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Optimized ARROW-Based MMI Waveguides for High Fidelity Excitation Patterns for Optofluidic Multiplexing

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Abstract

Multimode interference (MMI) waveguides can be used for multiplexing and de-multiplexing optical signals. High fidelity, wavelength dependent multi-spot patterns from MMI waveguides are useful for sensitive and simultaneous identification of multiple targets in multiplexed fluorescence optofluidic biosensors. Through experiments and simulation, this paper explores design parameters for an MMI rib anti-resonant reflecting optical waveguide (ARROW) in order to produce high fidelity spot patterns at the liquid core biomarker excitation region. Width and etch depth of the single excitation rib waveguide used to excite the MMI waveguide are especially critical because they determine the size of the input optical mode which is imaged at the MMI waveguide's output. To increase optical throughput into the MMI waveguide when light is coupled in from an optical fiber, tapers in the waveguide width can be used for better mode matching.

Index Terms

Dielectric waveguides; Fluorescence; Fluorescence spectroscopy; Integrated optics; Multimode waveguides; Multiplexing; Rib waveguides

I. Introduction

Photonic devices utilizing multimode interference (MMI) waveguides have predominantly been used for fiber-optic communications. Such devices typically operate in the infrared between the wavelengths of 800 nm and 1700 nm. One such device is the MMI coupler, a passive component capable of multiplexing or splitting optical signals [1–3]. MMI waveguides have many advantages in their design such as low loss, small footprint and generous fabrication tolerances [4, 5]. Recently, MMI waveguides have also been applied to multiplexed optofluidic biosensors operating in the visible wavelength regime [6–10]. The optofluidic platform puts bioparticles into the direct path of an excitation beam, enabling high sensitivity fluorescence detection. Standard fluorescent dyes, intercalating dyes, oligo probes and molecular beacons can be used to allow selective detection of DNA, and thus the determination of genetic information [11–12]. These fluorescent dyes also provide wavelength selectivity because they fluoresce at particular wavelengths, typically in the visible regime. Combining MMI waveguides, which produce different excitation patterns at different wavelengths, with wavelength selective targets is advantageous for medical diagnostics because it allows for simultaneous testing of different targets, such as DNA sequences. In this way, different species or gene characteristics can be identified in the same test. Enhanced signal-to-noise ratios (SNR) are also possible when utilizing MMI produced excitation patterns [6, 13]. With these many advantages, multiplexed fluorescent sensors will be important components in lab-on-chip diagnostic instruments for use at the point of care.

In order for multiplexed fluorescence sensors to accurately detect with a high sensitivity, the excitation beam emerging from the MMI waveguide needs to produce a high fidelity spot pattern of N evenly spaced, wavelength dependent copies of a self-imaged mode (the excitation beam coupled into the MMI waveguide). The evenly spaced peaks enable the use of a signal-processing algorithm to identify targets with enhanced SNR [13]. This algorithm takes the collected fluorescence signal and shifts by the time between peaks, t , to create the enhanced signal. High fidelity spots should be narrow to avoid overlap, which can raise the background signal noise floor. They should also have high peak to valley ratios to achieve high SNR enhancement [13].

Here we explore how the geometry of MMI rib waveguides built over ARROW layers can be optimized to provide the highest fidelity spot patterns possible. Especially critical are the single-mode excitation waveguides used to excite the input side of the MMI waveguide. The modes from these single-mode excitation waveguides are imaged in the MMI waveguide; so well confined modes with small FWHMs are expected to produce high fidelity spot patterns. We concentrate on the rib width and height for the excitation waveguides and demonstrate how these parameters directly affect the resulting spot patterns. Our conclusions lead us to a tapered waveguide design which will ultimately allow for high optical throughputs along with high fidelity spot patterns.

II. Optofluidic Platform

As previously shown [6–8], our optofluidic platform with an MMI waveguide is capable of simultaneous identification of diverse biological targets, including single viruses and labeled

