# Detection of light backscattered from liquids by means of integrated optical waveguides

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***Abstract.*** *A silicon nitride based waveguide device is presented for the detection of light backscattered from liquids. The device is composed of a source waveguide and a series of collector waveguides displaced relatively to the source. The experimental result shows that detection of photons backscattered from the interior of a droplet in direct surface contact with source and detector waveguides is feasible, although the amount of light captured by the latter is extremely small. The intensity of the backscattered light measured from each of the collector waveguides is found to be in good agreement with simulation results based on a Monte-Carlo approach.*

## Introduction

We present a device for the detection of light backscattered from liquids, which is realized in silicon nitride technology. The device, shown in Fig. 1, is composed of a source waveguide and a number of collector waveguides. The collector waveguides are placed directly in contact with the sample's surface and are used to measure the backscattered light intensity as a function of distance from the source. The spatial information retrieved through this measurement is then used to validate our numerical model based on a Monte-Carlo approach. Several devices were designed by varying parameters such as waveguide width and spacing. In this paper we present measurements carried out on one of these devices in which the distance between adjacent waveguides at the device/sample interface is approximately 2.6 µm. The waveguides, which are multimode at the excitation wavelength of 633 nm, have a width of 1.45 µm and core layer thickness of 45 nm, as can be seen in Fig. 2.

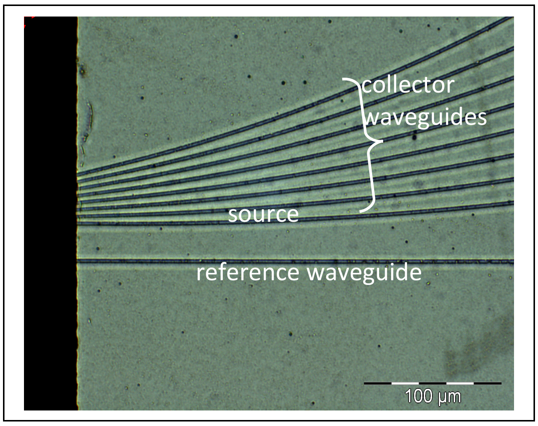


**Fig. 1 -** Multi-waveguide based collector device for backscattered light detection from liquids. The reference waveguide is not used in the measurement technique discussed in this paper.

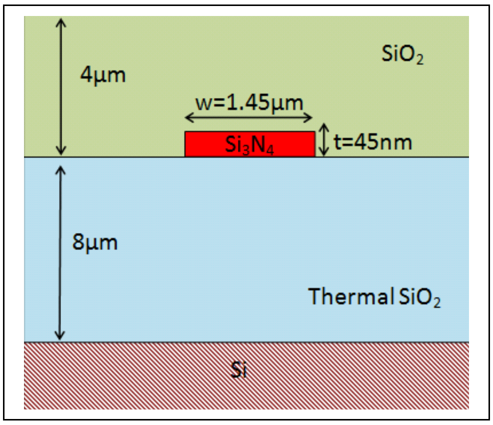


**Fig. 2** – Cross-section of $Si_3N_4$ waveguides. Refractive index of thermal oxide and PECVD oxide is approximately $n_{clad}$ = 1.4579, while index of core is $n_{core}$= 2.0124.

## Monte-Carlo simulation

We have developed an algorithm based on a Monte-Carlo approach to simulate photon propagation through scattering media, following the implementation steps described in the work of Wang et al. [1].

We simulated photon propagation through a water suspension of latex spheres of a diameter of 88 nm. The optical properties of the suspension are shown in Table 1. The scattering coefficient and anisotropy factor were calculated using the values of concentration, refractive index, and diameter of spheres by making use of Mie's functions [2].

| | |
|---|---|
| Diameter (nm) | 88 |
| Refractive index | 1.339 |
| Weight/volume concentration (g/100 ml) | 2.62 |
| Concentration (particles/ml) | $69.93 \times 10^{12}$ |
| Scattering coefficient ($cm^{-1}$) | 18.34 |
| Anisotropy factor (0<g<1) | 0.0584 |

**Table 1 –** Optical properties of latex sphere suspension used in Monte-Carlo algorithm.

The main result of the simulation is the backscattered photon density distribution on the surface of the sample. The simulation results are shown in Fig. 3 together with the experimental results.

## Comparison of measurements with simulation results

As previously described, the device has a total of 8 waveguides, 1 source (input) and 7 collector (output) waveguides. We access the device through a 9-µm-core fiber array by butt-coupling. Excitation at a wavelength of 633 nm is made by a He-Ne laser. The backscattered light intensity collected by each of the output waveguides is measured with a photomultiplier. For reproducibility, two measurements were carried out with a time delay of several hours. In between the two measurements the device was removed from the holder, cleaned, and realigned with the fiber array. The results of the measurements are shown in Fig. 3, in which the intensity of the detected light is given as a function of the distance from the source waveguide. As the distance from the source increases the intensity of the detected signal decays exponentially, reaching values close to the detection limit of the photomultiplier.

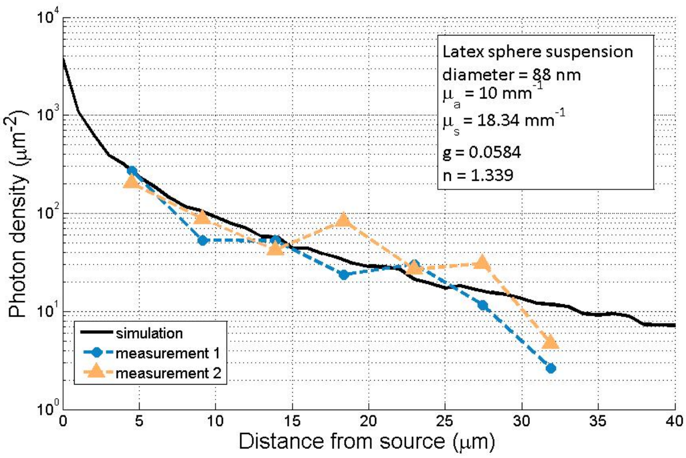


**Fig. 3 –** Photon density distribution on the surface of the liquid sample as a function of distance from the source. Experimental data points from two measurements are compared with simulation.

## Conclusions

We have presented a collector system based on multiple waveguides for the detection of light backscattered from liquids. The good agreement found between the experimental data and the simulation results consents us to validate our Monte Carlo model. Furthermore, we demonstrate that integrated optical waveguides can be adopted for direct detection of backscattered light within the vicinity of the source.

## Acknowledgments

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## References

[1] L. Wang, S. L. Jacques, and L. Zheng, "MCML-Monte Carlo modeling of light transport in multilayered tissues", Computer methods and programs in biomedicine **47**, 131-146 (1995).

[2] C. F. Bohren and D. R. Huffman, "Absorption and scattering of light by small particles" (Wiley, New York, 1998).