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Optical Characterization of Optofluidic Waveguides Using Scattered Light Imaging

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Abstract

The use of scattered light images is shown to be an attractive method for the characterization of optofluidic waveguides. The method is shown to be capable of measuring waveguide propagation losses and transmissions between solid and liquid-core structures. Measurement uncertainties are considered and characterized and were typically less than 15%.

The relatively new field of optofluidics refers to a class of optical systems that are synthesized with fluids [1] and has seen rapid development over the last few years for several reasons [2]. Fields such as chemistry, toxicology, and environmental studies regularly use optical methods to analyze liquid solutions [2]. Likewise, research in micro and nanofluidics has led to the miniaturization of fluidic control mechanisms [2], making it possible to optically analyze liquids on a small chip. Passive optofluidic structures such as waveguides with liquid cores promise novel device functionalities, optical reconfigurability, component integration, and low fabrication costs [1]. As for all waveguides, propagation losses and other signal attenuation mechanisms play critical roles in their operation. Existing methods for measuring the optical losses of optofluidic waveguides include the cutback method, prism coupling [3], and optically induced particle transport [4]. The cutback method offers an arguably reliable measurement, but is destructive to the sample and dependent upon the quality of multiple cleaved facets [3]. In addition, liquid core waveguides are difficult to measure with this technique because of evaporation out the end facets. The prism coupling method presents difficulties with launching light into liquid core structures [3]. Optically induced particle transport uses radiation pressure to transport tagged particles along the length of a liquid core, and uses the particle's position vs. time to calculate propagation loss. Although it is an effective means of device characterization, it does not account for potential inaccuracies due to parasitic sidewall adhesion and requires a high powered laser and sophisticated imaging equipment to track a moving particle [4].

In this letter, we experimentally demonstrate the use of scattered light imaging as an attractive method for the optical characterization of optofluidic waveguides. Most optofluidic devices require solid to hollow waveguide interfaces to confine sample liquids

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[5], and in general, there will be optical losses associated with them. The scattering imaging method is especially suited to accurately characterizing optical transmission through these interfaces. Using a CCD sensor to image the waveguide, propagation losses due to multiple waveguide sections, overall chip throughput, and interface transmissions can be calculated. Due to its simplicity, the method is fast, non-destructive, inexpensive, and reproducible. Using liquid core ARROWs (Anti Resonant Reflecting Optical Waveguides) as sample optofluidic waveguides [6], we show the method's efficacy and reliability. These waveguides were tested using water ($n = 1.33$) as the sample liquid, although in principal their losses should improve with higher index liquids [2].

The liquid core ARROW platform has several sources of optical loss, as shown in Fig. 1 and (1). The first and second solid core waveguides as well as the liquid core waveguide have propagation losses associated with them, represented by α_{sc} and α_{lc} respectively. Associated with α_{sc} and α_{lc} are lengths l_{sc} and l_{lc} which correspond to physical lengths of the solid and liquid core waveguide sections respectively. Additionally, interface transmissions κ_i as well as input and output coupling efficiencies κ_{e1} and κ_{e2} need to be accounted for in order to describe the overall throughput T .

$$T = \kappa_{e1} \cdot e^{-\alpha_{sc} l_{sc}} \cdot \kappa_i^2 \cdot e^{-\alpha_{lc} l_{lc}} \cdot \kappa_{e2} \quad (1)$$

The primary causes of loss are material absorption, radiation, and light scattering due to inherent surface roughness [3]. If the scattering centers due to surface roughness are uniform throughout each waveguide length, then the scattered light will be proportional to the optical power confined within the waveguide [7]. Images can in turn be used to capture the attenuation of scattered light [7], thereby characterizing its propagation losses. We can assume that the scattering centers due to surface roughness are uniform because each cladding layer was grown in one fabrication step [5].

By imaging each section of the liquid core ARROW, values for α_{sc} , α_{lc} , l_{sc} , and l_{lc} can be determined. Because the imaging only measures the scattered light from one end of the chip to the other, the coupling efficiencies κ_{e1} and κ_{e2} can be ignored. An on chip throughput T excluding coupling efficiencies is then measured, allowing κ_i to be solved for analytically, thus providing the means for full optical characterization in one measurement.

Fig. 2 shows the experimental setup we used for waveguide characterization. After aligning the sample using a 3D precision stage, bare, single-mode 633 nm optical fiber was used to couple a guided mode from a 650 nm laser diode into the first solid core. As light propagates through the waveguide, it is scattered upward due to the inherent leaky mode nature of the waveguides, as well as the surface roughness in the cladding layers. A 3.34 megapixel CCD sensor (Nikon Coolpix 995) attached to a microscope (30x magnification) was used to image the scattered light. Although light from different parts of the waveguide will travel different distances to reach the CCD, the microscope was positioned relatively far away from the sample device to minimize the effect this would have on the measurement. Fig. 3a shows an example image of the liquid core of an ARROW extending 4 mm in length.

