-line configuration. While the measured $Q = 3.6 \times 10^4$ of (ii) is comparable to the Q of resonance (i), the relative peak amplitude of (i) is $\sim 20$ times greater than that of (ii). Additionally, it is important to note that the in-line coupling configuration leads to broadband signal loss from $\lambda \sim 1500$nm − 1610nm, which precludes serial integration of in-line coupled PCNs with other optical components. Side-coupled PCN cavities, on the other hand, are compatible with multiplexed applications on-chip. Comparing relative peak depth in the side coupled case to the relative peak amplitude with respect to unity transmission at the band edge in the in-line case, there is a significant peak amplitude improvement of $\sim 40$ times for peak (ii) with side-coupling. Since the fundamental resonance, (i), is suppressed below the measurement signal noise for in-line coupling, we calculate an enhancement of $> 100$ times for peak (i) by comparing the side-coupled peak depth to the standard deviation in the transmitted signal near that wavelength in the in-line spectrum.

5. Conclusion

We demonstrate design rules for side-coupled PCN cavities that enable critical coupling by appropriately tuning the wave-vector mismatch between modes of the PCN cavity and bus waveguide. The wave-vector of the bus waveguide can be adjusted in a straightforward manner through modification of the waveguide width. Using this design strategy, we demonstrated a greater than 100 times enhancement in signal amplitude in experiment for the fundamental
PCN cavity resonance when excited by evanescent coupling from a bus waveguide instead of using a traditional in-line coupling configuration. The side-coupled PCN scheme has the additional advantage of allowing a high baseline intensity of transmitted light, which opens the door to multiplexed applications that are not possible with the in-line coupling configuration. The generality of the analysis presented in this work should enable its application toward highly efficient coupling between other types of advanced photonic devices.

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**Disclosures**

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