Vertically emitting distributed feedback laser for active label free biosensing

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Abstract: A distributed feedback laser has been demonstrated as a label free biosensor. The stimulated emission wavelength changes with the refractive index variations on the sensor surface. The sensor exhibits high resolution and wide dynamic range.

OCIS codes: (280.1415) Biologic sensing and sensors, (140.3490) Lasers, distributed-feedback

Recently, researchers demonstrated passive high Q-factor optical resonators as label free biosensors to resolve very small resonant wavelength shifts [1]. These biosensors have the ability to detect samples at low concentrations, or biomolecules with low molecular weight. However, high Q-factor passive resonators require precise optical alignment and lack sufficient dynamic range of wavelength shift. Active optical oscillators, such as the distributed feedback (DFB) laser, can produce their own narrow linewidth radiation with simple coupling to the excitation source and collection optics for detecting small changes in wavelength, while retaining excellent wavelength shift caused by changes in surface dielectric permittivity resulting from the adsorption of biomolecules [2]. DFB lasers may be designed to operate with a single vertically emitting mode, enabling simple collection and monitoring of emission wavelength [3].

The DFB laser biosensor demonstrated in this report utilizes a dye-doped organic film as an optically pumped gain material, thereby enabling the uniform, cost effective production of DFB lasers over large surface areas using nanoreplica molding techniques to produce the grating structure [4]. The fabricated sensor arrays are single-use and disposable. A cross-sectional diagram (not to scale) of the DFB laser structure adopted for the present experiments is shown in Fig. 1. A grating is formed on the surface of a dielectric substrate by replica molding, followed by spin-cast coating of the active layer which also serves as the waveguide layer. A high refractive index (RI) thin film is deposited on the top surface. The DFB laser biosensor chip is pumped by a frequency-tripled Nd:YAG laser (λ = 355 nm) from an arbitrary incident angle and the resulting stimulated emission is monitored by a fiber-coupled spectrometer along an axis nearly orthogonal to the surface.

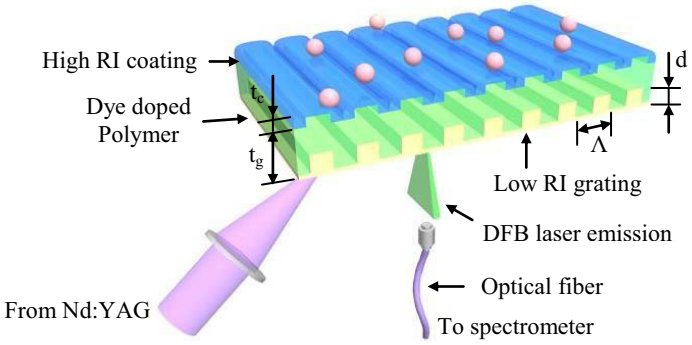

Fig. 1. Schematic diagram of the sensor structure and experimental setup. The grating structure has a periodicity Λ = 360 nm, depth d = 40 nm, and RI of 1.17. The dye doped polymer layer and dielectric coating (HfO_2), have a thickness of t_g and t_c, respectively.

The DFB laser consists of the nanoporous glass grating substrate (RI ~ 1.17), the laser dye (Coumarin 503) doped organic gain film (t_g = 350 nm, RI = 1.51), and the HfO_2 coating (t_c = 40 nm, RI = 2.0). With the DFB laser surface exposed to air, spectra representative of those recorded for pump fluences of 0.8 μJ-mm^{-2} and 5.5 μJ-mm^{-2} are presented in Fig. 2 (a). At higher intensities, laser oscillation occurs at λ = 497.53 nm with full wave half maximum ~ 0.07 nm (Fig. 2 (b)). The laser threshold fluence is ~1.8 μJ-mm^2.

Fig.3 summarizes measurements of radiation spectra when the device surface was exposed to air, submerged in deionized (DI) water, and coated with a monolayer of protein polymer Poly(Lys, Phe) (PPL; 0.5mg/mL; Sigma-Aldrich) solution. The peak wavelengths were measured as 497.53 nm, 509.64 nm, and 510.18

