Evanescent-Field Intra-Cavity Sensing with a Dual-Wavelength Distributed-Feedback Laser

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Abstract: We demonstrate an integrated optical particle sensor based on a dual-wavelength distributed-feedback waveguide laser. Micro-particles were detected down to a size of 1 μm, which represents the typical size of many fungal and bacterial pathogens.

OCIS codes: (140.3490) Lasers, distributed-feedback; (140.3615) Lasers, ytterbium; (280.3420) Laser sensors

1. Introduction

There is an ever-increasing demand for sensors which are capable of detecting DNA, bacteria, as well as other micro- and nano-sized biological specimens. Monolithically integrated optical sensors are attractive for this application, because they are robust, highly sensitive, mechanically stable, can be combined with microfluidic channels, and provide the prospect of mass production [1].

In this paper we describe the realization of a dual-wavelength ytterbium-doped alumina (Al_2O_3:Yb^{3+}) distributed-feedback (DFB) channel waveguide laser and its application as a highly sensitive particle sensor, where it is shown to detect particles down to a size of 1 μm.

2. Device Fabrication

An Al_2O_3:Yb^{3+} waveguide layer with an Yb^{3+} concentration of 5.8×10^{20} cm^{-3} and a thickness of 1 μm was deposited onto a standard, thermally oxidized silicon wafer by means of reactive co-sputtering [2]. 2.5 μm wide channel waveguides were defined by means of standard lithography and etched with a chlorine-based reactive ion etching process [3], after which a silicon dioxide cladding layer was deposited on top of the waveguides. A Bragg grating structure with a length of 1 cm was defined on the top surface of the cladding layer by means of laser interference lithography. The grating structure was etched into the cladding with a CHF_3:O_2 reactive ion plasma.

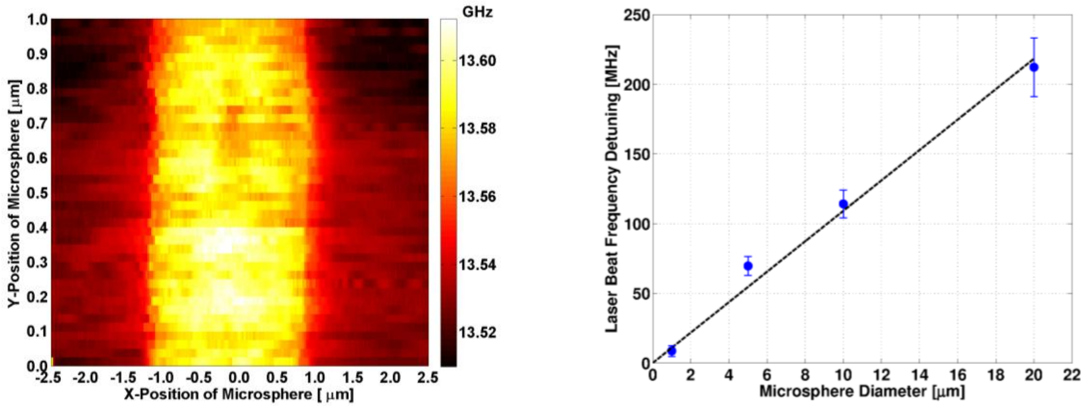
Two quarter-wavelength phase-shifts were introduced to the waveguide Bragg grating by locally widening the width of the waveguide in two separate 2 mm long regions [4], thereby inducing two ultra-narrow resonant wavelengths in the broad reflection band of the uniform grating [5]. These two resonances share a common cavity consisting of both phase-shift regions, and the wavelength spacing between these resonances depends on the spatial separation of the phase-shifts.

3. Sensing Principle and Characterization

The interaction between the intra-cavity evanescent field of the laser mode and a micro-particle on the top surface of the cladding creates a scattering-induced intra-cavity loss. Such a scattering event leads to a reduction in the intra-cavity laser power and, consequently, a decrease in the temperature of the waveguide. The sensing principle of this dual-wavelength laser is based on the fact that such a scattering event induces a change in the laser-induced thermal chirp of the Bragg grating, which in turn affects the wavelength spacing between the two laser wavelengths.

A (980/1030) ± 10 nm wavelength-division-multiplexing (WDM) fiber was butt-coupled to the optical chip and fixed into position with UV-curable glue. The continuous-wave 976 nm diode pump light was launched into the waveguide via the 980 nm port of the WDM fiber, while the 1020 nm laser emission was collected through the 1030 nm port, which also contained an isolator to prevent optical back-reflections into the laser cavity. A microwave beat signal of ~13.5 GHz was observed by measuring the laser emission with a 40 GHz photodetector which was connected to an electrical spectrum analyzer. The beat-signal frequency produced by the laser implies a wavelength separation of 47 pm between the two individual longitudinal laser modes.

In order to demonstrate the sensing principle we have probed the intra-cavity evanescent laser field with various borosilicate glass microspheres of diameters ranging between 1 μm and 20 μm. Each microsphere was attached to a low-stiffness (spring constant 0.01-0.02 N/m) atomic force microscope cantilever. The cantilever was mounted on a 3-dimensional computer-controlled translation stage.



(a) (b)

Fig. 1. (a) Center frequency of the microwave beat signal as a function of the 2-dimensional position of a 5-μm-diameter microsphere as it is scanned across the surface of the laser. This particular scan was performed in the center of the phase-shift region nearer to the unpumped side of the laser cavity. (b) Laser microwave beat frequency detuning as a function of the diameter of the microspheres. The black line represents a linear fit through the origin with a slope of 11 MHz/μm.

This experimental setup allowed us to scan a microsphere in contact mode across the top surface of the waveguide laser with a lateral resolution of 25 nm, while recording the center frequency of the microwave beat signal for each position of the microsphere. Figure 1a shows the center frequency of the microwave beat signal as a function of the 2-dimensional position of a 5-μm-diameter microsphere as it was scanned across the top surface of the laser. This particular scan was performed in the center of the phase-shift region which is nearer to the unpumped side of the laser cavity. The 5-μm microsphere induces a maximum shift of ~70 MHz in the free-running microwave beat signal when being scanned across the waveguide. This measurement was repeated for various other sizes of microspheres and the result is shown in Fig. 1b. The largest microsphere with a diameter of 20 μm induced a 212 MHz increase in the microwave beat signal, while the smallest microsphere, with a diameter of 1 μm, induced an increase of 9 MHz in the microwave beat signal. If we assume that the laser-generated beat frequency has a linear dependence on the size of the microspheres, as shown in Fig. 1b., then the resolution of the sensor is currently limited to particles of ~500 nm diameter. This size limitation is due to the frequency stability of the laser of ~5 MHz, which is most likely due to fluctuations in the pump power as well as some optical back-reflections into the laser cavity. By using a more stable pump laser and further isolating the back-reflected laser power, we believe that this device has the potential to detect particles with a diameter of ~50 nm.

4. Summary

We have demonstrated an integrated optical particle sensor based on a dual-wavelength distributed-feedback waveguide laser. Borosilicate glass microspheres were detected down to a size of 1 μm. This result holds great potential for the detection of single fungal and bacterial pathogens and potentially even single molecules.

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5. References

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