Al_2O_3:Yb^{3+} microdisk resonator for active biosensing

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Passive whispering gallery mode biosensors are limited by their linewidth, which imposes a limit on the smallest variations of the resonance wavelength shift that can be detected. Using an active, laser-based biosensor could allow for the detection of smaller shifts, since its linewidth is typically much smaller. Here, an integrated, single-mode Al_2O_3:Yb^{3+} microdisk laser is realized that operates in an aqueous environment and that can be used for sensitive, active biosensing applications.

Introduction

Integrated whispering gallery mode (WGM) optical sensors are numerously used for the detection of clinically relevant biomarkers. They detect the binding of a specific biomarker from a shift of the resonance wavelength of the passive cavity [1]. This shift results from elongating the optical path length of the mode inside the cavity upon biomarker binding. Such biosensors are ultimately limited by their cavity linewidth, which poses a fundamental limit on the smallest detectable wavelength shift [2]. This issue can be avoided by realizing an active biosensor that has a much narrower linewidth for more precise sensor operation [3]. Lasers integrated on chip can reach linewidths down to kHz [4], [5], a significant improvement over the linewidth of passive cavities. Furthermore, such active sensors have the additional benefit of allowing for simpler detection schemes that do not require a tunable laser to continuously monitor the location of the resonance wavelength. A good example thereof is the detection of a beat note generated on an integrated optical chip whose frequency is proportional with the analyte, allowing for microparticle [6] and even single virus detection [7]. These considerations motivate the development of an integrated, active sensing platform. This work presents such a system on the Al_2O_3:Yb^{3+} material platform based on a microdisk resonator.

Al_2O_3:Yb^{3+} microdisk laser

Rare-earth ion doped aluminum oxide is a well-suited material for realizing integrated amplifiers and lasers. It has low optical losses [8] covering a wide window of the visible and near-infrared [9] and can easily be integrated monolithically on a chip [10]. Furthermore, upon optical pumping lasing can be achieved [11]. Ytterbium is an excellent dopant for realizing active biosensors, since it emits around 1030 nm where water absorption losses are negligible.

A microdisk laser was designed and realized on this material. First, a 550 nm thick Al_2O_3:Yb^{3+} layer was deposited onto a thermally oxidized silicon wafer using reactive cosputtering from an Al and Yb target. Then, the microdisk and bus waveguide were patterned using contact UV lithography and reactive ion etching. The microdisk radius was 150 µm with a coupling gap to the bus waveguide of 0.6 µm. A SiO_2 cladding was locally deposited such that the microdisk remained exposed to the environment whereas the bus waveguide was buried in it. Finally, after dicing a small chip a PDMS microfluidic channel was bonded on top of it and water was flown through it (Figure 1 (a)). Upon pumping the device with light of 976 nm, single-mode lasing was observed (Figure 1 (b)). This laser could already serve as a sensor by monitoring the lasing wavelength upon flowing liquids of differing refractive index over the cavity, as shown in Figure 1 (c). The lasing wavelength shifted to higher values for higher refractive index liquids, indicating that it can be tuned by modulating its environment. This property is exploited to use it as a precise, active optical sensor.

