Evanescent coupling between optical fiber tapers and photonic crystal waveguides (PCWG) allows highly efficient and mode selective interfacing between fiber optics and planar photonic crystal devices. Circumventing the intrinsic spatial and refractive index mismatch of fiber to PCWG end-fire coupling, this coupling scheme takes advantage of the strong dispersion and undercut geometry inherent to PC membrane structures to enable efficient power transfer between modes of a PCWG and a fiber taper. The coherent interaction over the length of the coupling region between phase matched modes of each waveguide manifests in nearly complete resonant power transfer between waveguides, and by varying the position of the fiber taper it is possible to tune the coupling strength and phase matching frequency, allowing the dispersive and spatial properties of PCWG modes to be efficiently probed.

In previous work, the coupling efficiency of this technique was studied by analyzing the signal transmitted through the fiber taper as a function of wavelength and fiber taper position. Although transmission measurements are sufficient to infer the efficiency of this coupling scheme, a measurement of power coupled into and then back out of a PCWG is of interest since it allows the lower bound of the input-output coupling efficiency to be directly established. By studying light which is coupled into a PCWG, reflected by an end-mirror at the PCWG termination, and then coupled into the backward propagating fiber mode, we show in this letter that this coupling scheme has near unity efficiency.

Figure 1(a) shows an illustration of the fiber taper evanescent coupling scheme. A fiber taper, formed by simultaneously heating and stretching a standard single mode fiber until it has a minimum diameter of roughly a micron, is positioned above and parallel to an undercut planar PCWG. The small diameter of the fiber taper allows the evanescent tail of its fundamental mode to interact with the PCWG, while the undercut geometry of the PCWG prevents the fiber taper from radiating into the PC substrate. A schematic detailing the optical path within the fiber taper and the PCWG is shown in Figure 1(b). To spectrally characterize the taper-PCWG coupler, an external cavity swept wavelength source with wavelength range 1565 nm - 1625 nm was connected to the fiber taper input. At the fiber taper output, a photodetector was connected to measure the transmitted power past the taper-PCWG coupling region. An additional photodetector was connected to the second 3dB coupler input to measure the light reflected by the PCWG.

The PCWGs used in this work were fabricated from a silicon-on-insulator (SOI) wafer. The air holes were patterned in the 300 nm thick silicon (Si) layer using standard electron-beam lithography and dry etching techniques, after which the suspended membrane structure
was created by selectively removing the 2 µm thick underlying silicon dioxide layer using a hydrofluoric acid wet etch. The PCWGs were formed by introducing a grade in hole radius along the transverse direction of a compressed square lattice of air holes [6], as shown by Figure 2(a-b). Coupling in this case occurs between the fundamental linearly polarized fiber mode and the TE-1 PCWG mode, whose field profile is shown in Fig. 3(a). This PCWG mode has a negative group velocity, resulting in a contractional coupling as depicted in Figure 2(b) and was designed to be integrated with recently demonstrated [7] high-Q cavities formed using a similar grading in hole radius.

On the opposite end of the PCWG, a poor reflector with low reflectivity (r2) was realized by removing (over several lattice constants) the transverse grade in hole radius while keeping the central waveguide hole radius fixed, resulting in a loss of transverse waveguiding within the end mirror section and allowing the TE-1 PCWG mode to diffract into the unguided bulk modes of the PC.

In the absence of reflections due to the PCWG termination (i.e. r1,2 = 0), the fiber-PCWG junction can be characterized by

\[
\begin{bmatrix}
  a_F^+(L)
  \\
  a_{PC}(0)
\end{bmatrix} =
\begin{bmatrix}
  t & \kappa' \\
  \kappa & t'
\end{bmatrix}
\begin{bmatrix}
  a_F^+(0)
  \\
  a_{PC}(L)
\end{bmatrix},
\]

where \(\kappa\) and \(\kappa'\) are coupling coefficients, \(t\) and \(t'\) are transmission coefficients, and \(a_F^+(z)\) and \(a_{PC}(z)\) are the amplitudes of the forward propagating fundamental fiber taper mode and the backward propagating TE-1 PCWG mode, respectively. The coupling region extends along the z-axis, with \(z = 0\) corresponding to the input and \(z = L\) to the output of the coupler. As illustrated by Figure 2(b), non-zero \(r_{1,2}\) introduce feedback into the system. This allows input light coupled from the forward propagating fundamental fiber taper mode into the TE-1 PCWG mode to be partially reflected by the PCWG termination, and subsequently coupled to the backward propagating fundamental fiber taper mode. In the presence of this feedback within the PCWG, the normalized reflected and transmitted powers in the fiber taper are given by [8]

\[
T = |a_F^+(L)|^2 = \frac{t + \kappa \kappa' t' r_1 r_2}{1 - r_1 t' r_2 t'^*}^2,
\]

\[
R = |a_F^-(0)|^2 = \frac{\kappa \kappa' r_1}{1 - r_1 t' r_2 t'^*}^2,
\]

for \(a_F^+(0) = 1\) and \(a_{PC}(L) = 0\). By measuring \(T\) and \(R\), and considering Eqs. (2,3) we can determine the efficiency of the fiber-PCWG coupling as measured by \(|\kappa \kappa'|\).

