Optical Waveguide with Freestanding Grating Couplers

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This paper presents a freestanding waveguide for bio-medical applications. It features grating couplers to couple light in and out of the ultra-thin membrane ridge waveguide. The ridge waveguide is made of two layers, TiO_2 rib and SiN substrate. The freestanding waveguide was fabricated and tested. Freestanding grating couplers is designed to avoid light to be coupled into the underlying silicon which has a higher refractive index. And also the height of the coupler is the same with the waveguide, so no extra loss will be induced, which makes the coupling more efficient.

Introduction

Patients who suffered from colon cancer need to cut part of their colon and then reconnect them. The reconnection is called anastomosis. There is a possibility of leakage after anastomosis which can cause severe complications or even death [1]. Thus an optical waveguide is designed to monitor patients after colon surgery to detect the leakage. By detecting the existence of E.coli in patients' drain fluid, whether there is leakage or not can be known. Detection time and detection sensitivity are dominant in this situation. The waveguide is designed to be freestanding to increase the sensitivity and decrease the detection time simultaneously. Simulations are done to guarantee the feasibility of the freestanding waveguide. For optical waveguide, couplers are also a major part. Here, freestanding grating couplers are considered to couple the light in efficiently [2].

Waveguide design and simulation

A. Structure design

The schematic structure shown in Figure 1 [3] shows how freestanding waveguide works. There will be evanescent wave on the surface in the freestanding region. The evanescent wave intensity decays exponentially with the increasing distance from the interface. Both surfaces are functionalised to be able to capture E-coli when patient's drain fluid is applied on it. The evanescent wave is used to sense the captured E.coli. Figure 2 shows the cross section of the waveguide. The thickness of TiO_2 (H_t)and SiN (H_{SiN}), the width of TiO_2 (W_t) and the height of the rib (H_r) need to be designed to confine the light in the waveguide and maintain proper evanescent wave tails on the upper and lower surface at the same time, which should be enough to be sensitive to E.coli and not too much to influenced by the surface roughness.

By simulation, as indicated in Figure 3 shows the light distribution on the cross section, light is mostly confined in the core (TiO_2) and then decrease gradually. By simulation, the parameters are chosen as H_t=250nm, H_{SiN}=250nm, H_r=50nm, W_t=3µm. Figure 4 shows the vertical evanescent wave profile on the cross section. It indicts there is enough optical energy outside the waveguide.

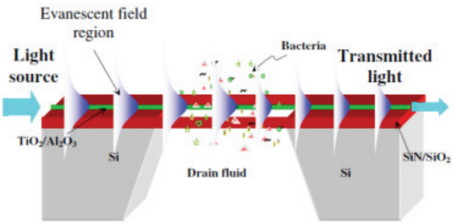

Figure 1: Schematic of optical waveguide

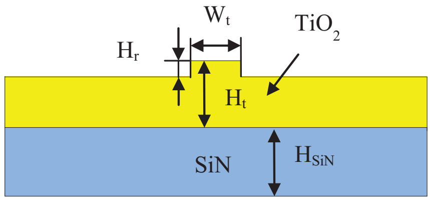

Figure 2: Cross section of waveguide

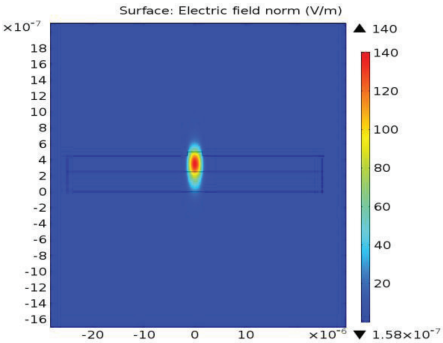

Figure 3: Optical distribution on the cross section

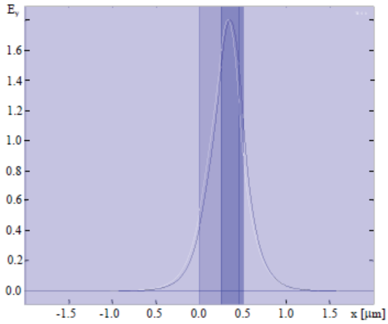

Figure 4: The vertical profile of the light distributed on cross section

B. Material

The materials are chosen as TiO_2 for rib and SiN for ridge. SiN is chosen as the substrate mainly for its excellent mechanical stability [4]. It has the fracture strength of more than 5GPa and a proper refractive index of 1.45 which is a slightly higher than the air or detected drain fluid (1.3). TiO_2 is chosen as the rib material for its high refractive index (2.49) and also the bio-compatibility [5]. It is much higher than SiN and drain fluid, which ensures the light to be confined in the waveguide. While it is lower than Si (about 3.5), thus it will leave enough wave tails outside than commonly used SIO waveguides. TiO_2 is also a material can be deposited by ALD to control the thickness precisely.