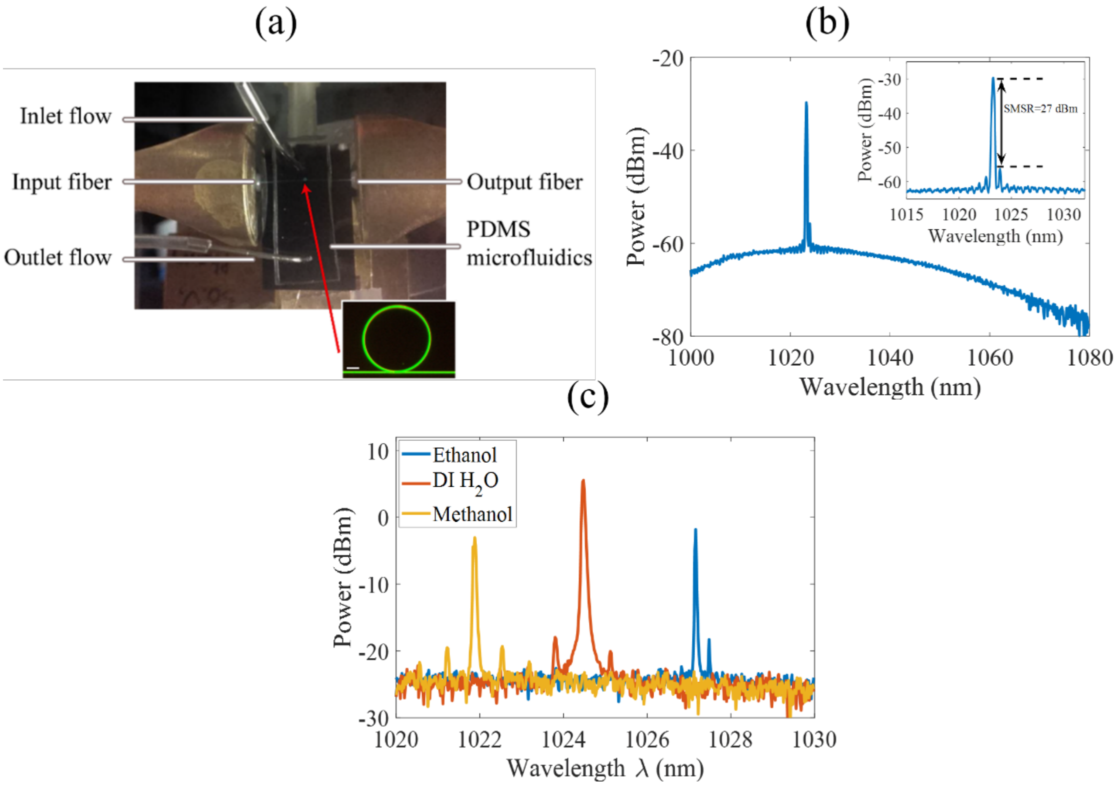

Figure 1: (a) Photograph of the optofluidic chip mounted on a temperature-regulated stage. The inset contains the laser cavity under pump illumination. Scale bar is 50 µm. (b) Single-mode lasing spectrum of $Al_2O_3:Yb^{3+}$ microdisk resonator in deionized water. Inset: zoom of lasing peak showing the side-mode suppression ratio (SMSR). (c) Tuning of lasing wavelength by variation of its cladding environment.

Active sensing

To detect variations of the microdisk lasing wavelength smaller than the optical spectrum analyzer (100 pm), a narrow linewidth, external laser was used to form a difference heterodyne beat note. This was done by combining the external laser light with the microdisk laser emission and guiding it to a radio frequency (RF) spectrum analyzer (Figure 2 (a)). The difference frequency is then given by $f_{beat}=c(\lambda_1-\lambda_2)/\lambda_1\lambda_2$,where c is the speed of light in vacuum, λ_1 the lasing wavelength of the $Al_2O_3:Yb^{3+}$ microdisk laser and λ_2 the lasing wavelength of the external laser. The difference beat note has a frequency in the range 1—15 GHz, which is sufficiently low to be detected on the RF analyzer. Now, the device can be turned into a sensor by keeping the external laser wavelength fixed, while changing the refractive index of the aqueous cladding. Upon such variations λ_1 will vary, which is translated into a change of difference beat note frequency that will be recorder by the RF spectrum analyzer.

To demonstrate this sensing functionality, the bulk refractive index sensitivity of the microdisk laser was determined. First, deionized water was flown through the microfluidic channel. This was then followed by a series of increasing NaCl concentrations in deionized water, ranging from 0.1—0.5 wt% NaCl, corresponding with an effective bulk refractive index variation up to 9E-4 RIU. At the same time, the difference beat note RF spectrum was repeatedly acquired. The frequency of the difference beat note was extracted from this spectrum and tracked over time while flowing the different NaCl concentrations through the channel (Figure 2 (b)). For increasing NaCl concentrations the difference beat note frequency increases to higher values, due to the shift of the lasing wavelength of the microdisk laser. Upon switching back to deionized water, the signal shifts back to the water baseline. The corresponding slope sensitivity equals 5.74±0.21 THz/RIU, or 21.3 nm/RIU in wavelength units. Given an uncertainty in the frequency of the difference beat note of 7 MHz, a limit of detection of 3.7×10^{-6} RIU was found. These performance parameters, which are comparable to those of the traditional passive WGM sensors [12], demonstrate the potential of realizing precise, laser-based sensors integrated on-chip. Furthermore, their operation in an aqueous environment indicate their viability for active biosensing experiments.

