Ultrasensitive Spectroscopy Based on Integrated Photonic Waveguides on Al_2O_3/ SiO_2 Platform

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Abstract: Integrated photonic waveguides on Al_2O_3/SiO_2 platform are proposed to cover the 220~320nm wavelength-range, which is of paramount significance in protein and nuclei acid quantification. The proposed system requires 500x less volume of solutions compared with NanoDrop™.
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In molecular biology, nucleic acid and protein quantitation is frequently performed to determine their concentration and purity. Since plenty clinic specimens are rare and give extremely limited amount of target nuclei acids and proteins, it is very crucial to quantitate the purified deoxyribonucleic acid/ ribonucleic acid (DNA/RNA) and proteins. Nucleic acids and proteins are traditionally quantified with a spectrophotometer. One of the main problems of the conventional spectrophotometers is that the cuvettes are large, and thus a considerable portion of precious samples will be inevitably lost during the quantification [1]. This micro volume spectrophotometric instrument can accurately quantify RNA, DNA, and proteins with volumes as little as 0.5 μL and with concentrations ranging from 2 ng/μL to 15,000 ng/μL [2,3]. Although the use of surface tension significantly reduces the required sample volume, it limits the maximum optical path length to 1 mm and consequently makes it impossible to quantify samples with even lower concentration. Here, we propose a novel ultrasensitive spectroscopy based on integrated photonic waveguides on Al_2O_3/SiO_2 platform for picogram/microliter (pg/μL) level nuclei acids solution quantitation.

The scheme of the proposed structure is shown in figure 1. The system is designed to be "drop-and-play", same as conventional design (Nanodrop™) while the functionality will outperform it. In this design, light is coupled from the bottom to the Al_2O_3 waveguide through grating couplers. Sensing surface can be cleaned by wiper since the light coupling is implemented on the backside of the slide. Transverse magnetic (TM) polarized light is used to increase the fraction of optical field interacting with analytes. Light will be coupled out through another grating coupler and collected by a fiber, through which light is delivered to a spectrometer. The absorption spectroscopy is based on Beer-Lambert-Bouguer law [4,5], per which the transmitted intensity is described as:

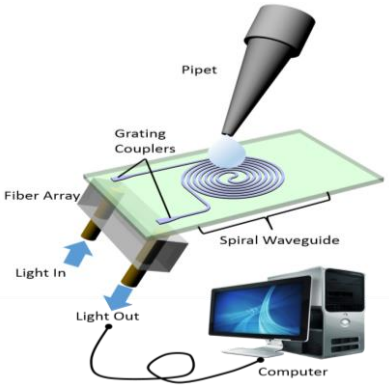

Fig. 1 Schematic of the proposed platform.

$$I = I_0 \exp(-(\gamma\alpha_m + \alpha_{wg})L) \quad (1)$$

where, I_0 is the light intensity α_m is the absorption coefficient of the analyte, and α_{wg} is the propagation loss of the waveguide and $\gamma = f\frac{c/n}{v_g}$. (f is the percentage of energy of the mode volume inside the analyte v_g is the group velocity of the optical mode, c and n are the velocity of light in vacuum and the refractive index of the analyte, respectively).

To enhance the minimum detectable concentration (MDC) to pg/μL level [6], the interaction between photons and analytes must be further enlarged. Strip waveguide is one of the fundamental building blocks for integrated photonics. Through tuning the waveguide dimensions, could be as large as 20% for the TM polarized mode following conventional approach. The mode profile of a 300 nm × 100 nm Al_2O_3 waveguide at 300 nm wavelength is shown in Fig. 2. Continue to increase the length of the strip waveguide is a viable option but limited by its propagation loss (10 cm on-chip strip waveguide is 100x the path length of a NanoDropTM). Thus although is only 20% of NanoDropTM, an MDC improvement of at least 20 times is assured with strip waveguides.

