INTEGRATED OPTICAL WAVEGUIDES FOR *IN SITU* MICROFLOW MEASUREMENT

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ABSTRACT

The need for quantitative microscale chemical and biological experiments has resulted in the increasing utilization of microfluidics with integrated sensors, allowing such architectures to synergistically enhance function and performance [1]. This work focuses on the design and characterization of optofluidic devices that easily integrate optical fibers into microfluidic waveguides. We demonstrate optical components that transmit and collect light from substances in microflows, such as fluorescent liquids. Optimization of the components for splitting light into multiple paths, focusing light into the microchannel, and collecting fluorescence emission while excluding excitation light is described. An integrated system is demonstrated for real-time and continuous flow-monitoring using caged fluorophores. These tools provide new methods to probe dynamic fluid properties and to measure samples using microfluidic cytometry.

KEYWORDS: Optofluidics, microfluidics, fluorescence, flow meter

INTRODUCTION

Microfluidic devices are widely used for investigations in chemistry, biology, and physics because they enable unique fluid transport regimes, dynamic control of small fluid volumes (femtoliters to nanoliters), and high-throughput experiments. Integration of on-chip optical components provides even greater benefit to miniaturization, portability, and speed of sensitive and multimodal measurement capabilities [2]. We aim to incorporate optical sensing elements into microfluidic devices in order to accurately and reproducibly measure microflows and characterize the optical properties of materials in flow using sensitive chemical and biological assays. Application areas include cytometry, drug delivery, and diagnostic assays. A key objective is to create optofluidic devices that can perform rapid, high quality measurements in both industrial and distributed/point-of-use applications.

EXPERIMENTAL

(Identification of commercial products does not imply recommendation/endorsement by the National Institute of Standards and Technology (NIST); materials/equipment used may not necessarily be best for purpose). Photolithography was conducted at the Center of Nanoscale Technology (CNST) at NIST. Chrome masks (Heidelberg Instruments DWL-2000) were made to create topographic features onto SU8 (Microchem) masters (Suss MicroTech MA8). Optofluidic devices were cast in poly(dimethylsiloxane) (PDMS) (Sylgard 184, Dow Corning) against masters [3-4]. Optical waveguides were filled with optical adhesive (NOA 88, Norland) followed by insertion of optical fibers (Thor Labs) and UV curing. A 10 mW tungsten light source and fiber-coupled LEDs (ThorLabs) were used with a power meter (2936-R, Newport) to deliver and measure light, respectively. Flows were monitored in series with the syringe pump with a commercial flow meter (Sensirion). Flows within the optofluidic devices were visualized with fluorescein and CMNB-caged fluorescein (Sigma Aldrich).

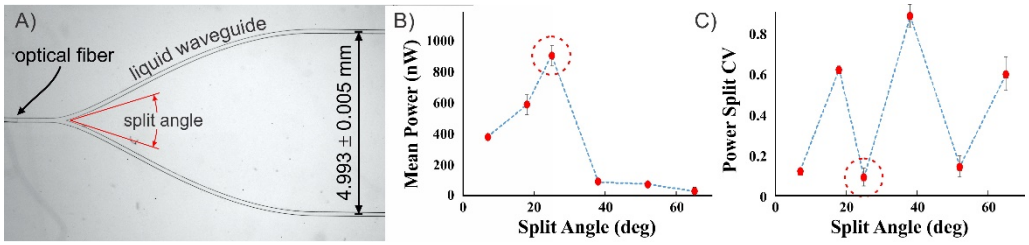

Figure 1: A) Image of an optofluidic device showing optical fiber coupled into a bifurcating waveguide that crosses a microfluidic channel (vertical) at two points. B) The mean power achieved at various split angles. C) The variation in power through the branches of the split normalized to the mean. Dashed red circles indicate the best conditions for power and coefficient of variation (CV). We show means and standard deviations from measurements of 3 replicate devices.

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RESULTS AND DISCUSSION

Using a single light source to interrogate multiple points along a flow path is advantageous for simplifying fabrication and aiding reproducibility. A range of branching angles (5° to 65°) was tested to optimize power delivered through the split. Both total power (mean) and power variation between the branches were optimized at a 25° split angle, where mean power of 900 nW was observed with deviation of less than 5% between the branches (Figure 1).

To focus light from the waveguides across the microchannel, lenses with varying radii of curvature (Rc) were placed on the ends of the waveguides (flat [no Rc], 250, 175, 100, 75, and 50 µm; smaller curvatures were not practical given the width of the waveguides in these tests). A lens with 50 µm Rc led to the highest power transmission from a fiber-coupled light-emitting diode (11 µW of the 22 µW input) across the flow channel, which is in good agreement with what is expected from refractive index differences between NOA 88 (1.56) and PDMS (1.42). The shape of the illumination was imaged by exciting fluorescein in the flow channel with 488 nm light (Figure 2). We optimized collection of emitted light (520 nm) from fluorescein by placing a collection waveguide at an angle of 35 degrees from the nominal excitation direction, which is in the expected "shadow" of excitation light reflected from the wall of the microchannel.

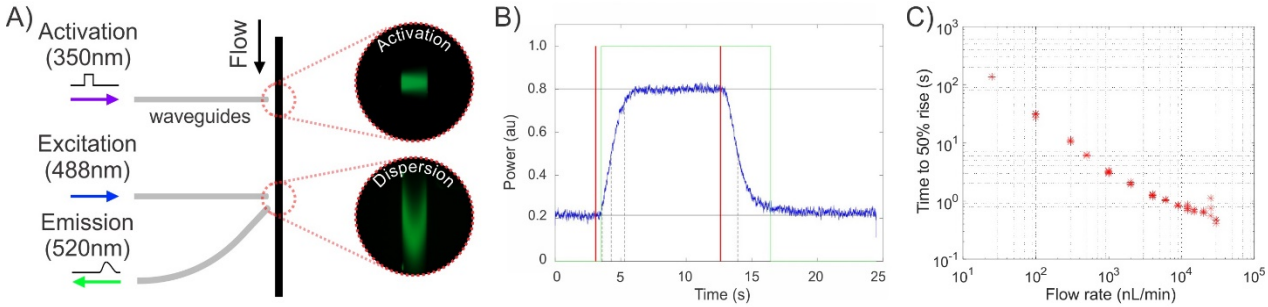

Figure 2: Use of optofluidic components to make a flow meter. A) CMNB caged fluorescein in the flow is activated by crossing a UV light pulse. A fluorescence image shows the activated "stripe" of fluorescein. Dispersion of the fluorescent stripe is shown by the fluorescence image at a point down the flow channel. Fluorescence emission is excited and collected by a pair of waveguides at a fixed distance downstream. B) A recording of the measured fluorescence by the power meter is shown following a long (saturated) UV activation upstream (between the red marks). C) Measurement of the time for the fluorescence to reach 50% of maximum is shown for various flow rates (triplicate for each flow rate).

We demonstrate use of the photonic elements to realize a continuous flow meter (Figure 2). Ultraviolet light delivered to an upstream waveguide was used to activate caged fluorescein, which "marks" the flow. Dispersion of the dye downstream is measured by collecting the emitted fluorescence when the dye crosses a waveguide carrying excitation light (488nm). Measurements were found to be reproducible with CV's lower than 9% over approximately 3 orders of magnitude in flow, from 20 nL/min to about 20 µL/min.

CONCLUSION

We have demonstrated optofluidic devices that can efficiently deliver and collect light across microfluidic channels. These devices were combined to create a microflow meter. These systems are useful for measuring dynamic fluid properties and provide new routes to characterization of particle and cells in microfluidic cytometry.

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