DNA strands. As the purpose of this paper is to discuss the optimization of the MMI waveguide for producing high fidelity excitation patterns, an overview of the platform will be given here so as to outline its scale and operation constraints. The device is represented by the illustration in Fig. 1a. To excite a passing fluorescently labeled particle (such as a DNA strand or collection of DNA strands), visible laser light is butt coupled via an optical fiber with a 4 μm diameter core. When the MMI waveguide is properly designed, multimode interference produces a spot pattern, similar to the top down image in Fig. 1b, which consists of multiple copies of the input mode. The number of spots corresponds to the excitation wavelength and the waveguide geometry governed by

$$N \cdot \lambda = \frac{n_c w^2}{L}, \quad (1)$$

where n_c is the core index, w is the effective width (which takes into account the lateral penetration depth of each mode field), L the length of the MMI waveguide, and λ the wavelength of excitation light [14]. When used for multiplexing, the MMI waveguide needs to be designed such that the device length achieves high fidelity spots across multiple wavelengths. This requires a specific length L to get an integer numbers of spot patterns for different wavelengths at the liquid core (LC) intersection [15]. For our design which is meant to give $N = 6$ spots at 738 nm, $N = 7$ spots at 633 nm, $N = 8$ spots at 554 nm and $N = 9$ at 492 nm, the MMI waveguide for optofluidic multiplexing is 75 μm wide by 1,932 μm long or 100 μm wide by 3,442 μm long. The MMI waveguide intersects the LC, which is between 5 and 6 μm tall and 12 μm wide. The multi-spot pattern from the MMI waveguide is used to excite the labeled target, which gives off a fluorescence signal that is collected by the LC waveguide and coupled off chip by a 12 μm wide solid-core collection waveguide through an objective lens to an avalanche photodiode (APD). To filter out the excitation laser wavelengths, a filter is placed between the APD and objective lens. All waveguides in the device are anti-resonant reflecting optical waveguides (ARROWs) so that the structure can be built on silicon substrates, which allow for the integration of liquid and solid core waveguides [6]. ARROWs are interference based waveguides that enable light to propagate in the lower index liquid core [16].

From this brief overview, we can point out several challenges when constructing MMI waveguides for use in optofluidic multiplexing:

1. There is a need for a wide MMI waveguide to provide sufficient spacing between spots in the output spot pattern and to attain high fidelity patterns for multiple wavelengths. This results in longer waveguides which must hold their fabrication tolerances over a relatively large area [17–18]. MMI waveguide tolerances are defined in reference [17].
2. With fluorescent dyes more readily available in the visible regime, we cannot use light in the infrared which limits the selection of materials that can be used for the guiding cores. Further, our guiding layer must be deposited at low temperatures, achieve high thicknesses and have low photoluminescence. These

constraints limit us to the use of SiO_2 , $n_c = 1.51$, deposited by plasma enhanced chemical vapor deposition (PECVD). The use of SiO_2 for the core and air for the cladding results in a refractive index contrast of 28.1%. MMI waveguide based devices used for telecommunications in the infrared would have a 45.8% contrast [17]. The contrast affects the resolution of the self-imaged pattern, with higher contrast resulting in better spot resolution [14, 20].

3. The use of fluorescent dyes poses tighter fabrication tolerances as we need to be in the wavelength range of maximum absorption for each color across multiple wavelengths. This translates to tight tolerances of approximately ($\pm 0.8\%$) on the required widths for the MMI waveguides. A $75\ \mu\text{m}$ wide waveguide can only have a variation of $\pm 0.6\ \mu\text{m}$.

III. Fabrication and Design

Devices with and without LCs were fabricated in order to characterize the MMI waveguides. The full fabrication procedures for the LC-ARROW structure have been described previously [21–22], while this paper focuses specifically on MMI waveguide fabrication procedures. We began with a single $\langle 100 \rangle$ oriented silicon wafer, Fig. 2a. ARROW layers were sputtered on the surface, Fig. 2b, consisting of six alternating films of silicon dioxide (SiO_2 , $n = 1.47$) and tantalum pentoxide (Ta_2O_5 , $n = 2.107$). A $6\ \mu\text{m}$ silicon dioxide ($n_c = 1.51$) layer, which serves as the guiding layer for the excitation, collection and MMI waveguides, Fig. 2c, was then deposited using PECVD. The oxide was patterned with AZ3330 photoresist, Fig. 2d, to perform a nickel liftoff step, which created a Ni mask used to protect the waveguides during plasma etching, Fig. 2e–f. The oxide was anisotropically etched to varying depths, using an inductively coupled plasma (ICP) reactive ion etcher (RIE), to create the rib or ridge waveguides, Fig. 2g. Lithography masks contained geometries for different waveguide widths so comparable structures could be made on the same wafer. Different etch depths were achieved by cleaving sections of the wafer away after different etch steps. The Ni and etch residues were then removed. To determine optimal input waveguide widths, we designed a mask with five $75\ \mu\text{m}$ wide MMI waveguides that had various excitation waveguide widths (nominally $2\text{--}6\ \mu\text{m}$) on a single chip, Fig. 2h.

