Efficient photon collection from reconfigurable photonic crystal slab resonator operating at short wavelengths

Indra Karnadi,1 Ju-Young Kim,1,* Byeong-Hyeon Ahn,1 Hee-Jin Lim,1 and Yong-Hee Lee1,2,3

1Department of Physics, KAIST, Daejeon 305-701, South Korea
2Graduate School of Nanoscience and Technology (WCU), KAIST, Daejeon 305-701, South Korea
3e-mail: pcvcsel@gmail.com
*Corresponding author: peterfish.jy@gmail.com

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The efficiency of photon collection from a reconfigurable photonic crystal (PhC) resonator through a curved microfiber is investigated by means of k-space analyses. We observed that efficient photon collection through the microfiber can be achieved when the PhC slab is thinner than 0.6a, where a is the lattice constant of the PhC. For thicker slabs, loss through the slab TM mode, which stems from the broken mirror symmetry of the slab, becomes significant. It was found that this TM-mode coupling can be suppressed considerably by reducing the thickness of the slab. © 2012 Optical Society of America

1. INTRODUCTION
A semiconductor quantum dot (QD) coupled to an optical microcavity has become a subject of great interest as an efficient single-photon source [1–10]. High quality factor (Q), small mode volume (V) photonic crystal (PhC) resonators have drawn much attention as a result of their potential to provide a high Purcell factor [11–20]. However, the high Purcell factor of a PhC resonator becomes effective only when both the spatial and spectral locations of a QD are accurately overlapped with those of the PhC resonator of interest. In other words, placing a “correct” QD in the “correct” location remains as a challenging issue [19–21].

Curved-microfiber-coupled high-Q “reconfigurable PhC resonators” (RPCRs), which are relocatable and spectrally tunable, were proposed and demonstrated with an InGaAsP slab at wavelengths near 1550 nm [22–24]. In that scheme, the location of the PhC resonator can be defined repeatedly according to the contact of the microfiber. Furthermore, the spectral resonance and the coupling efficiency can be adjusted by changing the curvature of the curved microfiber [23,24].

An RPCR working at a shorter wavelength, near 950 nm for GaAs-based In(Ga)As QD emitters, is expected to be scaled down by a factor of ∼2/3. However, thinner slabs introduce several practical problems. For example, thin slabs have been found to be more fragile during the undercut wet-etching process through which free-standing slabs are made. For thick slabs, the phase matching between the resonator mode and the microfiber would become worse. Therefore, the search for the optimum slab thickness that can support both a high Q factor and high photon collection efficiency is interesting for both an understanding of the physics of photon coupling and for practical reasons.

In this paper, we investigate the effect of the slab thickness on the efficiency of photon collection and the Q factor of the RPCR. It was found that there exists an upper bound of the PhC slab thickness beyond which the optical coupling into the microfiber becomes degraded very rapidly. This criterion would be a useful guide for efficient photon collection with a RPCR through a curved microfiber.

2. FORMATION OF AN RPCR
An RPCR is formed by placing a highly curved microfiber on a PhC waveguide [Figs. 1(a) and 1(b)]. The principle behind its formation is based on the local perturbation of the PhC waveguide in the presence of a curved microfiber [22–24]. In the proximity of the contact point, the effective refractive index of the waveguide is slightly increased. As a result, the cutoff frequency and the mode gap position of the PhC waveguide (TE-like mode) near this point shift downward [Figs. 1(c) and 1(d)]. This local modulation of the mode gap generates a photonic well, where photons with specific frequencies can be confined. In the case of the parabolic air gap, the spatial profile of the mode gap position follows the shape of a Gaussian function [22–24].

3. THICK-SLAB RPCR VERSUS THIN-SLAB RPCR
To identify the resonant modes in a RPCR, three-dimensional finite-difference time-domain (FDTD) simulations were performed. The computational domain was surrounded by perfectly matched layers to prevent reflected electromagnetic waves at the domain boundaries. A point dipole source was placed at the antinode of the RPCR mode.

