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Optimization of Y-splitting antiresonant reflecting optical waveguides-based rib waveguides

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Abstract

Antiresonant reflecting optical waveguide power splitters, designed for use around the 635-nm wavelength, are characterized for multiple split angles ranging from 0.5 deg to 9 deg. Theoretical expectations and simulations predict lowest transmission losses at this split junction for the lowest angles. This is confirmed by the experimental structures built in SiO₂ films on silicon substrates. A fabrication nonideality affects the achievable splitting angle. Design considerations are discussed based on tradeoffs between loss and the required length for a Y-splitter.

Keywords

Y-splitters; antiresonant reflecting optical waveguides; rib waveguides; integrated optics

1 Introduction

Integrated optical devices in the visible range are important for biosensing because many fluorescent labels used for particle and molecular detection emit in the visible regime.¹ Such devices generally use SiO₂ as the guiding layer due to its low photoluminescence and ready availability in micro-fabrication processes. For integrated biosensors, it is convenient to have a variety of optical structures to allow for directing, combining, and splitting signals. When it comes to splitting light, the Y-splitter design is the simplest element to implement and study.

Y-splitter waveguides used in the infrared and visible regimes have been studied extensively for applications in planar lightwave circuits and microfluidic devices.^{2,3} Desired compactness in chip size has also led to the development of other splitter configurations, such as multimode interference couplers, photonic crystal beam splitters, indexed tapered, and trench based splitters.^{4–7} Although device performance and size can be further optimized with more design complexity, the Y-splitter continues to be studied for its

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simplicity. Some Y-splitter structures include buried channel, ion-exchanged sol-gel channel, plasmonic slot, multilayer plasmonic, ridge waveguides, and antiresonant reflecting optical waveguides (ARROWs).^{3,8–12} Here we will study Y-splitter rib waveguides on ARROW layers.

ARROWs enable light propagation in low index hollow or liquid cores. This is due to the cladding structure which consists of alternating thin film dielectric layers that produce an interference-based waveguide. Liquid and hollow core ARROWs have been used for on chip spectroscopy and gas sensing, optofluidic sensors, and complete on-chip systems for highly sensitive detection in the single molecule level.^{13,14} Recent studies of Y-splitters specifically on ARROW layers include a dual power splitter structure with remote coupling.¹²

Y-splitter rib waveguides on ARROW layers have also been shown to be useful for single molecule fluorescence detection in optofluidic biosensors.¹⁵ Using Y-splitters to produce multispot fluorescence detection, as shown in Fig. 1(a), increases the signal-to-noise ratio for particle detection when combined with signal processing.¹⁶ Improving the signal-to-noise ratio requires a time-dependent fluorescence signal with multiple peaks separated by the time difference of a particle passing between each excitation beam. The distance between spots, d , determines the spot patterns, and thus the time difference between the fluorescence peaks.

The simplest Y-splitter designs rely on a linear divergence between two waveguides at a specific angle. For very small split angles, achieving the necessary waveguide spacing may require a very long total length. When chip area is at a premium, compromising between the split angle and length of the excitation waveguide is important to reduce cost (smaller chip size) and ensure adequate detection capability (throughput). This paper provides a modeling and experimental study of linear diverging Y-splitters specifically designed for visible wavelengths. Based on calculated optical losses at the split junction, design decisions can be made regarding the proper split angles to use when creating an integrated optical chip containing splitter elements.

2 Device Design

The Y-splitters studied here used a rib waveguide design [see Fig. 1(b)]. They were formed in SiO₂ ($n = 1.46$) films, 3 μm thick by 4 μm wide. The bottom ARROW layers produce an interference effect enabling low loss propagation in a low-index core on top of a planar silicon substrate ($n = 3.88$). They consist of alternating SiO₂ ($n = 1.47$) and Ta₂O₅ ($n = 2.107$) thin films designed for light propagation at a 635-nm wavelength.¹⁷ Plasma-enhanced chemical vapor deposited (PECVD) SiO₂ was selected as the guiding material because of its low photoluminescence and propagation loss in the visible regime¹⁸ as well as its ease and speed of deposition.

To achieve optimal angle comparisons by limiting fabrication variances across the silicon wafer, 18 different angles from 0.5 deg to 9 deg, in varying increments, were located on the same 8 mm $\times$ 7.5 mm chip to be tested. Figure 2(a) shows a top view image of a Y-splitter with dimensions labeled. The spacing, d , was held constant in the experiment (25 μm) as a

typical desirable distance between waveguides and the previously used spacing in the multispot detection design.¹⁵ With d held constant, the length, L , controls the angles θ and ϕ , where θ is the angle at which two waveguides linearly diverge from a split point and ϕ is the angle at which these waveguide bend in order to be parallel with the original waveguide

[Fig. 1(a)]. These quantities are related by the equations, $\theta = \tan^{-1}(d/L)$ and $\Phi = 180 - \frac{\theta}{2}$. A shorter length, L , defines a higher split angle, which we in turn expect to result in increased split loss. We expect a longer length to decrease split loss but increase chip size and propagation loss.