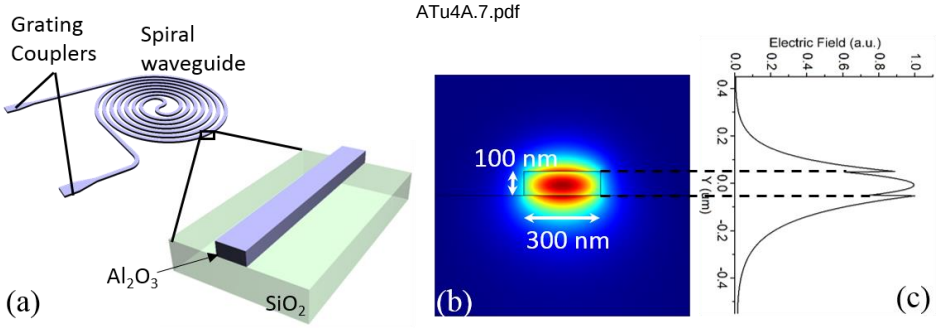

Fig. 2 (a) Schematic of the strip waveguide. (b) and (c) Mode profile (TM) of a 300 nm × 100 nm single mode Al_2O_3 at waveguide. Wavelength of 300 nm.

Figure 3 (a) shows a fish-bone waveguide design, where the "bones" on both sides of a strip waveguide will modulate the photons at a lower speed than conventional waveguide. Here a bandgap appears in the band diagram, as plotted in figure 3 (b) a slow-down factor of over 30 is achievable at the band edge, resulting to an ultra-compact device through enhancing the interaction between photons and analytes, and therefore improves the MDC. An Improvement of 400x could be achieved compared to the NanoDrop™ by exploiting this new concept. Here, the slow light characteristic of the "fishbone" structure is tuned by adjusting W_1, W_2, fill-factor, and Λ. Here the waveguide is designed with 200 nm thick, W_1 and W_2 are set at 300 nm and 500 nm, respectively and filling factor $f = W_3/\Lambda = 0.5$ is used. As large group index is always accompanied by large group velocity dispersion, a few "fishbone" waveguides with different working wavelength will be multiplexed to expand the working wavelength range. Besides, to couple light into such a thin waveguide, grating couplers need to be used.

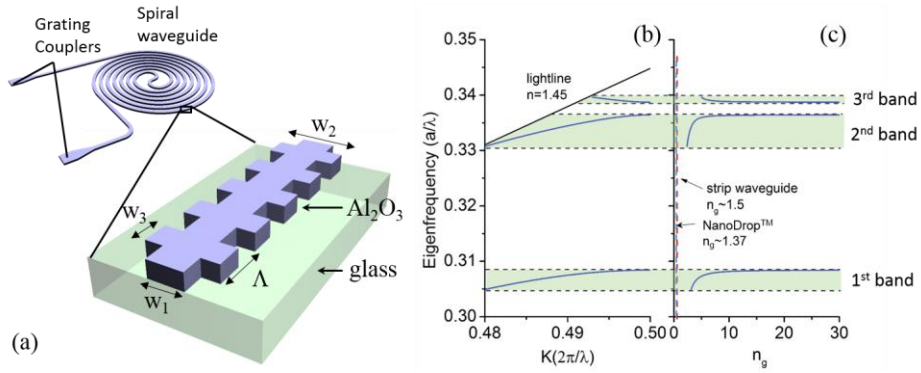

Fig. 3 (a) Schematic of the fishbone waveguide; (b) band diagram of the "fishbone" waveguide; (c) Group index in relation to wavelength.

As a conclusion, our proposed system requires 500 times less volume of solutions. While with strip waveguides, the MDC is improved by 20x, equivalent to save 95% of sample; with "fishbone" waveguides, the MDC is improved by 400x, equivalent to save more than 99% of sample. At the same time the operation of the system is as simple as NanoDropTM. The proposed device is useful for the next generation of bio-spectroscopy.

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