High optical coupling efficiency quasi-vertical taper for polymer waveguide devices

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ABSTRACT

Quasi-Vertical tapers are designed to enable high coupling efficiency from a conventional single mode fiber into a single mode polymer rib waveguide. A triangular region fabricated under the single mode waveguide is adopted to adiabatically transform the fiber mode into the polymer rib waveguide mode. This structure works as an optical mode transformer. Because the trenches are deeper at the facets than at the active regions of the waveguide, the waveguide mode size in vertical direction becomes larger at the facets and can better match the input and output fiber mode. A coupling efficiency of 82.95% is achievable with a tip width of 1 μm.

Keywords: Polymer, waveguide, taper, coupling efficiency, mode transformer, single mode fiber, butt coupling, micro-optical devices

1. INTRODUCTION

Flexible polymeric waveguide devices usually rely on butt coupling method to couple light between input/output (I/O) fibers, which usually has large mode profile mismatch in the vertical direction and limits the coupling efficiency. To address this problem, we designed a Quasi-Vertical Taper [1-15] to enable high efficiency coupling from a conventional single mode fiber (SMF) into a single mode polymer rib waveguide. In this design, a single mode waveguide comprising of 3.5 μm thick UV15LV (n=1.501 @ 1.55 μm) bottom cladding; 3 μm thick UFC-170A (n=1.496 @ 1.55 μm) top cladding; and 2.3 μm thick (0.5 μm rib height, 1.8 μm slab) and 8.5 μm wide SU8 (n=1.575 @ 1.55 μm) core layer, is considered. An SU8 taper is adopted below the waveguide core to transform the fiber mode into the polymer rib waveguide mode, and comprises of a triangular region with a 7.5 µm height, whose width is linearly tapered from 8.5 μm at the fiber end to a narrow tip at the waveguide end. This structure works as an optical mode transformer. Because the taper trenches are deeper at the facets than at the active regions of waveguide, the waveguide mode size in the vertical direction becomes larger at the facets and can better match the I/O fiber mode. The effect of the tip width and the taper length on the coupling efficiency is numerically calculated using beam propagation method. For a tip width of 1.0 μm and a taper length of 1.2 mm, 82.95% coupling efficiency is obtained. We chose 1.0 μm as the tip width considering photolithography limitations. Our design is compatible with roll-to-roll (R2R) imprinting and inkjet printing technique [16, 17], which enables high throughput and low cost fabrication of polymeric photonic devices on both rigid and flexible platforms.

2. QUASI-VERTICAL TAPER

High coupling efficiency between an SMF and polymer waveguides is crucial for the device packaging. Due to the large mode mismatch between the SMF and the polymer waveguide, large coupling loss will be encountered, if the light is directly coupled from the conventional SMF into the polymer waveguide. Thus, in our previous work [17, 18], we utilized single mode lensed fibers to couple light into and out of the polymer photonic devices. Still, the coupling loss

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of 3.02 dB, calculated by the overlap integral, is large. Additionally, lensed fibers are also more expensive than conventional SMF. In order to achieve low-loss coupling with a low-cost packaging option, in this work, we utilize Quasi-Vertical Taper [1-15] to directly couple light from conventional low cost SMF into the polymer waveguides. A schematic of the coupling section, and the simulated mode profiles at different cross sections along the taper, are shown in Figure 1. The red arrow in Figure 1 depicts the propagation direction from the fiber side to the device side. Because the taper trenches are deeper at the facets than at the active regions of waveguide, the waveguide mode size in the vertical direction becomes larger at the facets and can better match the I/O fiber mode.