3 Fabrication

The fabrication process shown in Fig. 2(b) started with a silicon substrate in the $\langle 100 \rangle$ orientation. Six ARROW layers commercially sputtered on top of the wafer by Evaporated Coatings Inc. with the specific thicknesses of 265 nm (SiO_2) and 102 nm (Ta_2O_5). We then deposited a 6- μm PECVD SiO_2 ($n = 1.46$). The coated wafer was then masked using SU8 to pattern the splitter structure. SU8 was chosen because of the ease of application (basic negative photoresist lithography processes), and its achievable heights with good aspect ratios.¹¹ The SU8 was spun to achieve a thickness of around 6 μm ; it was then baked at a max temperature of 95°C, which prepares the wafer for alignment. The photomask was aligned to the flat edge of the wafer to take advantage of the silicon $\langle 100 \rangle$ orientation such that the wafer could be cleaved perpendicular to the rib waveguides, creating clean input/output facets. This eliminates the need to polish the facets. A post exposure bake at a max temperature of 95°C strengthens the exposed SU8 chemical bonds, and the wafer was developed leaving the desired pattern behind. The lithography process used was not able to perfectly define the intended small separations between the linear diverging waveguides. As shown in Fig. 2(a), there is a distance, R , over which the intended gap is filled in. We expect this fabrication nonideality to have some effect on splitter performance. The SU8 structures were hard baked at 200°C to strengthen the mask so it could withstand etching. An RIE/ICP etcher was used to create anisotropic patterns of the splitters in the oxide. The SU8 mask was removed by a strong acid and the wafer was placed in a dehydration bake oven, until it was ready to test, to prevent moisture absorption by the SiO_2 films.¹⁹

4 Experimental Testing Setup and Procedures

Measurements of maximum throughput for each leg were made for Y-splitters at each design angle. A chip with all 18 angles was mounted to a metal mount attached to a five axis stage and aligned such that the desired angle's output facets could be seen by a mode imaging CCD camera. The CCD was focused on the chip edge by an objective lens. A collimated white LED was used to illuminate the facet through a beam splitter such that both legs' facets could be viewed in real time. Once the desired facets were aligned to the camera, a 635-nm light source (Thorlabs S1FC635) was coupled by a single-mode fiber to the input facet and the mode became visible on the CCD. The flip out mirror and beam splitter were removed so that the mode could focus directly on a photodetector (Thorlabs SM1PD2A). The fiber's alignment was then adjusted to maximize the power measured on the detector. The mirror was then replaced and the power attenuated to capture the mode image on the

CCD camera. If the mode image appeared to be guiding correctly in the waveguide (not aligned above the chip giving a false maximum), the maximum power was then recorded and the mode image saved. The mode images were then used to adjust the measured throughput to account for only the power coupled into the splitting waveguides. For example, in Fig. 3 the mode image for the 9-deg case, only the intensity in the rib portion was recorded and the optical power in the mode between the ribs was discarded. A top view image for each measurement was taken at a 10-dB laser power attenuation to record the occurrence of scattering loss throughout the waveguide (Fig. 3). As seen in the top view images in Fig. 3, for a larger angle (9 deg) there is an intense bright spot at the split and the scatter has a broader spread from the splitter structure. In contrast, smaller angles (0.5 deg) do not have the scattering spot or the large spread away from the rib structures. The mode images provide insight on the coupling at the split angle. For the small angles, the fundamental mode almost completely couples into the diverging waveguides. The larger angles, however, couple a large portion of the optical power through the oxide between the ribs, as shown in the example side view mode images in Fig. 3.

5 Simulations

In addition to experimental testing, Photon Design's FIMMWAVE software was used to simulate light propagation through the Y-splitters using a finite difference mode (FDM) solver. The total power transmitted into the arms of the each Y-junction is simulated versus angle. The distance, d , was held constant and the change in angle was obtained by varying the length. The simulations do not account for propagation loss, they account only for the loss at the split angle.