C. Experiment

After functionalization, the absorbance is 7.1 dB. Different absorption was acquired by dropping different concentrations of drain fluid on it, the experiment results are shown in Figure 5. Sensitivity is calculated using formula in [6] to be 1dB/%. The results shows that the sensor is quite sensitive to different concentration of drain fluid. And further experiment shows that the sensor is able to detect as low concentration as 3.74×10^{2}CFU/ml cultured E.coli, which is lower than the average detected concentration around 10^{3} CFU/ml. Samples of drain fluid with E.coli was provided by Erasmus University Medical Centre Rotterdam and was grown in a Luria Agar (LA) medium.

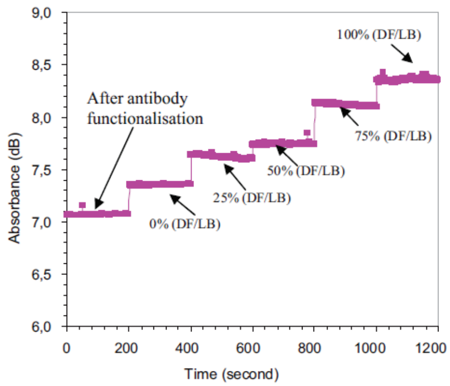

Figure 5: Absorbance of different concentration drain fluid in LB medium

Grating couplers

To improve the coupling efficiency between the optical fibre and the waveguide, grating couplers are proposed. Considering the refractive index of Si (3.45), SiN (1.45) and TiO_2 (2.49) [5], if the couplers are fabricated on the silicon, light will be gradually coupled into the silicon substrate. Thus the grating coupler is designed freestanding to eliminate this phenomena.

Λ is the grating period, θ is the angle between fiber and the normal direction of waveguide plan. It cannot be too large, the fiber would be far away from the grating and the beam divergence will limit the coupling efficiency. If it is too small, there will be a strong reflection from the grating back to the fiber and vice versa [7]. In this design (Figure 6), the incident light is set at an angle of 10° with respect to the normal surface. Here grating cycle is taken as 50% and the TiO_2 is etched to the bottom for just single lithography step. The relationship of the coupling angle and the grating period is described as [8]:

$$n_3 \sin(\theta) = n_{eff} - q\lambda_0 / \Lambda$$

n_3 is seen as 1.3 which is the refractive index of drain fluid, λ_0=1.3µm. n_{eff} is the effective refractive index of the grating, which is determined by the effective refractive index of the slot and rib in the grating part:

$$n_{eff} = (n_{eff1} + n_{eff2})/2$$

here it is n_{eff}=1.69, thus Λ is calculated to be 0.908 µm.

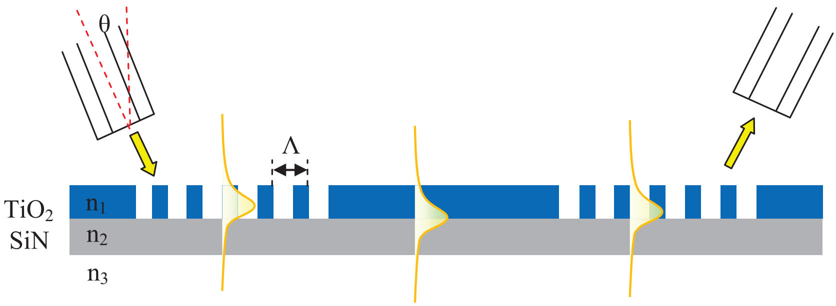

Figure 6: The grating coupler design

Conclusions

In this paper a freestanding waveguide is fabricated and demonstrated to be sensitive to the chosen bacteria to a level of 1dB/%. In order to improve the coupling efficiency between fibre and waveguide, freestanding grating couplers are put forward and designed. The work is continuing to improve the efficiency.

References

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