IV. EXPERIMENT

Multiple experiments and simulations were conducted to optimize the geometry of the input waveguide to the MMI waveguide and characterize how the modes produced by these input waveguides affected the subsequent output spot patterns for the MMI waveguide. We take advantage of the $\langle 100 \rangle$ orientation during fabrication such that we can cleave orthogonally to the MMI waveguide and excitation waveguide. Multiple chips of each etch depth were cleaved with a diamond scribe to produce clean and smooth facets suitable for optical testing.

First, in order to examine which excitation waveguide geometry would produce the optimal input mode, the fabricated waveguides with varying excitation widths and depths were characterized by capturing mode images for each geometry. Each chip with various widths ($2\ \mu\text{m}$, $4\ \mu\text{m}$, $6\ \mu\text{m}$) and a specific etch depth was fixed to a chip mount attached to a five

axis stage and aligned to a 633 nm laser (Thorlabs S1FC635) which was used to couple light to excite the fundamental mode. The output at the chip edge was captured by an objective lens, imaged onto a CCD camera, and the mode images recorded. We then calculated the horizontal FWHM for each mode from the images. Simulations of the mode profiles expected for the various widths and depths were also run using Photon Design's FIMMWAVE software.

To characterize the output patterns of the MMI waveguides, we measured the average FWHM for the spots and the average Peak-Valley difference, which is defined as the normalized intensity difference between a detected peak and an adjoining valley. These metrics are used to quantify the fidelity of the MMI waveguide interference/spot pattern. We characterized this Peak-Valley difference versus number of spots and length of the MMI waveguide using a white light laser source (NKT Photonics) coupled into the ARROW chip. Scans were made between the wavelengths from 430 nm to 670 nm to generate a different number of spots at the MMI waveguide end facet. A microscope objective, beam-splitter and CMOS camera were used together to image the facet and record the MMI pattern.

V. Results and Discussion

A. Excitation Input Waveguides

The results of the experiments and simulations of the single-mode waveguides used to excite the MMI waveguides are shown in Fig. 3. Scanning electron microscope (SEM) measurements indicated an error in lithography resulting in the excitation waveguides being 2.8 μm , 4.9 μm and 6.7 μm wide. The 6 μm etch depth experimental data were made on a separate wafer resulting in narrower waveguides, 2.7 μm , 4.6 μm , and 6.3 μm , which is why the corresponding experimental data points are lower. We can conclude that in general the narrower the excitation waveguide the narrower the FWHM for the waveguide's optical mode. The etch depth also plays a large role in the lateral confinement independent of waveguide width. This trend is not linear and at an etch depth around 4.5 μm (our total SiO_2 thickness is 6.0 μm), the improvement to the FWHM stops and we no longer get significant reductions in the FWHM, Fig. 3. Both simulated and experimental mode images are for 2.8 μm wide waveguides with different rib etch depths. As the etch depth increases, the optical mode becomes more elliptical in shape as it becomes more confined within the area of the rib itself. In the extreme case of a shallow rib (very evident in the first experimental image), there is little mode confinement and light spreads throughout the SiO_2 layer on either side of the rib. Simulated and experimental data tend to match well. Interesting to note is that for shallow ribs the narrower the waveguides tend to have less rib confinement evident in the higher FWHM.

From this experiment, we have determined that the optimum width for the excitation waveguides (in order to get narrow, high fidelity spot patterns) is as narrow as the lithography and etching process resolution can provide. The optimum etch depth for a 6 μm thick SiO_2 layer is between 4.5 μm and 5 μm . For other SiO_2 thicknesses, the optimum etch would be one at which the optical mode is almost completely confined in the rib of the waveguide without etching completely through the oxide. Etching through the SiO_2 and into the underlying ARROW layers and silicon substrate should be avoided because such etching

results in the creation of micropillars which can make for a very rough surface and also break off and land on the uncovered waveguide adding scattering loss.

Further evidence to the improvement made from deeper etching is the correlation between the excitation waveguide input mode and the output from the MMI waveguide. We see in Fig. 4 images of the single excitation mode and its corresponding interference pattern at the MMI waveguide output. The average FWHM for the MMI spot pattern of the 5 μm etch depth was 2.2 μm and the FWHM of the 3 μm etch depth was 4.5 μm . A MATLAB script was also used to analyze these images taken from the MMI waveguide facet in order to extract the Peak-Valley difference. The MMI signal is computed as the normalized value of intensity integration in vertical direction to study only horizontal pattern features. For a pattern of multiple peaks (spots), Peak-Valley is averaged on all the spots to give a single normalized value, with a value of one being ideal. For the spot patterns in Fig. 4, the poorly confined mode resulted in a Peak-Valley value of 0.76 whilst the well confined mode resulted in a 0.81 Peak-Valley value. The poorly confined etch also raises the normalized noise floor from 0.41 to 0.45 - a direct result of light excitation where the valleys between spots should be. Further and arguably more damaging to the fidelity of the spot pattern is the spread of the peak and randomness of the extra light peaks visible in the valleys of the spot pattern. This causes the distance between spots to be inconsistent, which negatively affects the signal-processing algorithm used to enhance the SNR and identify the fluorescently labeled biomarkers from the temporal spacing of the fluorescence peaks.