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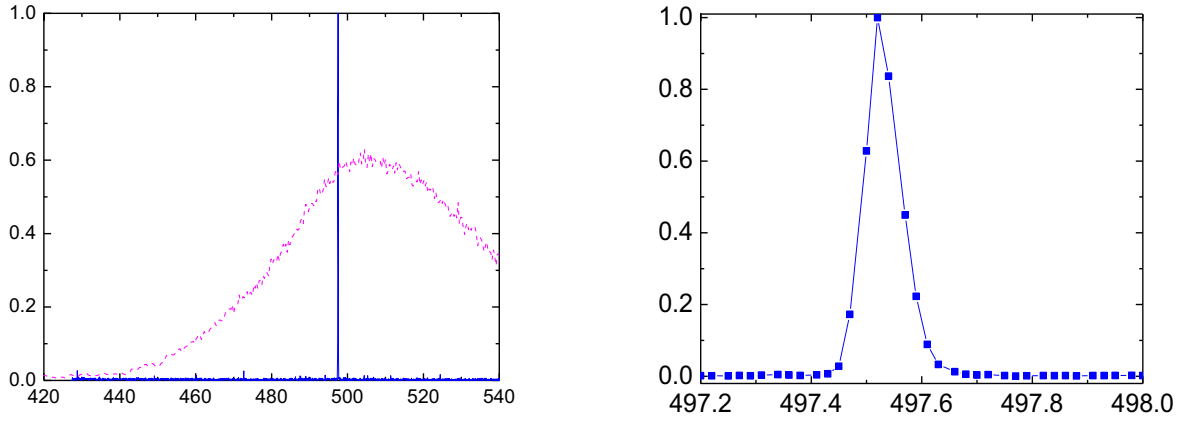
nm, respectively. The spectral width of the laser remains narrow ($\Delta\lambda < 0.1$ nm) throughout the experiments. By taking several measurements with the same sensor as a function of time, the kinetic characteristics of mass adsorption are shown in Fig. 4 for the dynamic detection of the growth of a single PPL layer which has been shown to deposit a ~15 nm thick monolayer with a mass density of ~2.5 ng/mm^2. A baseline value for the laser wavelength was initially established with the sensor surface soaked in phosphate buffered saline (PBS) solution. After 4 minutes, the PBS solution was replaced with a PPL solution and stabilized for 10 min. Then the sensor surface was rinsed with PBS solution to remove any PPL that is not firmly attached to the sensor. The sensor produced a wavelength shift of 0.53 nm for PPL monolayer adsorption.

The minimum detectable laser wavelength shift was determined by exposing the sensor to DI water and measuring the wavelength every 100 ms for a total period of 10 seconds. Since the wavelengths were found to vary from 508.158 nm to 508.168 nm with a standard deviation (σ) of 2.2pm, the system resolution was found to be $\Delta\lambda = 3\sigma = 6.6$ pm. Results demonstrating biochemical assays for detection of small molecule analytes will be presented.



(a) (b)

Fig. 2. (a) Spontaneous emission (dashed line) and laser spectrum (solid line) for the DFB laser with pump energies blow and above threshold. (b) The zoomed in spectrum when the device was excited at 5.5 μJ-mm^{-2}.

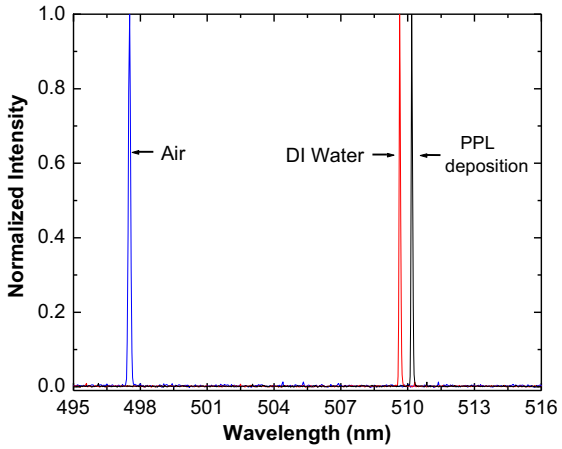


Fig. 3. Normalized laser emission spectra as sensor surface soaked in Air, DI water, and PPL solution, respectively.

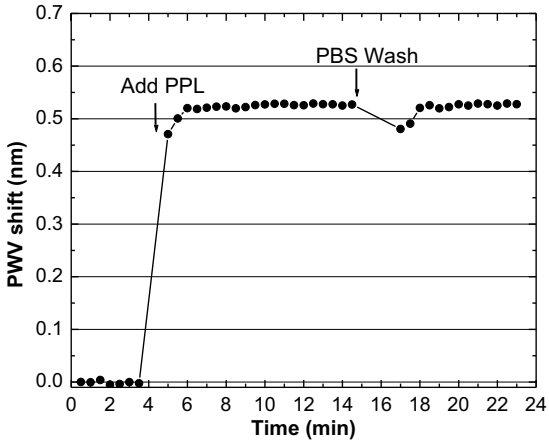


Fig. 4. The time dependent emission wavelength shift for polymer monolayer deposited onto DFB laser sensor. surface.

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