Intra-laser-cavity Sensing with a Dual-wavelength Distributed-feedback Laser

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Abstract: An integrated intra-laser-cavity microparticle sensor based on a dual-wavelength distributed-feedback channel waveguide laser in $Al_2O_3:Yb^{3+}$ on silicon is demonstrated. Real-time detection and accurate size measurement of single micro-particles with diameters of 1−20 μm are achieved. A limit of detection of ~500 nm is deduced. The sensing principle relies on measuring changes in the frequency difference between the two longitudinal laser modes as the evanescent field of the dual-wavelength laser interacts with micro-sized particles on the waveguide surface.

Introduction: Lasers find numerous applications in spectroscopy, optical communications, and optical sensing. These applications place stringent requirements with respect to efficiency, output power, spectral characteristics, compactness, robustness, and thermal stability on the laser. Waveguide lasers allow one to realize compact, rigid, and robust optical devices, since the entire laser cavity can be fabricated on the same substrate. In this work, surface-corrugated Bragg gratings are integrated with $Al_2O_3:Yb^{3+}$ channel waveguides to realize a monolithic distributed-feedback (DFB), dual-wavelength laser and demonstrate intra-laser-cavity micro-particle sensing.

Sample fabrication: 1-μm-thick $Al_2O_3:Yb^{3+}$ layers with a doping concentration of 5.8×10^{20} cm^{-3} were deposited onto standard thermally oxidized silicon wafers.[1] 10-mm-long, 2.5-3.0-μm-wide ridge channel waveguides supporting single-transverse-mode operation at the pump and laser wavelengths were etched to a depth of ~0.1 μm via a chlorine reactive ion etching process.[2] A SiO_2 cladding layer was deposited on top of the ridge waveguides by plasma enhanced chemical vapor deposition. Surface-relief Bragg gratings were fabricated on the top surface of the SiO_2 cladding by means of laser interference lithography. A grating pattern was defined in a 120-nm-thick negative resist layer on top and etched into the SiO_2 cladding using a $CHF_3:O_2$ reactive ion plasma.[3] The grating period is 316 nm, resulting in a Bragg wavelength of ~1020 nm. The waveguide propagation losses, including grating-induced scattering losses, are as low as 0.14 dB/cm. With a grating coupling coefficient of κ = 6.5 cm^{-1}, the 1-cm-long Bragg gratings possess reflectivities higher than 99% for TE polarization.[4] A quarter-wavelength phase shift was induced by adiabatic widening of the waveguide, resulting in a resonance with a passive *Q*-factor up to 1.35×10^6.

Distributed-feedback lasers: The single-longitudinal-mode $Al_2O_3:Yb^{3+}$ DFB laser,[5] which is diode-pumped at 976 nm, has a threshold of 5 mW. The laser operates at a wavelength of 1022.2 nm, where the maximum measured laser output power exceeds 55 mW at a launched pump power of 91.5 mW, resulting in a slope efficiency of 67%. Based on two 2-mm-long quarter-wavelength phase shifts centered at 3.5 mm and 5.5 mm (as measured from the end-facet from where the light is launched) in a DFB cavity, a dual-wavelength $Al_2O_3:Yb^{3+}$ DFB laser is demonstrated. A stable electrical beat signal is created at the output of a photodetector, with the frequency of the beat signal corresponding to the wavelength spacing of the two optical waves.[6] The two resonances share a common cavity which consists of both phase-shift regions, and the wavelength spacing between these resonances depends on the spatial separation and values of the respective phase shifts. The laser output was measured with a photodetector and an electrical spectrum analyzer, which confirmed a microwave beat signal at 15.0426 GHz. The long-term frequency stability of the microwave beat signal was measured over a period of 45 min. with a 100 ms interval. The standard deviation of the microwave frequency during this period was found to be ±2.5 MHz.

Intra-laser-cavity sensing: An integrated intra-laser-cavity microparticle sensor based on this dual-wavelength DFB channel waveguide laser in $Al_2O_3:Yb^{3+}$ is demonstrated.[7] Real-time detection and accurate size measurement of single micro-particles with diameters ranging between 1 µm and 20 µm are achieved, which represent the typical sizes of many fungal and bacterial pathogens as well as a large variety of human cells. The sensing principle relies on measuring changes in the frequency difference between the two longitudinal laser modes as the evanescent field of the dual-wavelength laser interacts with micro-sized particles on the surface of the waveguide.

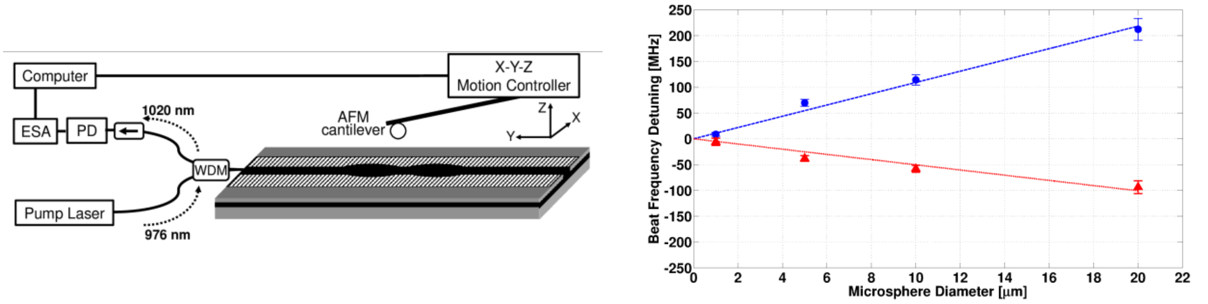

Fig. 1: (left) Experimental setup used to characterize the intra-laser-cavity micro-particle dual-wavelength laser sensor. ESA: Electronic spectrum analyzer;PD: Photodetector; WDM: Wavelength division multiplexing fiber; AFM: Atomic force microscope. (right) Laser microwave beat frequency detuning as a function of microsphere diameter. The red triangles were measured in the center of the phase shift on the pumped side, while the blue circles were measured in the center of the phase shift on the unpumped side of the laser cavity.

We demonstrate optical sensing by systematically probing the intra-cavity evanescent laser fields with various borosilicate glass microspheres of diameters ranging between 1 µm and 20 µm, attached to an atomic-force-microscope cantilever mounted on a 3-dimensional computer-controlled translation stage as shown in Fig. 1 (left). Each microsphere was scanned across the waveguide laser in the center region of each of the two phase shifts with a lateral resolution of 25 nm, while the frequency detuning of the microwave beat signal was observed, see Fig. 1 (right). Inside the first phase-shift region, the largest investigated microsphere with a diameter of 20 µm induced a 94 MHz decrease in the microwave beat signal, while the smallest microsphere, with a diameter of 1 µm, induced a frequency decrease of 6 MHz. In the second phase-shift region, the largest and smallest microspheres induced an increase in the microwave beat signal of 212 MHz and 9 MHz, respectively. Assuming that the frequency detuning of the laser-generated beat signal has a linear dependence on microsphere size, the resolution of the sensor is currently limited to particles of ~500 nm diameter. This size limitation is due to the free-running 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.[6]

Conclusions: We have demonstrated DFB channel waveguide lasers in $Al_2O_3:Yb^{3+}$ on silicon substrates with an output power of 55 mW and a slope efficiency of 67%. A dual-phase-shift DFB laser with dual-wavelength emission was operated and a stable microwave beat signal at ~15 GHz was created via heterodyne photo-detection. By measuring changes in the microwave signal, we could detect single micro-particles with diameters between 1 µm and 20 µm on the waveguide surface.

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