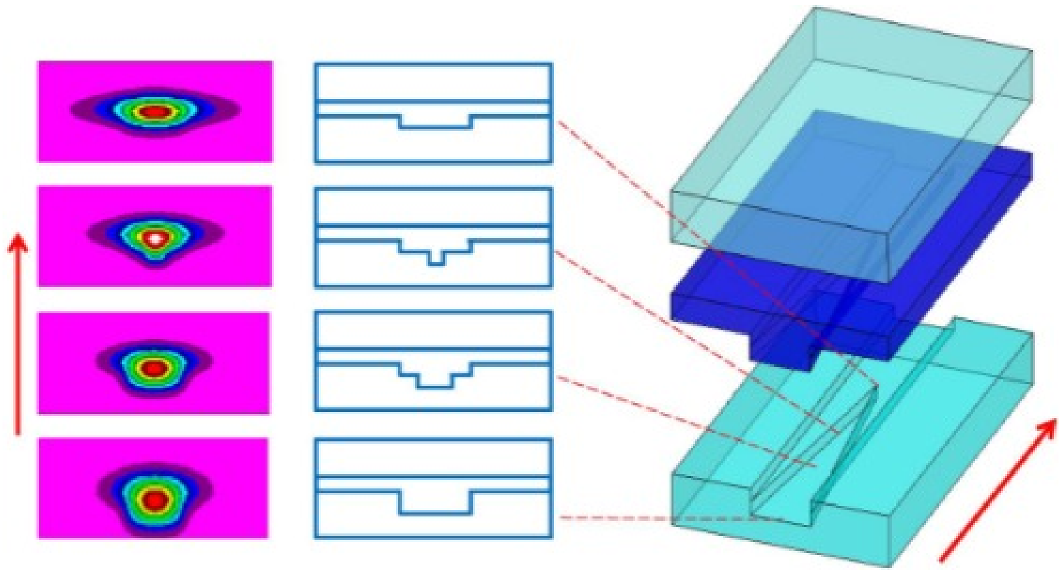


Figure 1. A Quasi-Vertical Taper at the facet of polymer waveguide. The red arrows indicate the beam propagation direction [2].

3. COUPLING EFFICIENCY

The fiber coupling efficiency is defined as a normalized overlap integral between the fiber and waveguide modes [3]:

$$\eta = \frac{\left|\iint F(x,y)W'(x,y)dx\,dy\right|^2}{\iint F(x,y)F'(x,y)dxdy \iint W(x,y)W'(x,y)dxdx} \tag{1}$$

where $F(x,y)$ is the function describing the fiber complex amplitude, $W(x,y)$ is the function describing the complex amplitude of the waveguide eigen-mode, and the $'$ symbol represents the complex conjugate. Additional system losses due to reflection from the air-polymer boundaries and bulk absorption are not considered in this calculation.

The mode profile distribution for polymer waveguide with trench heights of 0.5 μm and 8 μm are plotted in Figures 1(a) and 1(b), respectively. The eigen-modes are calculated using the beam propagating method (BeamPROP from RSoft Suite). It can be seen that the mode for height 0.5 μm has large mismatch with the single mode fiber, and that for height 8 μm can give a better match. Video 1 shows the fundamental mode (left) and 2nd order mode (right) for the trench width of 8.5 μm with different trench heights. When the trench height is smaller than 1.2 μm, the higher order modes are cutoff and the waveguide becomes single mode. So, the waveguide with height 0.5 μm can satisfy the single mode condition, however, the waveguide with height 8 μm cannot satisfy the single mode condition.