In the measurements presented here a fiber taper with 2 µm diameter was used to probe the PCWG of Figure 2(b). Figures 3(a) and 3(b) show \(T\) and \(R\) as a function of wavelength when the taper is aligned with the PCWG at a height of \(g = 0.20\) µm, and indicate that the phase-matched wavelength is \(\lambda \sim 1598 \pm 5\) nm. As described in Ref. [9], coupling to the guided TE-1 mode of the PCWG was confirmed by studying the coupling dependence upon polarization, lateral taper displacement, and fiber taper diameter. Figure 3(c) shows \(T\) and \(R\) at the resonant wavelength of the PCWG nearest the phase-matching condition (the minima and maxima in \(T(\lambda)\) and \(R(\lambda)\), as a function of taper height \(g\) above the PCWG. Included in Figure 3(c) is the off-resonant (away from phase-matching) transmission, \(T_{\text{off}}\), through the fiber. A maximum normalized reflected power \(R_{\text{max}} - 0.88\) was measured at a height of \(g \sim 0.25\) µm, where the corresponding transmission was \(T < 0.01\). As can be seen in
the wavelength scans of Figure 3(a), at this taper height the Fabry-Perot resonances due to multiple reflections from the end mirrors of the PCWG are suppressed for wavelengths within the coupler bandwidth due to strong coupling to the fiber taper. Ignoring for the moment the effects of multiple reflections in eq. 3, the maximum optical power coupling efficiency is then $|\kappa|^2 = \sqrt{R_{\text{max}}}/|r_1|$, where the square root dependence upon $R_{\text{max}}$ is a result of the light passing through the coupler twice in returning to the backward propagating fiber mode. Assuming the high reflectivity mirror is perfect (unity reflection), for the measured $R_{\text{max}} = 0.88$ this implies 94% coupling of optical power from taper to PC waveguide (and vice-versa).

By further comparison of $T(g)$ and $R(g)$ with the model given above, this time including feedback within the PCWG, we find that the high reflectivity PCWG end-mirror is imperfect and that $R_{\text{max}}$ is in fact limited by mirror reflectivity, not the efficiency of the coupling junction. For this comparison we take the elements of the coupling matrix to satisfy the relations $|t|^2 + |\kappa|^2 = 1$, $\kappa' = \kappa$, and $t = t^*$ of an ideal (lossless) coupling junction.[8] For the phase matched contradirectional coupling considered here, the dependence of $\kappa$ on $g$ can be approximated by $|\kappa(g)| = \frac{\tanh (|\kappa_{\perp,0}| g)}{g_0 L}$, where $\kappa_{\perp,0}$ and $g_0$ are constants. Substituting these relations into eqs. 2 and 3, $T$ and $R$ can be fit to the experimental data with $r_{1,2}$, $\kappa_{\perp,0}$ and $g_0$ as free parameters.10 Note that waveguide loss can also be included in the model, however it is found to be small compared to the mirror loss and will be studied in detail elsewhere. Figure 3(c) shows the fits to the data for $g \geq 0.20 \mu$m; for $g < 0.20 \mu$m non-resonant scattering loss is no longer negligible and the ideal coupling junction model breaks down. Note that the off-resonant scattering loss is observed to effect the reflected signal at a smaller taper-PCWG gap than for the transmitted signal, indicating that within the coupler bandwidth $1 - T_{\text{off}}$ is an overestimate of the amount of power scattered into radiation modes. From the fits in Figure 3(c), the PCWG end-mirror reflectivities are estimated to be $|r_{1,2}|^2 = 0.90$ and $|r_{2,2}|^2 = 0.52$, and the optical power coupling efficiency $|\kappa|^2$ occurring at $R_{\text{max}}$ ($g = 0.25 \mu$m) is approximately 97%.

In conclusion, these results indicate that this coupling scheme allows highly efficient input and output coupling between photonic crystal devices and fiber tapers, and is promising for efficient probing of future integrated planar PC devices.

KS would like to thank the Hertz foundation and MB the Moore foundation for financial support.

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