Multi-Waveguide Based Collector for the Detection of Backscattered Light from Highly Scattering Media

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Abstract. *A novel technique to collect backscattered light from the surface of highly scattering media is presented. The design parameters for the proposed structure have been determined by simulating light transport in the target medium with a Monte Carlo approach. We also present a comparison of the simulation results with measurements.*

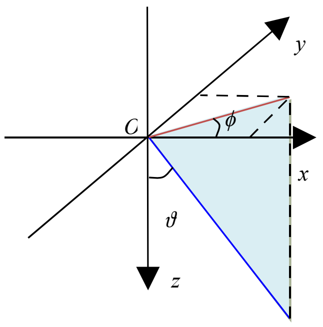
Introduction

The proposed structure is entirely based on integrated optics and is composed of a source waveguide and a number of collector waveguides disposed at increasing distances from the source and in direct contact with the target's surface. These distances, as will be discussed in the next section, are strongly related to the depth at which the detected scattering events occur. For the correct design of the structure we used a Monte Carlo approach to simulate light transport through the scattering medium and to gather information on the backscattered light, such as the positions and angles at which each output photon is leaving the surface. Different layouts have been fabricated and tested. In each of them the relative positions of the detector waveguides with respect to the source have been changed together with other relevant parameters. The devices have been fabricated in the MESA+ cleanroom using silicon oxynitride (SiON) waveguide fabrication technology[1].

Monte Carlo simulation

Light from a laser source is coupled into a rectangular SiON waveguide. The source waveguide and the detector waveguides end directly in contact with the surface of the sample to be measured. The photons which are not reflected by the surface will interact with the target material being absorbed or scattered. Our main interest is aimed towards the backscattered photons that get directed out of the medium after one or more scattering events. The distribution of the backscattered photons on the surface is of great importance together with their propagation direction and the position inside the medium of the last scattering event. This information allows us to design an efficient coupling mechanism between a hypothetical device and the sample.

The waveguides are SiON channel waveguides with core index of n_c=1.529 and cladding (SiO_2) index of n_{cl}=1.457 designed within the ePIXnet Joint Research Activity on sensors. The spatial distribution of the incident photons is obtained from the mode profile of the input waveguide. For each generated photon we associate an initial direction of propagation that in a polar coordinate system forms an angle ϑ with the z axis and an angle ϕ with the x axis as shown in Fig. 1.a. The origin of the x and y axes is chosen to be in the center of the source waveguide's facet, while the z axis origin is on the sample's surface.



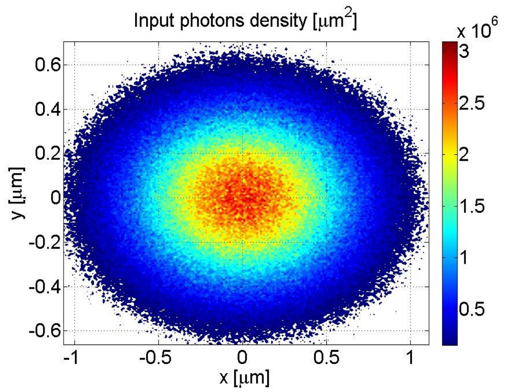


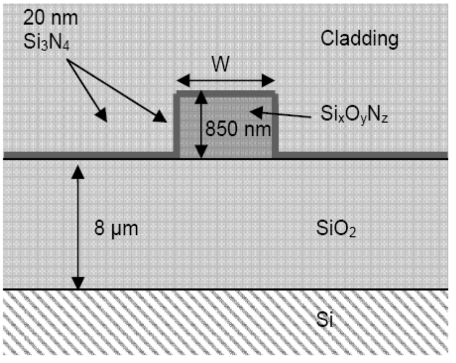
Fig. 1-a) Direction of propagation in polar coordinates.

b) Distribution of incident photons in case of 2 million total photons.

The angle ϕ is uniformly distributed between 0 and 360°, while ϑ is initially distributed between 0 and *arcsin(NA)*, with NA the numerical aperture of the waveguide. Since the waveguide is rectangular we consider two equivalent slab waveguides [2], assuming two different numerical apertures in x and y directions. Each of the randomly generated photons is tracked until it is absorbed or scattered/reflected out of the medium. All the photons that propagate outwards from the surface are considered as output photons: backscattered photons as well as photons that have been reflected from the surface. The two kinds of outputs can be easily distinguished by the program and each output photon is saved into an array that holds the position, the propagation angle relative to the z axis, the optical depth and the penetration depth inside the target as well as the path length of the photon.