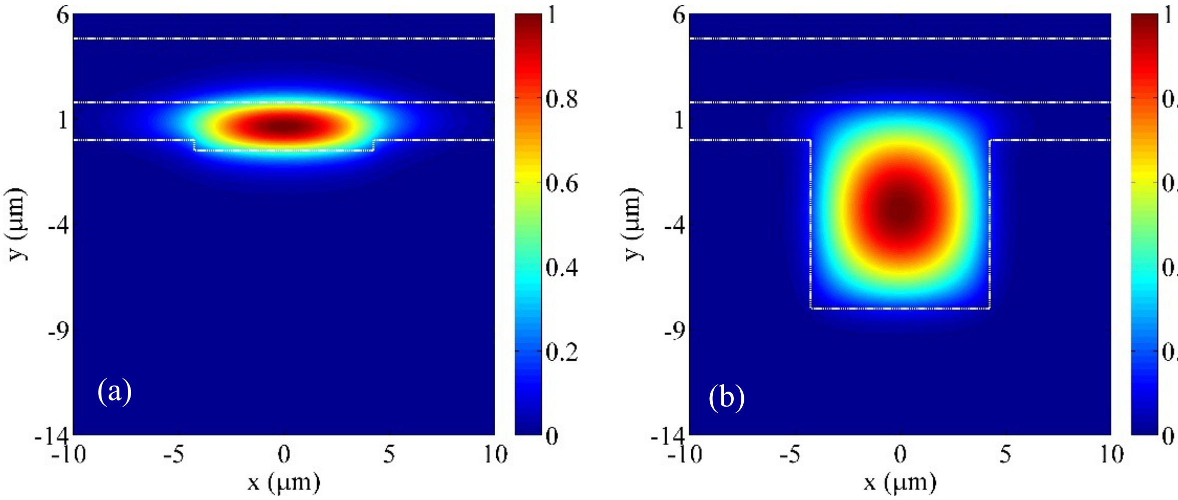
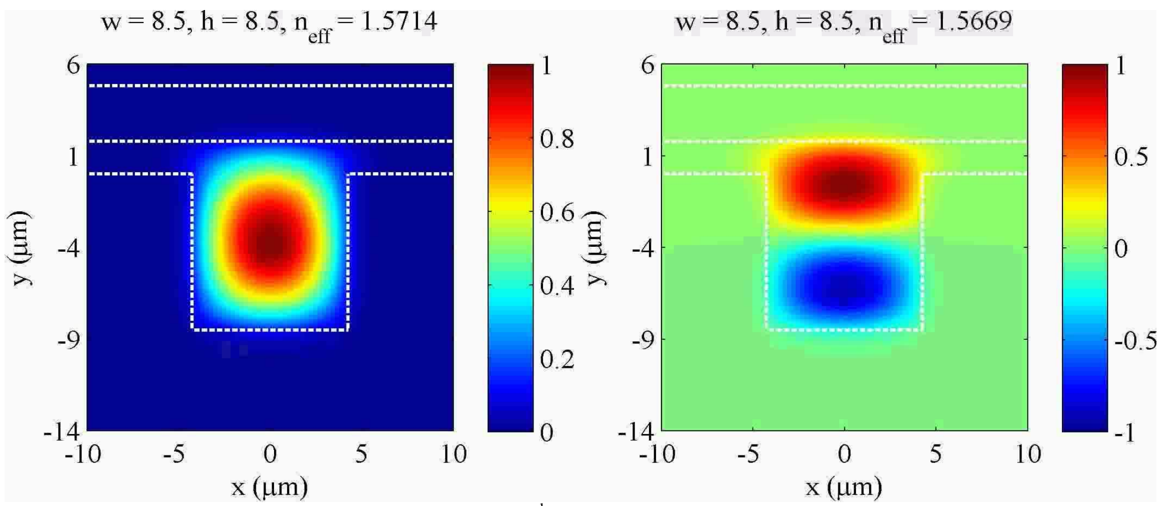


Figure 2. (a) The electrical mode profile distribution of a polymer waveguide (width 8.5 μm and height 0.5 μm). (b) The electrical mode profile distribution of a polymer waveguide (width 8.5 μm and height 8 μm).



Video 1. (Left) The fundamental mode and (right) the 2nd order mode of the waveguide with a trench width of 8.5 μm and trench heights from 12.5 μm to 0.5 μm. When height is smaller than 1.2 μm, the 2nd order mode is cutoff, and the waveguide satisfies the single mode condition. http://dx.doi.org/10.1117/12.2078560

The coupling efficiencies from the conventional single mode fiber (e.g., Corning© SMF-28) to the polymer waveguide with different geometries are calculated using Equation (1). The coupling efficiency of the taper waveguide at the fiber side versus the taper depth and width are plotted in Figure 3. The bottom left region under the white curve in Figure 3 indicates the single-mode region. The upper right region above the white curve in Figure 3 indicates the multi-mode region. Consequently, we choose the taper width at the fiber end as 8.5 μm and height as 8 μm to have a larger coupling efficiency with the SMF, and a waveguide width of 8.5 μm and depth as 0.5 μm at the device side to satisfy the single mode condition.

