Integrated $Al_2O_3:Yb^{3+}$ Microring Laser for On-Chip Active Sensing in an Aqueous Environment

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ABSTRACT

This paper presents an integrated on-chip $Al_2O_3:Yb^{3+}$ microring resonator laser that operates in an aqueous environment. By varying the refractive index of the bulk cladding, the lasing wavelength can be tuned, allowing this device to operate as an active refractive index sensor. In this manner, the lasing modes could be tuned over 15 nm with a sensitivity of 590 nm/RIU. In combination with the wavelength resolution of the detector (100 pm), a limit of detection of 1.5×10^{-4} RIU was achieved. The intrinsic limit of detection was not determined due to the incapability of measuring the laser linewidth. This work demonstrates the viability of realizing very sensitive, laser-based active sensors in an aqueous environment on the $Al_2O_3:Yb^{3+}$ material platform.

Keywords: $Al_2O_3:Yb^{3+}$, laser, microring resonator, sensor.

1. INTRODUCTION

Microring resonators are very often integrated on-chip for the realization of refractive index sensors. Such sensors typically operate by monitoring the wavelength shift of a resonance induced by a dielectric perturbation in the evanescent field region. Microring resonators sensors in the SOI [1], Si_3N_4 [2] and SiON [3] passive material platforms. Generally, wavelength tracking requires a setup containing a tunable laser to repeatedly scan the spectral position of the resonance, which leads to relatively expensive sensing modules

Al_2O_3 is an alternative material platform that can be doped with rare-earth ions to achieve gain [4] and to realize lasers [5]. On this material platform, an active sensor was already demonstrated that could detect particles through a variation of the beat note of a distributed feedback laser [6]. This type of active sensing has the attractive feature that it only requires simple hardware to transduce the sensing-induced change of the optical beat note of the laser output into an electronic signal. Furthermore, due to the high quality factors of this type of Al_2O_3-based lasers [7], a very low intrinsic limit of detection (*iLOD*) of an active sensor could be in principle realized.

In this paper, we present an integrated double microring resonator made out of $Al_2O_3:Yb^{3+}$ waveguides that operates in an aqueous environment. Upon optical pumping, the lasing wavelength could be tuned by varying the refractive index of the liquid flown over it. In this manner a bulk refractive index sensor was realized with a sensitivity of 590 nm/RIU, which, combined with the resolution of the spectral analyzer detector of 100 pm gave a limit of detection of 1.5×10^{-4} RIU. However, it is expected that the *iLOD* is lower due to the linewidth being much narrower than the detector resolution. The presented results, together with this consideration, demonstrate the viability of realizing ultrasensitive sensors on the $Al_2O_3:Yb^{3+}$ material platform that could lead to simple detection methods.

2. MICRORING RESONATOR LASER

The fabrication of the laser started with the reactive cosputtering of Al and Yb to deposit an $Al_2O_3:Yb^{3+}$ layer onto a SiO_2 substrate with an AJA ATC 1500 sputter coater. By controlling the ratio of applied power to both targets the Yb doping concentration can be tuned. The power was chosen to achieve a Yb content of 5×10^{-20} cm^{-3}. The waveguides and microring resonators were patterned with contact UV lithography and etched with an Oxford Plasmalab System 100 inductively coupled plasma reactive ion etcher. Then, a local cladding of SiO_2 was deposited onto the device to cover the input and output waveguides while leaving the microrings open to be addressed by the various liquids. To this end a PDMS microfluidic channel was bonded to the chip. Figure 1a shows the resulting devices inside the microfluidic channel.

After submerging the devices in water they were optically pumped by a diode laser at a wavelength of 976 nm and demonstrated lasing in the spectral range of 1010—1070 nm. The lasing spectrum obtained with an optical spectrum analyser of one of the devices contains three laser modes separated by the Vernier free spectral range, as shown in Fig. 1b. The spectrum of the first lasing mode in Fig. 1b as function of current injected into the diode laser is shown in Fig. 1c. It can be seen that its threshold lies around 200 mA of diode laser current, after which the spectral power increases upon increasing the current. Figure 1d shows the light-light curves of all three lasing modes, indicating the onset of lasing when the diode laser current exceeds the threshold.

