On-chip near field fluorescence excitation and detection with nanophotonic waveguides for improved bulk background suppression in bio-sensing

M. Mahmud-Ul-Hasan[1,2], P. Neutens[1], L. Lagae[1,2], P. Van Dorpe[1,2]

[1] imec, Kapeldreef 75, 3001 Leuven, Belgium.
[2] KU Leuven, department of Physics, Celestijnenlaan 200D, 3001 Leuven, Belgium

Fluorescence is a widely used transduction mechanism in bio-imaging, sensing or physical chemistry characterization applications. The ability to selectively excite desired molecules without generating considerable bulk background from nearby molecules is very important for all these applications. We propose a waveguide based platform to improve the surface and bulk fluorescence separation by combining near-field excitation and near-field collection. The effect of waveguide geometry on the efficiency of the proposed near-field excitation and collection based technology has been investigated in this work.

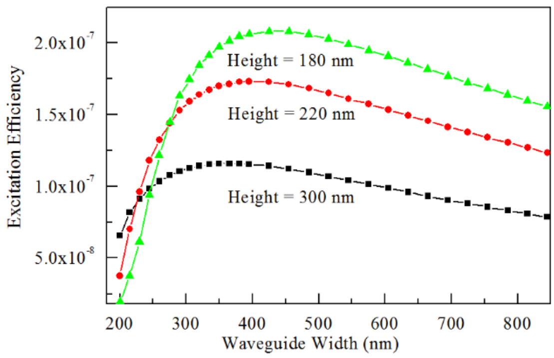
Introduction

In a bio-sensing application, the aim is to detect and quantify a target macro-molecule from the solution to find the concentration. Generally, it is done in two steps. In the first step, the bulk concentration is converted to surface concentration by capturing the target macro-molecule on the surface using antibody-antigen, complementary DNA, enzyme, etc interactions. The surface concentration is then transduced to an optical signal. This transduction can be done in different ways. One way is to insert an extra step to label the captured molecule with a fluorescent dye. The emission from the dye is then used to quantify the concentration. The transduction is also done in a label free manner in which the extra step of labeling can be avoided. However, in the label free transduction, a considerable amount of non-specific binding takes place[1]–[3]. This non-specific binding determines the Limit Of Detection (LOD) in label free biosensing. So, improving the sensitivity of the detector does not improve the LOD in practice. Instead, in most current bio-sensing techniques, such as ELISA, FISH, next generation DNA sequencing and others, people use fluorescence mostly as the transduction mechanism. These fluorescence based techniques require the transducer to respond exclusively to the target immobilized on the sensor surface. Most of the current well established techniques lack this high surface sensitivity. As a consequence, one or several washing steps are used to remove the bulk fluorescent molecules.

The evanescent field generated by Total Internal Reflection based sensing invented in 1983 [4] has been a good tool for surface–bulk separation. However, The need for compact bio-sensors in the areas of healthcare has driven the development of integrated analytical systems[5]. The evanescent based sensing for on-chip application has been also [6], [7]. The evanescent tail of the waveguides typically extends from 80 nm to 200 nm above the waveguide surface. However, the bio-sensing layer ends within 10 nm above the surface [8]. For that reason, a better confinement mechanism is desired.

We propose a PECVD Silicon Nitride (SiN) integrated nano-photonic rib waveguide based solution. At Imec, we developed and optimized a 200 mm CMOS compatible low-temperature PECVD process to fabricate low-loss nanoscale SiN waveguides [9], [10]. To obtain a better surface sensitivity, we used waveguides not only to excite the fluorescent dyes but also to collect the subsequent emission from the dyes. We found from Finite Difference Time Domain (FDTD) simulations that the coupling strength depends exponentially as a function of the waveguide surface–fluorophore distance. This way, both the excitation and collection efficiency have an exponential dependency on the distance between the molecule and waveguide surface. Therefore, it improves the separation between the surface and bulk fluorescence, paving the way for wash free bio-sensing.

Here, we have discussed effect of waveguide geometry on the excitation efficiency, collection efficiency and combined excitation and collection efficiency using FDTD simulation has been investigated. An optimized waveguide design has been derived for combined near-field excitation and collection based fluorescence bio sensing.



$$Exc.Eff. = \frac{Power\ absorbed\ by\ \ molecule}{Total\ Exc.Power}$$

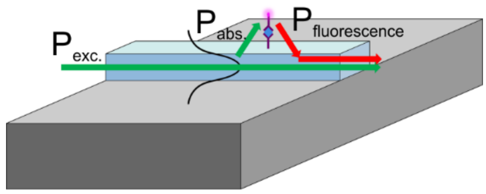


Figure 1. Single molecule excitation efficiency of a SiN waveguide as a function of the waveguide width and height for a fluorescent dye with typical absorption cross-section. Excitation efficiencies for a waveguide with 180 nm height (green line + triangle), 220 nm height (red line + circle), 300 nm height (black line + rectangle) are shown for different waveguide width.

Near-field excitation by the waveguide

The excitation efficiency is the ratio between the power absorbed by a single molecule located on the waveguide surface and the total power in the waveguide mode. A FDTD simulation was done to find the excitation efficiency. A refractive index of 1.91 for the waveguide material (SiN) has been used. The molecule is assumed to be in a water medium and positioned 10 nm above from the waveguide surface. A typical molar extinction coefficient value of 1.2 x 10^5 M^{-1} cm^{-1} was used for the calculation. The fundamental TE waveguide mode was used for the fluorescence excitation.

