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Optical Sensing with Picometer-level Precision using an Integrated Multispectral Chip

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Summary (max 6 lines of text, no symbols):

Optical sensors enable remote measurement at high-precision, but the need for expensive readout equipment, such as a spectrometer, hampers their practical application. To overcome this limitation, we propose multispectral readout as an alternative approach for sensor readout, using a small number of photodetectors in an integrated chip. We demonstrate this concept using a multispectral chip with four photodetectors, reaching a wavelength imprecision of 5 pm for refractive index sensing and biosensing.

Keywords: optical sensors, readout, resonance wavelength, integrated chip, photodetectors, high-resolution, picometer, refractive index, bio sensor

Introduction

Optical sensors enable measurement of many different physical parameters with high precision, are immune to electromagnetic interference and allow remote sensing via optical fibers. Encoding the measurand in the optical spectrum, such as the wavelength of a resonance peak or dip, is widely used as it is most tolerant to external disturbances. Mostly, expensive readout equipment with high spectral resolution is used, such as a spectrometer or a laser-based interrogation system. However, in terms of cost and robustness, this readout equipment is not suited for most practical applications, e.g. in industry or healthcare.

From a fundamental point of view, high spectral resolution is not required to detect small spectral changes, e.g. a shift in the resonance wavelength. We suggest multispectral readout as an alternative approach using a limited number of photodetectors with low spectral resolution. Measuring the photocurrent of these photodetectors with high signal-to-noise ratio enables an accurate determination of the resonance wavelength. Based on information theory [1], it can be shown that the lowest imprecision can be reached if sensor and photodetectors have approximately the same linewidth.

Here, we present an integrated readout chip with an array of four photodetectors with a total area of 1.6 x 1.6 mm^2, which can be mass-produced at low cost. We show that the wavelength imprecision in the measurement of spectral features exceeds the performance of a spectrometer at equal integration time. We demonstrate this readout approach for two sensing applications: Refractive-index sensing on the fiber tip and biosensing.

Integrated multispectral chip

The multispectral chip consists of four resonant-cavity-enhanced photodetectors [2], fabricated using InP-membrane-on-silicone (IMOS) technology. [3] The absorbing layer is embedded in a planar microcavity, leading to enhanced absorption at specific wavelengths. [2] The four photodetectors achieve peak responsivities of 0.78-0.9 A/W at different wavelengths (see Fig. 1), as the optical path length between the mirrors is varied by a tuning layer. [3]

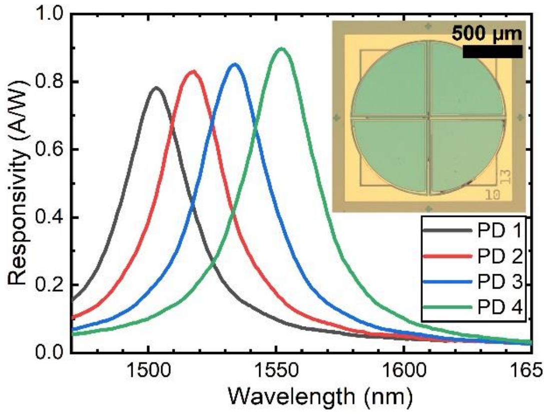

Fig. 1. Responsivity of the photodetectors (PD) in the multispectral chip (photo).

Refractive index sensing

The refractive index (RI) sensor consists of a 2D photonic crystal (PhC) (hexagonal lattice of holes in an InP slab) transferred to the cleaved facet of a multi-mode optical fiber with 105 µm core, using a mechanical transfer method developed within our group [4]. The PhC supports a resonance at 1519 nm, which leads to a peak with FWHM = 18.4 nm in the reflection spectrum. When the RI of the surrounding medium is varied by immersing the sensor in isopropanol-water mixtures with different concentrations, the resonance peak shifts (see Fig. 2) and the detected photocurrents change. Using a calibration set, for which the resonance wavelength is known, a prediction model is built to determine the wavelength directly from the measured photocurrents. Using this prediction model, we can experimentally demonstrate a wavelength imprecision of 5 pm, which exceeds the performance of the spectrometer (see Fig. 2). For this RI sensor, this wavelength imprecision corresponds to 3.7 x 10^{-5} RIU.

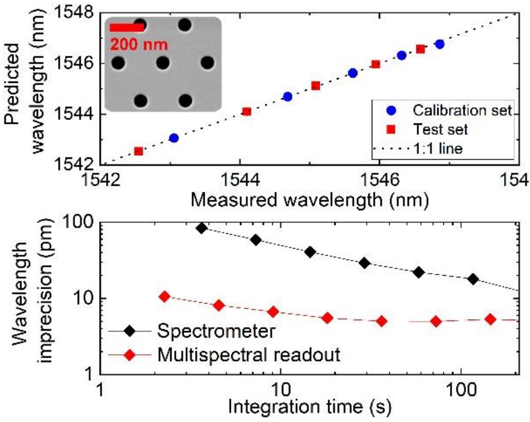

Fig. 2. RI sensing with multispectral readout. Top: accurate wavelength determination, Bottom: imprecision exceeds conventional spectrometer.

Biosensing

For biosensing, the surface of a 2D PhC (hexagonal lattice of holes in SiN layer on glass substrate) is functionalized with Immunoglobulin G (IgG, common biomarker) as receptor molecules by physisorption. This molecule specifically binds its natural antibody (anti-IgG), which leads to a local refractive index change and therefore a shift in the PhC resonant modes. From the corresponding photocurrent changes, the wavelength of the dominant resonance peak can directly be determined. To build a calibration data set, the biosensor is first exposed to isopropanol-water mixtures of various concentrations (see Fig. 3). The experimental data shows a clear correspondence of spectrometer data and the multispectral readout prediction. Additional experiments show that we can specifically detect anti-IgG molecules with in this way. When integrating over a few seconds, an imprecision of about 5 pm can also be reached for the readout of the biosensor. Assuming linearity between the biomarker concentration (anti-IgG, c=100 nM) and the total wavelength shift ($\Delta\lambda$=0.5 nm), this wavelength imprecision σ_λ corresponds to a limit of detection

$$LoD = 3\sigma_\lambda \, c \,/\, \Delta\lambda = 3 \text{ nM}$$

for this antibody-antigen pair.

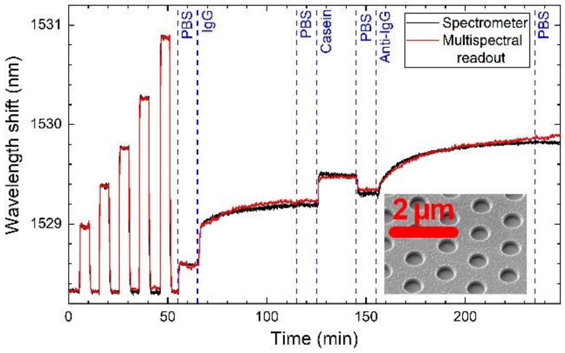

Fig. 3. Biosensing with multispectral readout: clear correspondence with spectrometer data.

Conclusion and Outlook

Resonance-based optical sensors enable the measurement of a large range of physical parameters with high sensitivity and under remote conditions. As an alternative to bulky, expensive and fragile readout equipment such as spectrometers, we propose multispectral readout, which is based on a limited number of photodetectors with low spectral resolution. We experimentally demonstrate this approach and show the detection of wavelength shifts down to 5 pm, exceeding the performance of a high-resolution spectrometer. As application cases, we present the readout of a fiber-tip refractive index sensor and a biosensor. This approach can pave the way for a broader application of optical sensors in industrial and health-care contexts without the need for expensive readout equipment.

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