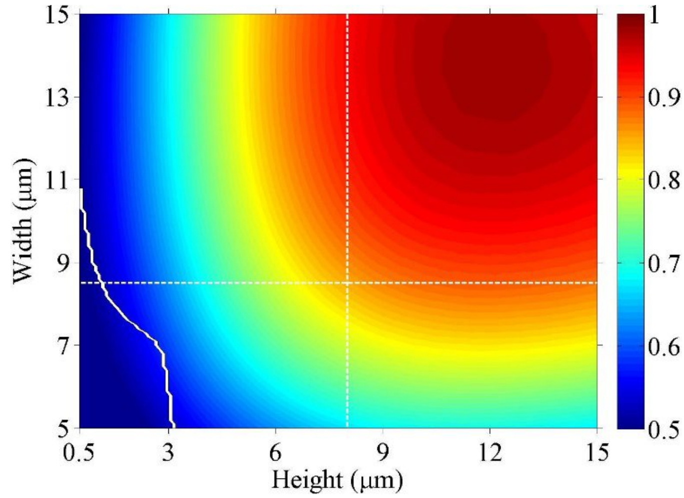
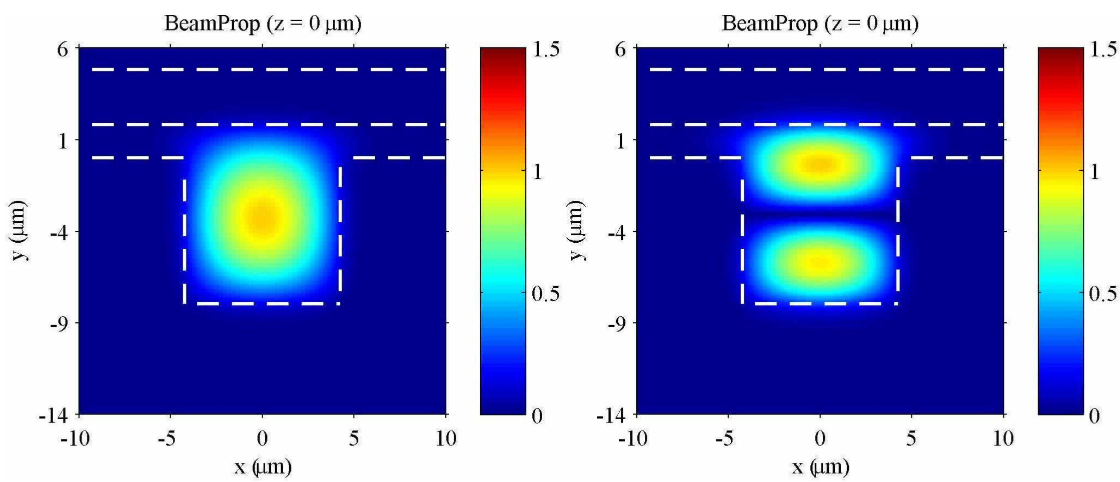


Figure 3. Coupling efficiency of taper at the fiber side versus the taper height and width. The bottom left region under the white curve and upper right region above the white curve indicate the single-mode and multi-mode regions, respectively. The intersection point of the white dashed lines indicates the chosen height of 8 μm and width of 8.5 μm at fiber side.

The effect of the tip width and taper length on the coupling efficiency is also numerically calculated using beam propagation method in PhotonDesign's FIMMPROP. For a tip width of 1.0 μm and a taper length of 1.2 *mm*, total coupling efficiency of 82.95% is obtained. We choose 1.0 μm as the tip width considering photolithography limitations. Video 2 shows the beam propagation through the Quasi-Vertical Taper to the active waveguide at device side. It can be seen that the higher order modes will be filtered by the Quasi-Vertical Taper.



Video 2. The beam propagation through the Quasi-Vertical Taper into the waveguide. Each frame shows the electrical field profiles (left: fundamental mode, right: 2nd order mode) at different location. The length of the taper is 1.2 *mm*. And due to the fabrication limitation, we choose the tip of the taper as 1 μm. The 2nd order mode can be filtered by the Quasi-Vertical Taper. http://dx.doi.org/10.1117/12.2078560

4. COUPLING MISALIGNMENT

A larger misalignment tolerance always helps in an easier packaging effort. The misalignment tolerance in the *x*- and *y*-directions for the case of direct coupling from a lensed SMF into a polymer waveguide with a width of 8.5 μm and a height of 0.5 μm [17, 18], and from conventional SMF to the Quasi-Vertical Taper are calculated using Equation (1). Figure 4(a) shows the coupling efficiency versus the x- and y- misalignments for the case of direct coupling from a lensed fiber into a polymer waveguide. Figure 4(b) shows the coupling efficiency versus the x- and y- misalignments for the case of coupling from a conventional SMF into a polymer waveguide through the Quasi-Vertical taper. Figure 4(c) shows the coupling loss for both cases along the x- and y- axes. By using the Quasi-Vertical Taper, the peak coupling efficiency from a fiber into a polymer waveguide is increased from 49.95% to 84.85% (coupling loss is reduced from 3.02 dB to 0.71 dB), and the 1 dB misalignment tolerance is increased from 1.25 μm to 4.34 μm, compared to the lensed fiber case.