Figure 1 shows the excitation efficiency as a function of the waveguide width and height. Results shows that the efficiency is maximum around the cut-off width for the second mode for a given height. For a given height, the efficiency decreases when the width is increased because the mode can be confined more tightly in the increased core area of the waveguide. That leads to decreased power in the evanescent field. The same phenomenon is observed when height is varied for a given width. For a fixed width, the efficiency decreases with an increasing height from 180 nm to 300 nm. So, the general design criterion is to design the waveguide geometry to operate near to single mode regime for maximum excitation efficiency. The maximum efficiency value of $2x10^{-7}$ from the graph tells that 0.2 nW power can be absorbed locally by a single molecule residing in the near field of the waveguide that carries a total 1 mW power.

Near-field collection by the waveguide

The collection or coupling efficiency is the ratio between the fluorescence coupled to the waveguide and the total fluorescence emitted by the molecule. It is well known that emitting fluorophores behave like radiating dipoles [11]. FDTD simulations were done by placing an electrical dipole source above the waveguide surface. Three separate simulations were done with a X, Y and Z polarized dipole source. The coupling efficiency was calculated by averaging the results of those three simulations.

$$Coupl.Eff. = \frac{Coupled\ Fluorescence}{Total\ emitted\ fluorescence}$$

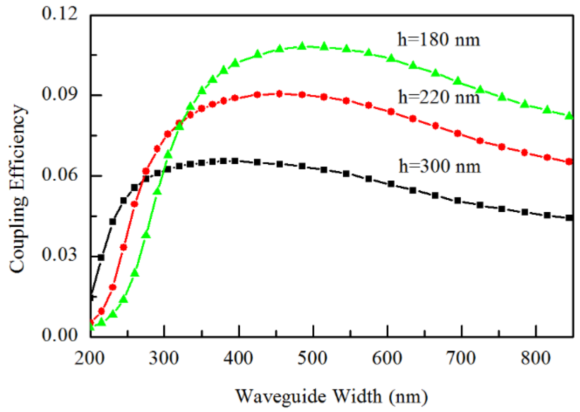


Figure 2. Collection efficiency of a PECVD SiN waveguide as a function of waveguide width and height. Collection efficiency for a waveguide with 180 nm height (green line + triangle), 220 nm height (red line + circle), 300 nm height (black line + rectangle) has been shown for different waveguide width.

Figure 2 shows the coupling efficiency as a function of waveguide geometry. The results show a similar dependency on geometry as the has been seen in Figure 1 for excitation efficiency. This is because the near field coupling is dominated by the interaction between the dipole field and the waveguide mode. So, the coupling efficiency follows the excitation efficiency profile. The maximum coupling efficiency value for the optimized geometry has been found to be 0.11. To put into perspective, the maximum collection efficiency with the state-of-the technology using a high NA objective is 0.44. So, an on-chip technique with collection efficiency of 0.11 can be considered as a promising technology.

$$Combined\ Eff. = \frac{Coupled\ Fluorescence}{Total\ Exc.Power\ in\ Wg.}$$

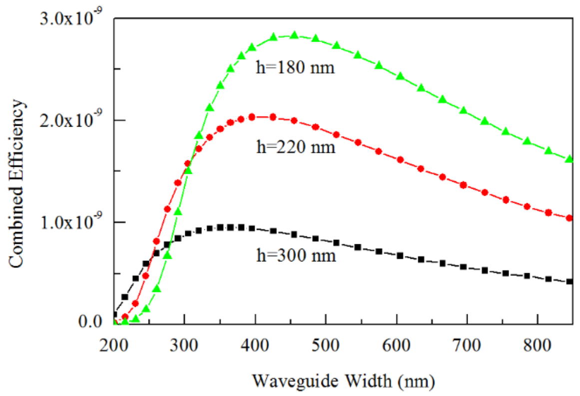


Figure 3. Combined efficiency when a single molecule is excited by the evanescent field of the waveguide mode and the subsequent emission is collected by the same waveguide in the near-field. The efficiency for a waveguide with 180 nm height (green line + triangle), 220 nm height (red line + circle), 300 nm height (black line + rectangle) are shown for different waveguide width.

Combined near-field excitation & collection by the waveguide

The combined efficiency is the ratio between the fluorescence collected by the waveguide from a single molecule and the total excitation power in the waveguide needed to excite that fluorophore. The combined efficiency has been calculated using the excitation efficiency and collection efficiency described earlier. A fluorescent quantum yield value of 0.2 has been used for this calculation. Figure 3 shows similar dependency of combined efficiency on the geometry as has been seen in figure 1 and 2. This is because the combined efficiency is proportional to multiplication of excitation and coupling efficiency. The maximum combined efficiency value of $3x10^{-9}$ for optimized waveguide design tells that a waveguide has to feed with 1 mW power to get a 3 pW fluorescence power coupled back from a single molecule excited in the near field of the waveguide.

Summary

To summarize, we found that a thinner, less confined waveguide operated in a single mode regime is most efficient for high efficiency. Simulations indicate that in these conditions, a waveguide can collect around 11% of the total fluorescence emitted by molecule residing very close to the surface. This value of collection can be considered as promising for an on-chip technique.

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