B. MMI Patterns

MMI waveguides with 4.9 μm wide excitation waveguides showed good spot patterns across multiple wavelengths. An example of their characterization can be seen in Fig. 5a, as a photographic image and as a plot of intensity versus position (plotted as the normalized intensity versus the horizontal scanline). We expected better Peak-Valley values for fewer spots, because they overlap less. As seen, for an MMI waveguide of a specific length, longer wavelengths produce fewer spots. These spots are distributed across the width of the waveguide, so larger numbers of spots tend to have more overlap, decreasing the Peak-Valley difference. Important to note is that shorter MMI waveguides can obtain better Peak-Valley quantities for the same number of spots as evident from Fig. 5b, which plots the Peak-Valley difference for three different MMI waveguide lengths. Excitation wavelength has been adjusted for these waveguides to produce integer numbers of spot patterns. We can attribute a better Peak-Valley difference for shorter waveguides to the refractive index variations [18]. The PECVD growth process can incorporate many defects, resulting in index variances throughout the film. This is especially true for thicker films, ours being 6 μm [23, 24]. This negative affect is enhanced by the longer MMI waveguide as there is more material for the mode to propagate through. This reduces the resolution of the spot pattern in the output, and thus causes the fidelity of the spot pattern to decrease. Unfortunately, shorter MMI waveguide designs are not feasible given the sensor's application. In order to optimally excite the fluorescent labels at their excitation wavelengths the waveguide is lengthened to achieve a common multiple of the beat lengths for each color [15]. The width cannot be adjusted to shorten the length (Equation 1) as the width must be kept wide to provide adequate spacing between excitation beams, which determines t . In summary, as seen in

telecommunications [15], shorter MMI waveguides can attain higher fidelity spot patterns and in order to obtain optimal spot patterns the etch depth and excitation waveguide width must be deep and narrow.

C. Tapered Waveguides

We have concluded that the optimized width for excitation waveguides into MMI waveguides should be as narrow as the lithography and etching processes will allow. For most practical waveguides, this translates to a width of about $2\ \mu\text{m}$. Waveguides this narrow pose constraints on the fiber coupling as the fiber mode's FWHM is larger than that of the facet. For example, the $2.8\ \mu\text{m}$ wide facet etched to $5\ \mu\text{m}$ produces an experimentally measured FWHM of $1.45\ \mu\text{m}$ where the fiber FWHM at the same $633\ \text{nm}$ wavelength produces a FWHM of $2.25\ \mu\text{m}$, and similar mismatches are seen across the desired wavelengths. This fiber to facet mode mismatch reduces coupling efficiency [25], translating to low optical throughputs. Low throughputs result in reduced sensitivity of the chip when high powered lasers are not available to offset the attenuation of the chip. For use at the point of care, high powered lasers will not be used as they are bulky and would increase the cost of the diagnosis.

A separate experiment was conducted to determine if a tapered excitation waveguide design would allow better alignment tolerances and improve coupling efficiency to the optical fiber while maintaining small excitation modes for our rib waveguides. A mask was made with 6 different taper lengths L_T , $10\ \mu\text{m}$, $50\ \mu\text{m}$, $100\ \mu\text{m}$, $500\ \mu\text{m}$, $1000\ \mu\text{m}$ and $5000\ \mu\text{m}$ long. These waveguides began at the chip edge with various widths ($6\ \mu\text{m}$, $10\ \mu\text{m}$ and $12\ \mu\text{m}$) and then reduced linearly in width down to $2\ \mu\text{m}$ along the length of the taper section. The design also included non-tapered waveguides varying in width from $2\ \mu\text{m}$ to $12\ \mu\text{m}$. A wafer with the various tapers was created and throughput measurements were conducted. From the non-tapered throughput measurements, we see a significant drop in throughput for waveguides narrower than a width of $4\ \mu\text{m}$ because of the mode mismatch between waveguide and fiber. For example, in comparing waveguides of the same length, waveguides wider than $4\ \mu\text{m}$ were able to achieve throughputs greater than 30% whereas the $4\ \mu\text{m}$ wide waveguide's throughput dropped below 20%. The results for the different taper throughput measurements are shown in Fig. 6. A tapered $2\ \mu\text{m}$ wide waveguide attains on average a total throughput of 30% compared to the non-tapered 10%. From this data we can conclude that for high confinement rib waveguides, taper lengths above $100\ \mu\text{m}$ improve fiber to chip alignment tolerances and coupling efficiency while still providing the desired narrow FWHM at the MMI waveguide input. The cost of added excitation waveguide design complexity is minimal compared to the gain of optical throughput.

