Integrated Optical Sensors

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Abstract: We review important progress made in the field of integrated optical sensors in 2011. This paper focuses on key aspects of integrated sensors, including new detection mechanism developments, integration progress, and efforts toward resolving the challenges associated with surface functionalization and analyte transport.

Index Terms: Sensors, resonators, surface plasmon resonance (SPR), fluorescence, infrared spectroscopy, photonic integration.

1. Introduction

We report on the progress made in 2011 on advancing the broad field of integrated optical sensing systems. We review integrated optical sensors for detection of chemical and biological species, including a) biological macromolecules (proteins, nucleic acids, other macromolecules); b) small molecules (chemicals); and c) nanoparticles and virus particles. This paper will focus on progress in the areas of new detection mechanisms and integration schemes as well as key developments that address outstanding challenges relating to sensor surface functionalization and analyte transport. Fiber-optic sensors and sensors monitoring other physical parameters are outside the scope of this review.

2. New Detection Mechanisms

The major sensing mechanisms utilized in integrated optical sensors can be categorized under a) refractive index (RI) sensing; b) absorption sensing; and c) fluorescence sensing. Of these, the most common mechanism is RI sensing.

Index sensing typically involves detection of wavelength shift due to molecular binding which results in a change in RI. Two common types of RI sensors are surface plasmon resonance (SPR) sensors and dielectric optical resonator sensors. SPR sensors feature much higher RI sensitivity compared to resonator sensors. Yu *et al.* report that SPR sensors achieve extraordinary spectral sensitivity due to multiple optical modes involved in the detection process [1]. Unlike optical resonance peaks, these dips in transmission indicate the phase matching wavelength where the SPR mode and the excitation light beam have identical in-plane wave vectors. Index perturbation changes this phase matching condition and leads to large SPR wavelength shift. Based on this theoretical insight, the authors further show that similar extraordinary RI sensitivity can be attained in an all-dielectric system as well, with the added benefits of reduced loss and higher quality factors.

Improved cavity designs such as notched microrings [2], ultra-high-Q microtoroids [3], and active microcavities [4] have been employed to boost the detection sensitivity of optical resonator index sensors. Novel photonic–plasmonic hybrid structures combining photonic resonance enhancement and plasmonic field concentration have also been demonstrated to significantly improve the detection sensitivity [5], [6]. Multiple ring resonators can be utilized to either leverage the Vernier effect to enable interrogation using broadband sources [7], or to improve multiplexing capabilities [8]. However, fabrication of multiple ring resonators, particularly coupled rings, can be challenging. Zhu *et al.* pioneer a new optothermal wavelength sweeping technique to improve the wavelength stability of resonator index sensors [9].

While index sensing relies exclusively on surface coatings for specific molecular recognition, absorption sensing offers inherent molecular discrimination capability by simultaneous detection of a multitude of characteristic infrared absorption lines, and is well suited for gas sensing given the sharp spectral features of gas molecules. Conventional absorption sensing resorts to benchtop instruments such as Fourier Transform InfraRed (FTIR) spectrometers. An ultra-compact chipscale spectrometer was demonstrated by Chao *et al.* which utilizes electro-optic liquid crystals to perform FTIR spectroscopy [10]. One standing challenge for on-chip absorption sensing is the limited optical path length accessible in a chipscale device; to resolve this challenge, microring resonators [11] and nanoslotted slow light photonic crystal slab waveguides [12] were employed to increase the effective path length without compromising the device footprint. Along this line, Hu *et al.* propose a photothermal detection technique where thermal confinement and double optical resonances at both pump and probe wavelengths dramatically improve the gas detection limit of on-chip devices to the sub-ppb level [13].

3. Integration

Integration of a light source and detector onto the same chip platform with the sensing element to complete the standalone "sensor-on-a-chip" platform has been a field of intensive investigation. Index sensors for protein detection usually operate in a disposable mode given the irreversible binding characteristics and short lifetime of antibody-based surface functionalization coatings, and therefore it is not practical to integrate expensive light sources and detectors with these devices.

Integration schemes involving organic components have attracted considerable interest due to their low cost and the progress made in the areas of organic light emitting diodes (OLEDs) and organic photodetectors (OPDs). One such integrated sensor platform utilizing ring-shaped OPDs is able to realize gas sensing via three different methods (fluorescence, absorption, SPR) on the same platform [14]. Vannahme *et al.* propose an integrated plastic "lab-on-a-chip" sensor relying on excitation of fluorescent markers [15]. The system employs an organic semiconductor laser, deep ultraviolet induced waveguides, and a nanostructured microfluidic channel integrated into a poly(methyl methacrylate) (PMMA) substrate and demonstrates successful detection of carboxylate-modified fluorescent microspheres and fluorescent dye-labeled antibodies. Optical biosensors comprised of a polymer-based light emitting diode (LED) acting as a light source coupled into a single mode Ta_2O_5 waveguide and a polymer photodiode array as a minispectrometer have also been demonstrated [16].