After a waveguide has been imaged, software tools such as the image processing toolbox in MATLAB can be used to extract information about scattered light intensities versus position. As light propagates along the waveguide it can be described by the following equation:

$$P(z) = P_0 e^{-\alpha \cdot z} \quad (2)$$

where $P(z)$ is the optical power at position z [7]. In order to extract the propagation loss α , the image from the camera should be rotated and cropped, allowing easy integration of grayscale pixel values transverse to the direction of propagation. After a vector of integrated intensity (power) versus position has been formed, the natural logarithm can be taken to allow the propagation loss to be solved for easily as the slope of a line.

$$\ln(P_0 \cdot e^{-\alpha \cdot z}) = \ln(P_0) - \alpha \cdot z \quad (3)$$

The α calculated here has units of loss/pixel. In order to convert to loss/cm, a scale was included in each image to determine the number of pixels per centimeter.

Fig. 3 shows how this process is carried out on an actual fabricated waveguide. The liquid core portion of the waveguide is imaged, as shown in Fig. 3a. The extent of the liquid core is noted, as well as any scattering singularities such as the solid to liquid core waveguide interfaces. The resulting integrated pixel intensities are shown in gray in Fig. 3b, and the subset of pixel intensities used for the calculation of α_{lc} are shown in blue. The resulting linear least squares fit is plotted as a red line and the extents of the liquid core waveguide portion are shown as black vertical bars. The process is then repeated with images centered on the solid core waveguides to calculate their individual contributions to the device loss.

After this method is used to calculate the loss coefficients for each of the various waveguides on the chip, the overall throughput of any waveguide can be found by simply examining the ratio of powers from the beginning of the waveguide to the end. Once the propagation losses in both types of waveguide and the on chip throughput are known, the interface transmissions κ_i can be solved for analytically using (1).

In order to determine the experimental uncertainties of this measurement technique, a single device was aligned and imaged 10 times and the solid and liquid core waveguide losses measured. These waveguides were fabricated on a silicon substrate using PECVD silicon dioxide and sputtered tantalum oxide films [5] as bottom antiresonant layers on a self-aligned pedestal [8]. The top coating consisted of a single oxide layer in order to improve interface transmission [9]. The results of this test are shown in Fig. 4, where the experimental uncertainty was calculated to be a value encompassing 70% of the measured values. An uncertainty of 15% was found for the solid core measurements and an uncertainty of 10% was found for the liquid core measurements.

With the measurement uncertainty determined, the scattered light imaging analysis was applied to a set of 8 complete ARROW devices of the same design (single-over coating, self-aligned pedestals) containing both liquid and solid core waveguides.

Fig. 5 shows the measurement results for solid core (squares) and liquid core (diamonds) loss coefficients with previously obtained confidence bounds shown as error bars. The average solid core loss for the set of devices was 0.52cm^{-1} with an experimental uncertainty of $\pm 0.03\text{cm}^{-1}$ and a standard deviation of 0.36cm^{-1} . The average liquid core loss was 3.29cm^{-1} with an uncertainty of $\pm 0.13\text{cm}^{-1}$ and a standard deviation of 1.31cm^{-1} . The average interface transmission across the set of devices was calculated using (1) to be $56 \pm 2\%$, where the uncertainty in the interface transmission results from the propagation of the measurement uncertainties through (1). The range of optical losses across the 8 sampled devices is fairly typical for ARROW platforms constructed in our laboratory.

In conclusion, the scattered light imaging method has been shown to be an attractive approach for the optical characterization of optofluidic devices. It has been shown to be effective in characterizing ARROW devices, but it could also characterize passive

optofluidic networks with varying geometries and interfaces. This method is only limited by CCD nonlinearities and limited dynamic range. Efforts can be made to overcome these discrepancies by characterizing the CCD response to various incident levels of light. This can be done by taking a series of images at varying exposure times using a constant light source as a reference. The primary benefits of using this method, including speed, reproducibility, and measurement of interface transmission, will typically outweigh any limitations.

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Fig. 1.
Sources of optical loss for liquid core ARROW platform.

Fig. 2.
Experimental setup used in scattered light imaging method.

Fig. 3. (a) Sample scattered light image of ARROW device, (b) associated integrated CCD intensity (ln scale) vs. position data (gray) and linear fit (red). Extent of liquid-core waveguide denoted by vertical black lines, and portion of intensity data used for fit calculation denoted in blue.

Fig. 4. Solid-core loss measurements (squares) and hollow-core loss measurements (diamonds) made on the same optofluidic platform multiple times. A mean value for these measurements is shown by the solid lines and experimental uncertainty is indicated by the error bars.

Fig. 5. Solid-core loss measurement (squares) and hollow-core loss measurement (diamonds) for 8 devices fabricated on a single substrate.