VI. Conclusions

ARROW based MMI waveguides used to produce high fidelity wavelength dependent multi-spot patterns, are useful for sensitive and simultaneous identification of multiple biomarkers in multiplexed fluorescence optofluidic biosensors. Through experiment and simulation, we conclude that in order to produce high fidelity spot patterns for MMI rib waveguides etched into $6\ \mu\text{m}$ of SiO_2 , the rib needs to be etched between $4.5\ \mu\text{m}$ and $5\ \mu\text{m}$ and the waveguides

should be as narrow as the lithography and etching processes allow. In order to improve mode coupling from fiber to these narrow waveguides, tapers with lengths longer than 100 μm can be implemented in the rib waveguides. Shorter MMI waveguide lengths could enable spot patterns with even higher fidelity, however, due to the chosen fluorescent dyes, design constraints for the desired wavelengths do not allow for such adjustments.

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Aaron R. Hawkins received the B.S. degree in applied physics from the California Institute of Technology, CA, USA, in 1994, and the M.S. and Ph.D. degrees in electrical and computer engineering from the University of California, Santa Barbara, CA, USA, in 1996 and 1998 respectively.

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Fig. 1.

Optofluidic platform (a) Representation of the optofluidic biosensor with key components indicated. (b) The top view image of a $75\ \mu\text{m}$ wide MMI waveguide, at the liquid core intersection, producing an 8 spot pattern (excited at a 600 nm wavelength). Liquid core filled with Cy-5 fluorophores at $15\ \mu\text{M}$ concentration.

Fig. 2.

Excitation and MMI waveguide's fabrication steps. (a) Start with silicon substrate (b) Sputter ARROW layers onto substrate (c) Deposit PECVD oxide, $6\ \mu\text{m}$ (d) Spin on and pattern AZ3330 photoresist (e) Evaporate Ni over resist and oxide (f) Liftoff photoresist in acetone removing Ni in undesired locations (g) Etch into oxide (h) Remove Ni mask. The measurements indicate each width and that the etch depth varies.

Fig. 3.

Experimental and simulated data for the excitation waveguides (a) FWHM for various width waveguides versus etch depth. (Diamonds = 2.8 μm , Triangles = 4.9 μm , Dots = 6.7 μm , Line with shapes are corresponding simulated data) Inset- Etch depth defined as the total, x μm , etched into the oxide. (b) Experimental mode images for 2.8 μm wide waveguides at various depths. Mode intensities are normalized, total transmission decreases with tighter confinement, deeper etches. (c) Simulated mode images for the same width and corresponding depths. All data acquired at a wavelength of 633 nm.

Fig. 4.

Comparison of a poorly confined excitation mode (top left) and spot pattern (top right) to a well confined excitation mode (bottom left) and spot pattern (bottom right). Both excitation waveguides are $4.9\ \mu\text{m}$ wide and both MMI waveguides are $100\ \mu\text{m}$ wide. The single excitation mode images (left) were taken with LED backlighting thus facet is visible in these images and the outline of the rib traced in white. Mode intensities are normalized.

Fig. 5.

Experimental data collected from exciting MMI waveguides at differing wavelengths. (a) Left- Side view images taken from the same $75 \mu\text{m}$ wide MMI waveguide cleaved to $L = 1.855 \text{ mm}$. Right- Intensity plots for each corresponding image. (b) Normalized Peak-Valley distance versus number of spots for different MMI waveguide lengths, L , and wavelengths.

Fig. 6.

Percent throughput verses the log scale of the taper length for various starting widths, ending with $2\ \mu\text{m}$ wide waveguides. (Diamond: $y = 12\ \mu\text{m}$, Triangle: $y = 10\ \mu\text{m}$, Square: $y = 6\ \mu\text{m}$) Taper length is defined as the length between the wider waveguide and the $2\ \mu\text{m}$ waveguide. A larger length gives a smaller taper angle and less scattering loss. Error bars are the experimental error and were found to $\sim 10\%$.