6 Data and Results

First we ran the FDM solver for the ideal case where the split happens where the gap between the diverging arms is perfectly defined. These resulting throughputs for each angle are shown as the triangles in Fig. 4. To try to understand possible discrepancies between experimental and simulated data, another simulation was run to account for the fabrication nonideality as described by the parameter R [see Fig. 2(a)]. These results are shown as squares in Fig. 4. The value for R was measured for all angles using a high-resolution optical profilometer on multiple devices and added into the simulation. Seven devices for each angle were measured and the averages of these measurements along with the experimental errors are recorded in Fig. 4 as a normalized transmission. The total measured percent throughput increases with decreased angle as intuitively expected.²⁰ The experimental error bars on the graph were found by measuring the same device 10 times, and were determined to be about 10% of the maximum throughput. As can be seen from the data, the limit to our fabrication process as described by the parameter R (see Fig. 5) appears to cause a deviation from the expected ideal in both the measured normalized transmission and the simulation. This is because as the waveguide diverges at the split point, it becomes multimodal in nature. Optical power is coupled into higher order modes which then do not couple correctly into the diverging single-mode waveguides that form the output legs of the Y-splitter. In general, however, the simulations and measurements confirm expectations regarding losses in the splitter as angle θ increases.

The loss, α_s due to each split angle was calculated from

$$\alpha_s = 1 - \frac{P_{out_n}}{P_{in_n}(1-\alpha_f)e^{-\alpha_L l_c}}, \quad (1)$$

where α_f is the loss from all facets, α_L is the propagation loss, l_c is the total length of the Y-splitter chip, and P_{out_n} and P_{in_n} are the powers out and in for each device, respectively. The facet and propagation losses were found experimentally using the cutback method on multiple straight (nonsplitting) rib waveguides from the splitter chips. The average propagation loss was found to be 0.781 cm^{-1} and the average coupling loss from all three facets was found to be 11.2%. Using the above equation and the measured propagation and facet loss values, the angle-dependent loss at the split location was calculated for each angle as shown in Fig. 5. The split loss at the Y-junction increases with increased angle as predicted. The higher loss with increased angle can be attributed to loss of mode confinement and increased scatter at the split. The top view images in Fig. 3 help us to visualize the scattering loss at the split due to the higher split angles. It is clear to see that the larger the angle, the more light is scattered at the point of the split.

Also plotted in Fig. 5 is the length parameter L versus angle. The length is proportional to

the inverse tangent of the angle, $L = \frac{d}{\tan(\theta)}$, with d held constant, θ increases as L decreases. When the angle is reduced below 1 deg, the length starts to increase drastically causing a 0.5-deg angle to take almost 3 mm of chip space, see Fig. 5. Judging from the split loss and total length necessary to realize the split, using angles less than 2 deg may not be practical or advantageous, especially if multiple Y-splitters are cascaded together in order to produce a 1 to N splitter.

7 Conclusion

Design optimization for Y-splitters relies heavily on chip size constraints as splitters with lower split loss require longer waveguides. We have provided experimental and modeling results for power transmission through Y-splitter elements. Both of these results confirm expectations that more shallow angles have lower split losses; however, fabrication constraints dictate split angles that can be achieved in practice. Based on our measured results, we conclude that using split angles less than 2 deg has little practical benefit in terms of performance and substantially increases the overall length of the splitter. Acceptable throughput relies heavily on the application of the splitter, and 30% transmission is reasonable for many applications. For future devices built from Y-splitters on ARROW layers, including cascaded Y-splitter elements, using a 2-deg split angle appears to be a reasonable engineering compromise between transmission performance and compactness.

Acknowledgments

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Fig. 1.

(a) Schematic of microfluidic biosensor using ARROW Y-splitters for multipot detection.

(b) A cross-sectional view of the rib structure with dimensions.

Fig. 2.

(a) Top view image of actual splitter showing dimensions. The distance, R , is a fabrication nonideality where the lithography process was unable to perfectly define the intended split angle. (b) Fabrication process, (i) initial ARROW layers on Si substrate, (ii) top 6 μm oxide growth, (iii) SU8 mask patterning, and (iv) SU8 mask removal.

Fig. 3.

Select top view and side view mode images of different split angle devices. All images were taken with a CCD camera. The white guide lines in the bottom two images are superimposed to indicate facet locations.

Fig. 4. Normalized transmission of experimental results (dots with error bars) and simulation data (ideal = triangles, nonideal = squares) versus angle, in degrees, for various angles. Each experimental point is a normalized average of seven measurements of seven different devices of the same split angle.

Fig. 5.

Experimental split loss in percentage (dots) versus angle in degrees, the limiting distance, R , in micrometers (triangles with line), and length, L , in micrometers (diamond with line) versus angle in degrees. Error bars propagated from the uncertainties of all measured quantities including throughput, facet loss, and propagation loss.