Test structure design and fabrication

The devices have been fabricated in the MESA+ cleanroom using our metal-free waveguide fabrication technology [3]. After standard cleaning a PECVD SiON layer of 850nm with a refractive index of 1.53 was deposited on a wafer of 8μm thermal oxide. After resist deposition and development, the wafers were dry etched in a CHF_3/O_2 plasma. A thin layer of LPCVD Si_3N_4 of 20nm was grown to serve as etch stop for the wet etching in case sensing windows have to be defined on the device. On top of the nitride layer, a PECVD cladding layer of 3.5μm SiO_2 with a refractive index of 1.47 was grown. Finally, the wafers were annealed to remove the hydrogen. The final waveguide structure is shown in Fig. 2.a. The architecture, as can be seen in Fig. 2.b, is based on a single source waveguide and multiple detector waveguides disposed in direct contact with the sample (dark region in Fig. 2.b). The container for the liquid sample has been integrated on a chip by wet etching a rectangular area in contact with the collector array and the source waveguides (etching through the Si_3N_4 layer and 5μm in the thermal oxide). Different layouts have been fabricated and tested. In each of them the relative positions of the detector waveguides with respect to the source have been changed together with other relevant parameters such as waveguide width, and distance between the waveguides of the collector.



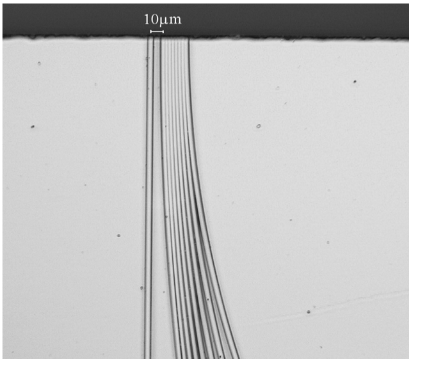


Fig. 2.a) The ePIxnet's JRA Sensors SiON waveguide used in the fabrication of the devices.

b) Optical microscope picture of a test device.

Comparison of measurements with simulation results

In the Monte Carlo simulation and in experiments we have used commercial milk as the scattering medium. The optical parameters of milk used in the simulation are μ_s'=40cm^{-1}, μ_a=0.01cm^{-1} and g=0.72, where μ_s' is the reduced scattering coefficient, μ_a is the absorption coefficient and g is the anisotropy factor. These values have been found in literature[4] for a concentration of 100% milk at a wavelength of 660nm. As source radiation a He-Ne laser (633nm) was used assuming that the scattering coefficient of milk would not significantly change at this wavelength. This is due to the fact that scattering in milk follows Mie scattering in this range of light frequencies and so it is little affected by wavelength. The simulation results are shown in Fig. 3.

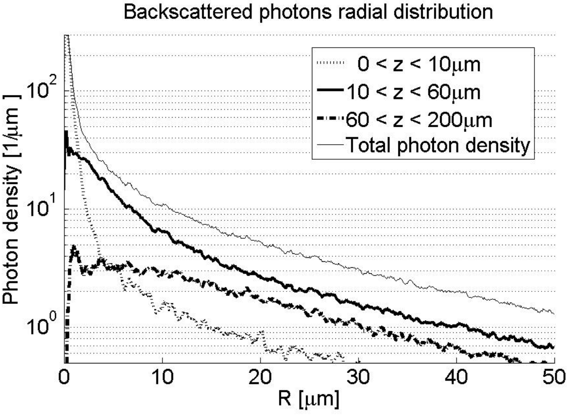


Fig. 3) Density of photons that are scattered to the surface from different depths inside the target medium.

In the experiments two different devices have been measured: the first device has a CSD (collector to source distance) of 25µm, waveguide width of 1.3µm, and waveguide spacing of 1.25µm; while the second device has CSD=10µm, w=1.6µm, and waveguide spacing of 0.95µm. The backscattered light intensity from the 8 output waveguides of the collector has been measured with a photomultiplier. The results of the measurement are shown in Fig. 4, in which the intensity of the detected light is given in function of the distance from the source waveguide for the two devices.

The measured points have been scaled to the simulation by applying a multiplication factor. It is clear that by simply changing the distance of the detector waveguides to the source it is possible to increase the sensing sensitivity only to those photons scattered from a given layer under the surface of the sample as can be seen in . This can be of great interest in spectroscopic applications in which it is mandatory to consider only certain layers of the medium under study.

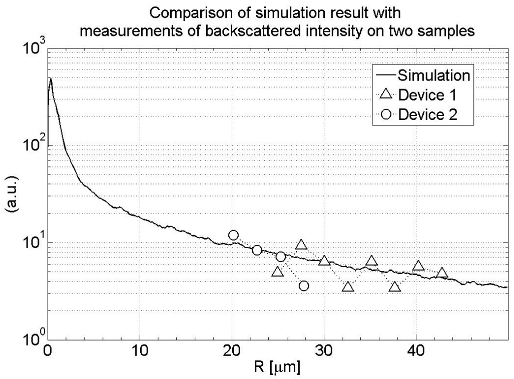


Fig. 4) Comparison of simulated and experimental backscattered intensity measured at the collector waveguides for two different devices. The intensity of the three sets of data is scaled linearly to obtain an optimum overlap.

Conclusions

This study provides a first step towards the design of integrated optics micro devices and sensors which can be directly coupled to the measurand, e.g. biological tissues, without means of lens systems. We have presented a collector system based on multiple waveguides for the detection of backscattered light in highly scattering media. From simulation results it can be seen that it is possible to detect photons backscattered from different depths inside the target by simple changing the CSD parameter.

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