Electronic Supplementary Information:

Polymer Waveguide Backplanes for Optical Sensor Interfaces in Microfluidics

Kevin S. Lee, Harry L. T. Lee and Rajeev J. Ram

Maximum Waveguide Width

We want to determine the maximum angle that the waveguide is able to collect from a uniformly emitting point source. If we know this angle, we can determine the maximum width of the waveguide required for a point source of a given height. Since our waveguide is large (1 mm^2), we can use ray optics to determine the required width as shown in Figure 1.

We start by defining the maximum angle θ_c allowed within the waveguide given by Snell's Law for Total Internal Reflection.

$$\sin\theta_c = \frac{n_{clad}}{n_{core}}$$

Then we determine at what angle θ_1 this maximum ray exits the waveguide. First we convert the critical angle on the waveguide sidewall to an exit angle at the waveguide output.

$$\sin\theta_1 = \sin(90\text{-}\theta_c) = \frac{\sqrt{n_{core}^2 - n_{clad}^2}}{n_{core}}$$

We note that the numerator is simply the numerical aperture.

$$NA = \sqrt{n_{core}^2 - n_{clad}^2}$$

Then we determine the output angle θ_2 through Snell's Law.

$$n_{core}\sin\theta_1 = n_{ext}\sin\theta_2$$

We can substitute in our expression for $\sin\theta_1$.

$$\sin\theta_2 = \frac{NA}{n_{ext}}$$

Since we are interested in the ratio of the waveguide width to the point source height, we want to determine the tangent of the output angle θ_2.

$$\tan\theta_2 = \frac{NA}{\sqrt{n_{ext}^2 - NA^2}}$$

This is simply the ratio of the half width to the height.

$$\frac{w/2}{h} = \frac{NA}{\sqrt{n_{ext}^2 - NA^2}}$$

We then solve for w to get an expression of the maximum waveguide width in terms of the numerical aperture and the point source height.

$$w = \frac{2h}{\sqrt{(n_{ext}/NA)^2 - 1}}$$

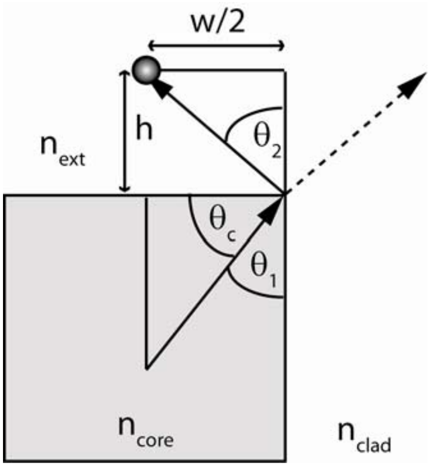

Fig. 1 Ray tracing approach to determining the maximum waveguide width necessary to collect a point source emission located a distance h away from the waveguide face.

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Loss and Roughness Measurements

To measure loss, a HeNe laser at 632 nm was coupled into a 90 µm x 90 µm waveguide through a 0.55 NA microscope objective. An image and a plot of the perpendicularly scattered light is shown in Figure 1. Coupling and CCD saturation effects at the input are ignored and a single exponential fit to the scattered power yields a waveguide loss of 1.26 dB/cm at 632 nm.

Due to the large size of the waveguides, sidewall roughness of replicated PDMS channels could be directly measured with a surface profilometer. From the surface profile, a histogram of the surface slope could be determined, indicating the extent of scattering from each sidewall reflection. This description of sidewall roughness was verified by measuring the diffuse reflection of the surface in a separate experiment. Both the profilometer and reflection measurements yielded similar results, as shown in Figure 2. By performing a Gaussian fit to the slope distribution, a 50% deviation (HWHM) of 0.01 (µm/µm) and 0.09 (µm/µm) are obtained for the waveguide sidewalls and vertical couplers respectively.

As a consequence of reflow polishing, the majority of sidewall roughness has a spatial extent greater than the wavelength of interest. Therefore, the measured distribution of the sidewall angle could be directly incorporated into Monte Carlo ray tracing simulations as statistical specular reflection, which accurately described the reduction in numerical aperture from increased loss for higher order modes.

As shown in Figure 3, roughness after polishing relates directly to output numerical aperture. Numerical aperture was determined by measuring the 50% intensity versus angle of the waveguide output emission using an optical power meter on a rotation stage. The input excitation for this measurement was a 626 nm LED focused into the waveguide with a 0.68 NA lens. The simulated NA reduction given profilometer measured roughness matches measured NA. For luminescence collection, rougher waveguides reduce the effective NA by increasing higher order mode loss which reduces the overall system efficiency.

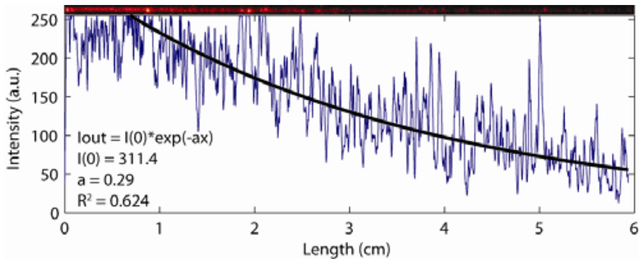

Fig. 1 An image of the perpendicularly scattered light and a single exponential fit to the intensity versus distance. The 90 µm x 90 µm waveguide measures a loss of 0.29 cm^{-1} or 1.26 dB/cm at 632 nm.