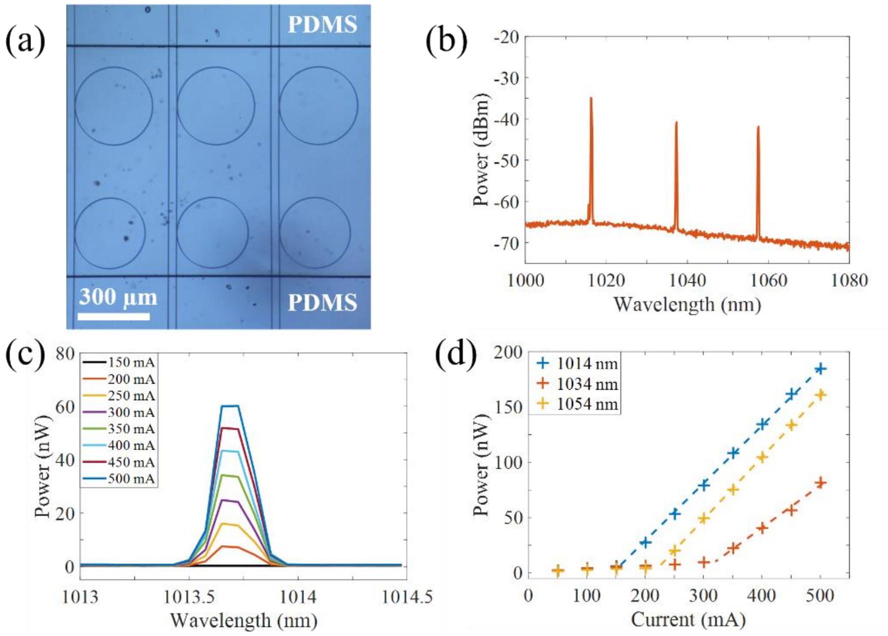

Figure 1. Al_2O_3:Yb^{3+} microring resonator laser operating in aqueous environment. (a), Optical microscope image of circuits containing the double microring resonator in a microfluidic channel. (b), Lasing spectra of the double microring resonator laser. (c), Lasing spectra of the first mode for varying input power. (d), Power characteristic of the laser.

3. ACTIVE SENSING

The laser was used as an active sensor by flowing varying concentrations of NaCl dissolved in water. By changing the refractive index of the top cladding, the optical path length of the microring resonator changes and shifts the lasing wavelength. This was done by flowing water over the active sensor containing NaCl concentrations of 0, 5, 10 and 15 wt%. Figure 2a shows the lasing spectrum of the first mode for these variations. By monitoring the lasing spectrum continuously, the lasing wavelength of all three modes was monitored in real time as shown in Fig 2b and 2c. Furthermore, by reversing the order of the flown liquids the lasing wavelength returned to its original wavelength, indicating reversible operation. Figure 2d shows the measured slope sensitivity of the active sensor that has a value averaged over all three modes of 590 nm/RIU.

The limit of detection (*LOD*) of the sensor is the smallest variation of bulk refractive index change that yields a detectable lasing wavelength shift and is given by [8]:

$$LOD = \frac{3\sigma}{S} \tag{1}$$

where σ is the standard deviation in the position of the lasing wavelength and *S* is the sensitivity of the active sensor. In this case the *LOD* is limited by the resolution of the used optical spectrum analyser of 100 pm, which has a σ of 29 pm. Combining this value with the measured sensitivity gives a LOD = 1.5×10^{-4}. However, the intrinsic limit of detection (*iLOD*) of the system is given by [8]:

$$iLOD = \frac{\lambda_{FWHM}}{S} \tag{2}$$

where λ_{FWHM} is the laser linewidth of the active sensor. With the currently used optical spectrum analyser a maximum laser quality factor of ~10^4 can be measured due to the limited resolution, although the actual value of similar, previously measured Al_2O_3:Yb^{3+} lasers lies much higher due to their narrow linewidth [7]. The true *iLOD* could be obtained by measuring the laser linewidth and it is expected that the *iLOD* is much lower than the currently reported *LOD.* These results could allow for sensitive, active sensor applications integrated on chip on this material platform.

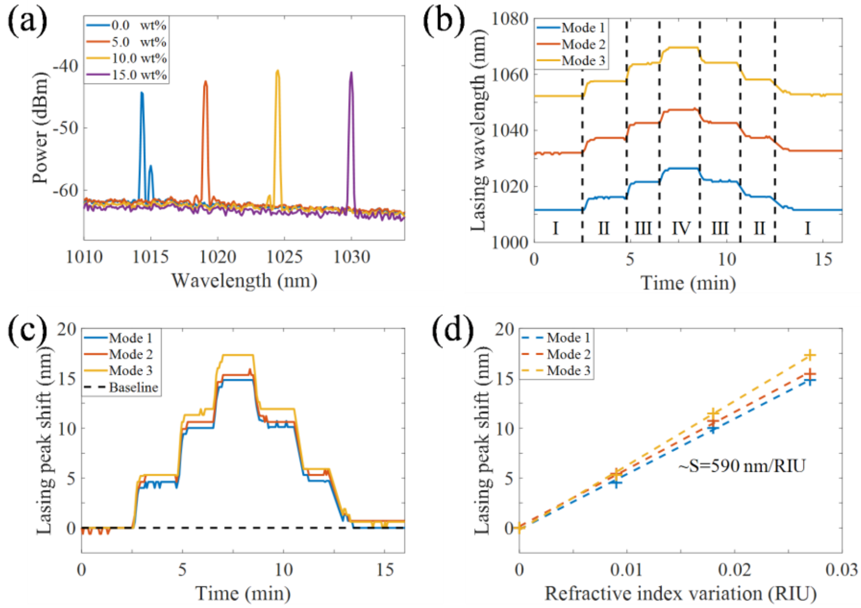

Figure 2. Active sensing experiment. (a), Lasing wavelength shift of the first lasing mode. (b), Real-time monitoring of the lasing wavelengths while flowing water (I), water containing 5.0 wt% NaCl (II),water containing 10.0 wt% NaCl (III) and water containing 15.0 wt% NaCl (IIV). (c), Relative lasing wavelength shift of data in (b). (d), Slope sensitivity of the active sensing experiment. Sensitivity is an average of the three modes.

4. CONCLUSIONS

A double microring resonator of $Al_2O_3:Yb^{3+}$ was realized that had three lasing modes separated by the Vernier free spectral range of the system. This laser was used as a sensor to monitor the refractive index of its liquid cladding. A sensitivity of 590 nm/RIU and LOD of 1.5×10^{-4} RIU was achieved. It is expected that the sensor has a lower *iLOD* and can be used for sensitive sensing. These results indicate that the active sensor could be used for sensitive, active biosensing with the prospects of simple detection schemes.

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