In our computation, the refractive index, lattice constant (a) and radius (r) of the air holes in the PhC structure were set to 3.45 (GaAs), 260 nm, and 0.30a, respectively. The lattice constant was set such that the resonant frequency of the RPCR would be around 950 nm, the typical emission...
The wavelength of an In(Ga)As QD. The diameter, radius of curvature, and refractive index of the curved fiber were set to 1 μm, 70 μm, and 1.45, respectively. We tested the convergence of our FDTD method by varying a grid size and used a grid size of \( a/40 \) based on the test (see Appendix A).

Figures 2(a) and 2(b) show cross-sectional views of the intensity and various field profiles of the RPCR modes with two different slab thicknesses: \( t = 0.8a \) and \( t = 0.5a \). The Q factors were \( 5.90 \times 10^4 \) and \( 1.24 \times 10^5 \), and the mode volumes were estimated to be \( 2.52(\mathcal{L}/n)^3 \) and \( 1.79(\mathcal{L}/n)^3 \) for the cases of \( t = 0.8a \) and \( t = 0.5a \), respectively. The mode volumes were calculated using the formula given in [25]. We investigated the case of \( t = 0.8a \) because the actual thickness in this case (\( \sim 200 \) nm) is similar to that used in an earlier study [22]. We investigated the case of \( t = 0.5a \) as well, which provides high photon collection efficiency through the curved fiber and a high Q factor.

As shown in Fig. 2(a), for the case of \( t = 0.8a \) (a thick slab) there is no observable coupling between the resonator and the curved fiber. Here, photons tend to couple easily with PhC slab modes and spread widely over the PhC slab, creating huge slab losses. Note that the \( E_y \) field [the second figure in Fig. 2(a)] does not have a node in the resonator region where a curved microfiber makes contact, whereas it does
have a node outside of the resonator region. This indicates that those modes flooding over the PhC slab have symmetry different from that of the resonant mode. Coupling between these modes of different symmetries (z-even or TE-like and z-odd or TM-like) is possible through the presence of the curved fiber, which induces the vertical asymmetry. The constraint of the orthogonality between TE-like and TM-like modes is removed [26–28]. The presence of the curved fiber also leads to mode mixing inside the resonator. This is indicated by the presence of the $H_z$ field (representative components of the TE-like mode) and the $E_y$ field (representative components of the TM-like mode) simultaneously at the center plane of the slab. The appearance of propagating and extended modes through the PhC slab in the $E_y$ field at the center is caused by the coupling between the TM-like components of the resonator mode and the TM-like slab modes.

In the case of a thin slab ($t = 0.5a$), the amount of slab loss becomes quite small and most of photons from the resonator funnel through the fiber, as shown in Fig. 2(b). The origin of the huge slab loss in the thick slab and the efficient collection of the thin slab will be discussed in the following sections.

4. SLAB LOSS IN A THICK-SLAB RPCR: K-SPACE ANALYSIS

In order to understand the physics of the huge slab loss in the thick slab ($t = 0.8a$) RPCR, we first investigate the band structure of the corresponding PhC waveguide (Fig. 3). When there is no fiber contact to the PhC waveguide, a PhC mode can be described safely as one of two orthogonal modes, the TE-like or the TM-like mode [30,31]. As shown in Fig. 3(a), in the frequency range of $0.24a/\lambda$–$0.32a/\lambda$, a photonic bandgap exists for TE-like modes but not for TM-like modes. Inside this bandgap, there are TE-like waveguide modes together with TM-like slab modes and TM-like waveguide modes. Here, “slab” mode indicates that the mode is extended over the slab and not confined by the waveguide line. The TM-like waveguide modes are formed not by the TE bandgap effect but by the effective index contrast between the waveguide line and its surroundings.