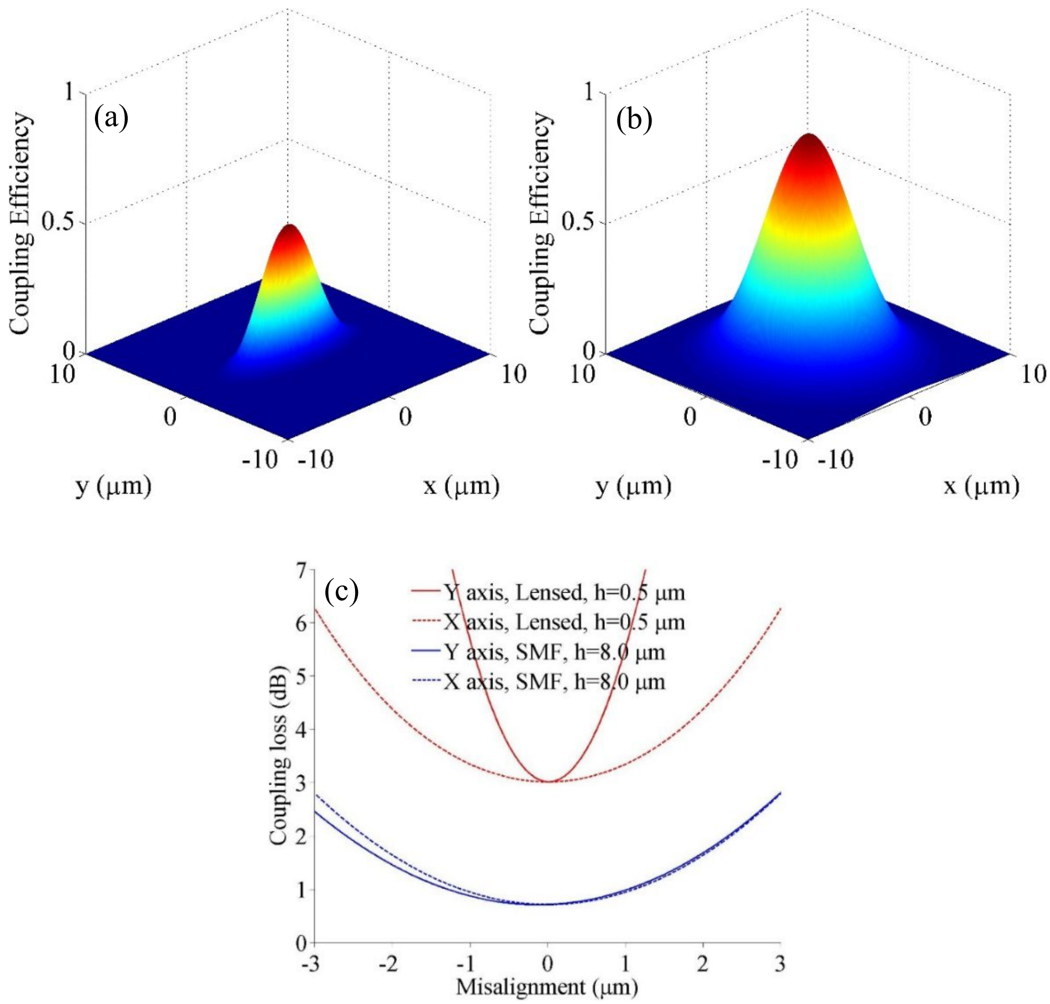


Figure 4. (a) The calculated optical coupling efficiency directly from a lensed SMF into a polymer waveguide (width 8.5 μm and height 0.5 μm) without a taper versus the misalignment in x- and y-direction. (b) The calculated optical coupling efficiency from a conventional SMF into a polymer waveguide through a Quasi-Vertical Taper (width 8.5 μm and height 8 μm) versus the misalignment in x- and y-directions. (c) The coupling loss in (a) and (b) versus the misalignment in x- and y-axis.

5. CONCLUSION

The Quasi-Vertical Taper, which is a triangular region designed under the single mode waveguide, is adopted to enable high coupling efficiency from a conventional SMF into a single mode polymer rib waveguide. Comparing our previous work (light coupling from a lensed SMF), using a Quasi-Vertical Taper (light coupling from conventional SMF), the coupling efficiency is increased from 49.95% to 84.85%, and the 1 dB misalignment tolerance is increased from 1.25 μm to 4.34 μm in the vertical direction, because a taper size 8.5 $\mu m \times 8$ μm at fiber facet can better match the conventional SMF. Moreover, the utilization of the conventional SMF can lower the overall cost of packaging. Thus, this vertical taper structure has various potential applications in some polymer-based active photonic devices such as electro-optic modulators [19], thermo-optic switches [17], photonic sensors [20], and optical interconnects [21]. Moreover, the polymer waveguides and Quasi-Vertical Tapers can be fabricated utilizing imprinting and inkjet printing techniques. These R2R compatible processes hold great promise for the roll-to-roll manufacturing on rigid as well as on flexible substrates.

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