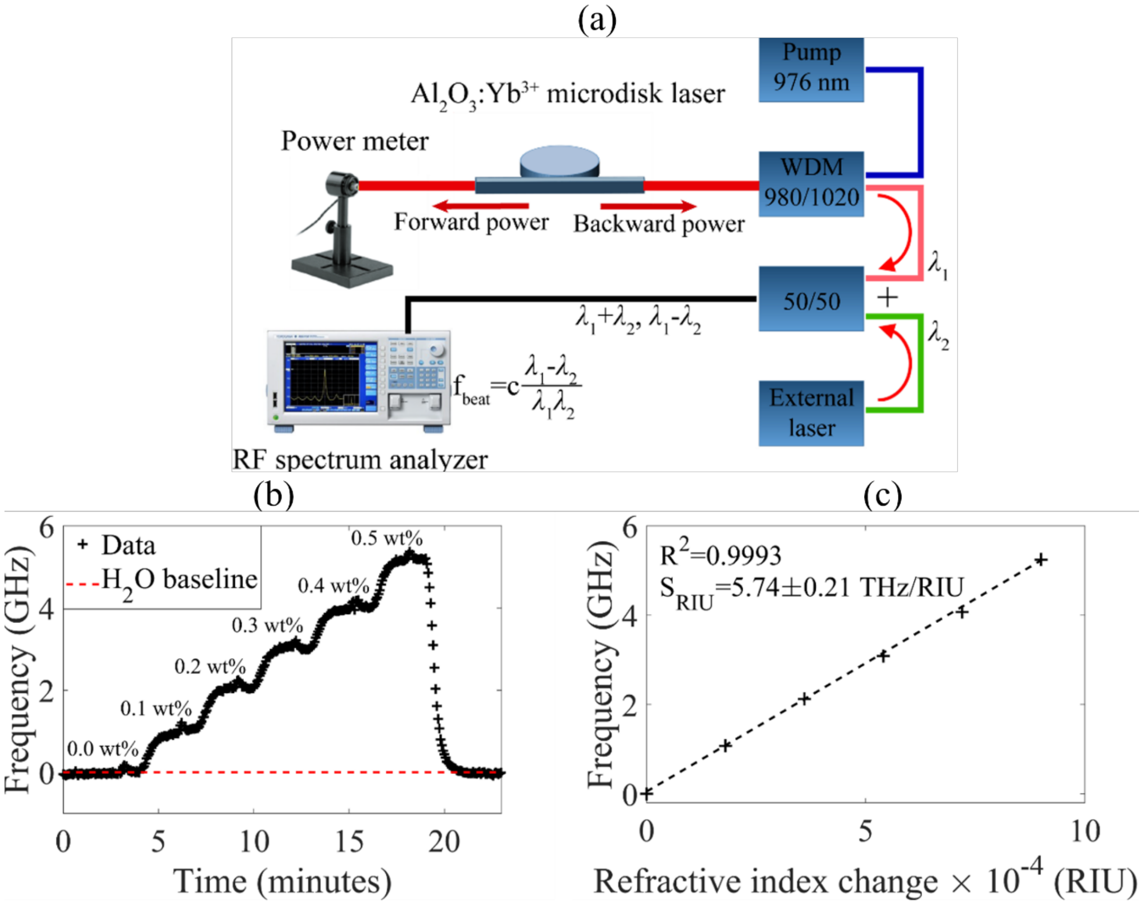

Figure 2: (a) Schematic of the experimental setup used for detecting the change of the microdisk laser frequency. (b) Real-time bulk refractive index sensing. The flow was switched every 3 minutes between 0.0 wt% and 0.5 wt% NaCl solutions in deionized water. The flow was kept constant at 30 µl/min and the stage temperature was fixed at 22 ºC. Data acquisition was at 15 points per minute. (c) Bulk refractive index slope sensitivity, dotted line is linear fit.

Future steps include improving the sensitivity of the active sensor and performing biosensing experiments with it. For the former the cavity can be redesigned based on a microring resonator with a smaller height, such that its evanescent tail extends more into the sensing region, enhancing the sensitivity. To transform the active sensor in a biosensor, an appropriate functionalization protocol will be applied to bind antibodies onto the device for biomarker capture [13]. Finally, improvements to the flow and temperature control should be implemented to further reduce the noise in the system. These efforts are currently ongoing.

Conclusions

A single-mode, integrated on-chip microdisk laser that operates in an aqueous environment was realized on the Al_2O_3:Yb^{3+} material platform. Small variations of its lasing wavelength could be monitored by translating those into a varying difference beat note frequency. In this manner the device could be transformed into an active sensor. Its sensitivity and limit of detection indicate that this system is well suited for the realization of a precise, sensitive, active biosensing platform.

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