When a curved fiber is placed on the top of the PhC waveguide, the orthogonality between the TE-like and TM-like modes is broken. This condition allows the resonator mode to couple with TM-like slab modes. To estimate the coupling strength between various modes with the RPCR mode, we plotted a $k$-space profile of the RPCR mode by taking the Fourier transformation (FT) of the $E_y$ field [Fig. 3(b)]. This $k$-space profile represents the plane wave components that are contained inside the mode. Possible wave vectors ($k$) for the TM-like modes and radiation modes at the RPCR resonant frequency are depicted together as gray and black regions, respectively. The wave vector $k$ of the fiber-guided mode is shown as a black line. The TM-like waveguide mode is not involved in the $k$-analysis because its electric field has symmetry opposite to that of the RPCR mode.

Two modes that have the same $k$ at the resonant frequency, thus satisfying the “phase-matching condition”, are able to couple to each other. Note that a large fraction of $k$-components in the RPCR mode are overlapped with the TM-like slab modes. However, the $k$ for the fiber-guided mode has little amplitude in the $k$-space profile of the RPCR mode.

From this $k$-space analysis, the reason for the poor photon collection of the thick slab can be understood. The required wave vector $k$ of the fiber-guided mode is located farther from the center of the $k$-profile of the resonator than the wave vector $k$ of the TM-like slab modes. Therefore, the coupling with TM-like slab modes dominates the coupling with the fiber-guided mode, which explains the origin of the huge slab loss in the thick-slab RPCR.

5. HIGH PHOTON COLLECTION EFFICIENCY IN A THIN-SLAB RPCR: K-SPACE ANALYSIS

The TM-like slab loss is greatly suppressed in the case of a thin slab. The band structure of the thin slab is shown in Fig. 4(a). Note that the maximum $k$ line of TM-like slab modes shifted considerably toward the radiation mode, in comparison to the previous thick slab. As a result, there is little overlap between the RPCR mode and TM-like slab modes in the $k$-space [Fig. 4(b)].

It was found that the resonant frequencies of the TM-like modes are much more sensitive to the thickness than those of the TE-like modes, as the electric field intensity of the TM-like mode is strong in the vicinity of the air/dielectric interfaces, whereas that of the TE-like mode is concentrated...
more at the center of the slab (Fig. 5). Thus, the fraction of energy residing in the air is easily changed with the slab thickness for TM-like modes.

Reducing the slab thickness is also advantageous for phase matching with the fiber-guided mode. As the slab becomes thinner, the resonant frequency of the RPCR increases. At the same time, the k-space profile of the RPCR becomes broader. Figure 6 displays these two effects simultaneously. The dashed and solid black lines correspond to the k-space profiles of the RPCR mode of the thick and thin slabs with the resonant frequencies of 0.247a/λ and 0.272a/λ, respectively. The dashed and solid blue lines indicate the wave vectors for the fiber-guided modes at RPCR resonant frequencies of t = 0.8a and t = 0.5a, respectively. Observe that the wave vector k of the fiber-guided mode becomes closer to the FT RPCR resonance and that the coupling rate to fiber-guided mode increases for the thin slab. In Fig. 6, we also observed broadening of the k-space distribution for the thin slab. This broadening is a direct consequence of the narrowing of the resonator mode size in the real space. The spatial size of the RPCR mode decreases with the slab thickness, as a narrower and deeper “photonic-well” is formed. In the case of the thinner slab, the frequency shift caused by the contact of the fiber is larger due to the longer evanescent field of the PhC slab waveguide mode.