Simple, low-cost flow-through chemical sensors utilizing a chemoreceptive film as the sensing element and two LEDs—one as a light source, one as a detector—in a paired-emitter-detector-diode (PEDD) can be used for easy measurements with an ordinary voltmeter [17]. Alternatively, visible wavelength Vertical Cavity Surface-Emitting Lasers (VCSELs) have been integrated with low dark current GaAs PIN photodiodes for parallel fluorescence and RI sensing [18]. Fluorescence sensing is accomplished by a fluorescence emission filter sensitive to visible-near-IR fluorescent proteins and a nanoimprinted 2-D photonic crystal allows for RI sensing, both on the same platform.

Due to the wide use of plasmonic designs in planar sensing systems, significant efforts have been made to integrate them with appropriate sources and detectors. Designs incorporating plasmonic sensors have been integrated with MOS photodetectors on a silicon platform [19] and the plasmon resonance has also been grating-coupled with a planar photodiode [20].

Chalcogenide glasses are being widely investigated for infrared (IR) photonics applications due to their superior IR transparency [21] and work is being done on integration of lead telluride (PbTe)-based detectors with mid-IR transparent chalcogenide microdisk resonator sensors [22].

Silicon-on-insulator (SOI) microring resonator-based vapor sensors have been integrated with a 200 GHz arrayed waveguide grating (AWG) spectrometer [23] that monitors ethanol vapor concentrations by measuring intensity ratios between adjacent AWG channels.

Integrated sensors have also been demonstrated for gene expression studies with quantum dots serving as fluorescence labels on an active CMOS microarray with a sensitivity of 100 pM [24]. This approach is expected to yield even higher sensitivities with improved surface modification of the CMOS microarrays.

4. Surface Functionalization

Surface functionalization of sensors involves the application of chemical or biological agents to the surface to introduce specificity allowing only the intended target species to bind to the sensor surface. Due to the small size of planar optical sensors and the use of multiplexed arrays of resonators, this low-cost, high-throughput surface functionalization often proves to be a challenging task. Kirk *et al.* propose a functionalization process that utilizes noncontact inkjet (piezoelectric) printing to directly print the functionalizing agents on to multiplexed arrays of silicon ring resonators [25]. This method enables a high degree of scalability and parallel detection of multiple species on the same sensing platform.

If sensors are to be reused rather than discarded after one use, it is essential to have a means for the removal of attached species from sensors without damaging the surface. In an attempt to recycle sensor devices, oxygen plasma treatments have been applied to refresh the surface of silica resonator biosensors after binding events [26].

5. Analyte Transport

Analyte transport involves the movement of analyte species under investigation to the optical sensing element. While microfluidic channels are in wide use, analyte transport remains a key challenge in the realization of low concentration detection of target species. Guo *et al.* demonstrate that flow-through micro/nanofluidic channels can be placed between two reflectors to form a simple and low-cost but robust Fabry–Pérot cavity-based 3-D sensing device [27].

De Angelis *et al.* tackle analyte transport by exploiting the phenomenon of superhydrophobicity where a drop placed on a surface adopts a quasi-spherical shape with a large contact angle $(> 150^\circ)$ instead of spreading or wetting the contact surface [28]. Evaporation of the drop can increase the concentration of the target species while maintaining the quasi-spherical shape until the drop collapses on top of the sensing surface. This approach is used in conjunction with nanoplasmonic sensors to localize and detect molecules of the target species in highly diluted solutions.

High-quality factor microring resonators have also been explored as a means to trap nanoparticles and perform sensing operations simultaneously [29]. By employing multiple ring resonators, it is possible to transport the trapped particles from one ring to another and perform velocity and particle counting measurements [30]. Analyte localization opens up the possibility of all-optical control of small particles and biological species (cells and virus particles) on an integrated platform.

6. Summary

This review summarizes new developments in detection mechanisms, integration schemes, surface functionalization methods, and analyte transport for integrated optical sensors. We envision monolithically integrated sensor systems that will be field-deployable and perform label-free, multimodal detection with high sensitivity and specificity.

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