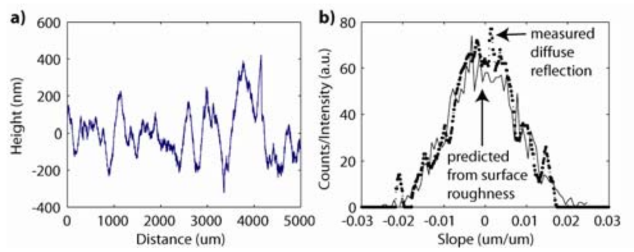

Fig. 2 a) Trace of the height versus distance taken with a DekTak Surface Profilometer. b) Comparison between slope distributions of a milled flat surface measured by reflected intensity and surface profilometry. Both measurements yield similar distributions, indicating specular scattering behavior due to surface roughness.

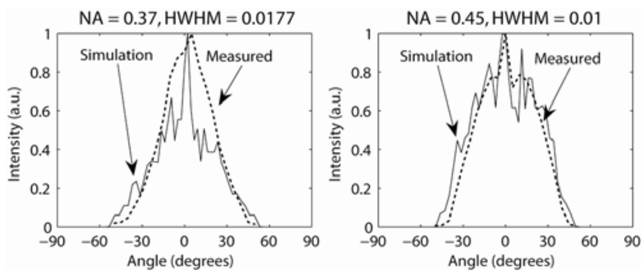

Fig. 3 Measured and simulated intensity versus angle plots are shown for 1 mm x 1 mm waveguides of varying roughness. Gaussians fits to the measured roughness with a HWHM of (Left) 0.0177 and (Right) 0.01 are used to perform Monte Carlo ray tracing simulations.

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System Measurements

We performed a comparison between the simulated system efficiency and the measured system efficiency of the fabricated device. To make an even comparison, the experimental input waveguide coupling efficiency was first measured and then incorporated into the simulation. Input waveguide transmission given the HeNe laser input versus a 1 mm diameter core multimode fiber input indicated a 49.8% coupling efficiency for the multimode fiber. A similar measurement to determine the output coupling efficiency was not performed since efficiency is dependent on the fluorophor emission properties. Relying on simulations, the finite area and separation distance of the photodetector from the waveguide results in 71.6% coupling between the waveguide output and the detector. The experimental output coupling will likely be less than the simulated value.

Since it is difficult to experimentally measure the collection efficiency independent of excitation, the overall system performance was measured. A 600 nm 17 µW fiber-coupled LED modulated at 5 kHz was coupled to the input waveguide and the phase offset resulting from the sensor phosphorescence lifetime was detected using a lock-in method with a bandpass filtered PIN diode (Thorlabs FDS100). With this detection system, the measured ratio of collected fluorescence versus fiber coupled LED power was 0.01%.

To determine whether this system is efficient enough to use simple excitation and detection schemes, the necessary input power for the simulated device must be determined. The noise in the total detection circuit, while not limited by the detector (Thorlabs FDS100), is the equivalent of 15 pA of current, meaning a minimum noise equivalent power of 30 pW at 760 nm is required. In addition, the flourophor will have a limited absorption cross-section as well as a limited quantum yield as given in Table 1. For example, the conversion efficiency of excitation light to fluorescence light is 1.8% as measured for our specific oxygen sensitive fluorophor, Platinum(II) octaethylporphine ketone (PtOEPK). Even with this low conversion efficiency, we would still only need 3 µW of optical power coupled into the input waveguide to achieve an intensity signal to noise ratio (SNR) of 10 given our noise level, which is easily achievable with any commercial LED. A summary of all of the relevant losses are given in Table 1, showing that simulations agree well with measured data.

To compare the waveguide collection efficiency with conventional fiber bundles, we also constructed a fiber bundle with a 1 mm core diameter PMMA center excitation fiber surrounded by 0.5 mm core diameter PMMA collection fibers. Measurements performed with the fiber bundle on the same oxygen sensor required 9 collection fibers in order to yield a similar collection efficiency of 0.0095%. Out of the 9 collection fibers, a maximum efficiency of 0.0014% was measured for a single fiber.

Table 1 Summary of the losses in the overall backplane system. Simulated transmission is compared to experimental measurements. By incorporating measured losses into simulation, the total efficiency from the simulation approximately matches the experiment.

Excitation/Collection	Sim	Exp
LED to Fluorophor (A)	**48.9%**	**47.5%**
Input coupling (experimental)	49.8%	49.8%
Waveguide Loss (1.14 cm)	-	97.4%
Bend Reflectivity	-	98%
Sensor Interface Reflections	98.1%	-
Fluorescence to PD (B)	**0.0223%**	**0.0211%**
Fluorophor Absorption	15%	15%
Fluorescence Quantum Yield	12%	12%
Output waveguide collection	1.73%	-
Bend Reflectivity	-	98%
Waveguide Loss (1.73 cm)	-	96.1%
Waveguide Output to Detector	71.6%	-
Total (A*B) (Efficiency)	**0.0109%**	**0.01%**
(Power to achieve SNR = 10)	**2.75 µW**	**3 µW**