6. CONDITIONS OF EFFICIENT PHOTON COLLECTION

The photon collection efficiency (η) is defined as follows:

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\eta = \frac{1}{Q_{\text{fiber}}} \frac{1}{Q_{\text{air}}} = \frac{1}{Q_{\text{fiber}}} + \frac{1}{Q_{\text{air}}} = \frac{1}{Q_{\text{fiber}}} + \frac{1}{Q_{\text{air}}} + \frac{1}{Q_{\text{slab}}} \]

Here, 1/Q is the dimensionless net loss rate. It can be written as the sum of all individual loss rates (or coupling rates), 1/Q_{fiber}, 1/Q_{slab}, and 1/Q_{air} represent the loss rates to the fiber mode, slab mode, and air (radiation modes), respectively. η shows the percentage of cavity photons that exit through both ends of the curved fiber. Here, η is dependent on the ratio of Q_{fiber}/Q_{air} and Q_{fiber}/Q_{slab}. In order to obtain a high η, one has to find a way to keep these loss rates (1/Q_{air} and 1/Q_{slab}) smaller than the fiber coupling rate (1/Q_{fiber}).

The photon collection efficiency was found to increase monotonically as the slab thickness decreases. The efficiency η (red line in Fig. 7) is almost zero when the slab thickness is
0.8\(a\), but it surpasses 98% when \(t = 0.4a\). In comparison, the slab loss through TM-like modes has the opposite tendency (the blue line in Fig. 7). Over 90% of the total loss occurs through the coupling with the TM-like slab modes when the slab thickness is \(t = 0.8a\). However, note that the percentage of the slab loss decreases dramatically once the slab thickness becomes thinner than 0.6\(a\).

The \(Q\) factor shows a maximum value of \(4.0 \times 10^7\) when all of the losses are simultaneously suppressed in the case of \(t = 0.6a\). The decrease in the \(Q\) factors for the slabs thinner than \(t = 0.6a\) is attributable to the “useful” loss (coupling) in the fiber-guided mode. The \(k\)-space profile of the \(t = 0.6a\) case is shown in Fig. 8. The envelope of the \(k\)-space mode is located relatively far from the wave vectors of the fiber-guided mode and the TM-like slab mode. The efficiency of photon collection through the fiber is estimated to be 20%, which is bound by the dominant coupling with the TM-like modes. It was found that the relative contribution of the TM-like mode loss can be suppressed effectively if one employs thinner slabs. Finally, the fiber collection efficiency can be increased accordingly, as summarized in Fig. 7.

Slabs thicker than \(t = 0.6a\) are not recommended for fiber-coupling applications. For example, even for a slightly thicker slab of \(t = 0.65a\), the photon collection efficiency is dropped down to 5.6%. The thickness of 0.6\(a\) can be the upper limit for photon funneling through the microfiber in the RPCR configuration. For coupling with GaAs-based In(Ga)As quantum dots emitting near 950 nm, the actual thickness of 0.6\(a\) equals 156 nm.

7. SUMMARY

We studied the loss mechanisms of the RPCR and found the upper limit of the PhC slab thickness for efficient photon funneling through the microfiber. It was found that huge TM-slab losses can be induced by the contact of the microfiber and that control of the slab loss is essential for efficient photon collection. Through \(k\)-space analyses, we studied the \(k\)-space profile of the RPCR mode as a function of the slab thickness and showed that the TM slab loss is strongly influenced by the slab thickness. This finding can serve as a useful guide for the realization of microfiber-based RPCRs applicable to a quantum-dot single-photon source.

APPENDIX A

The numerical convergence of the FDTD code was tested by varying a resolution (grid numbers per one lattice) from 16/\(a\) to 50/\(a\) for the case of \(t = 0.55a\). Figure 9(a) shows the fiber collection efficiency and \(Q\) factors of the RPCR as a function of the grid size with the slab thickness of 0.55\(a\). Figure 9(b) plots the frequencies of the TE-like waveguide mode and the TM-like slab mode (the lowest frequency) at \(k = 0.5\). The \(Q\) factor and the collection efficiency are slightly increased until the grid number of 36/\(a\), and then are converged after that, while the frequencies are nearly same from 16/\(a\) to 50/\(a\). We used a resolution of 40/\(a\) in this study based on this convergence test.
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