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Overview of the optofluidic ring resonator: a versatile platform for label-free biological and chemical sensing

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Abstract— **Highly sensitive detection of biological and chemical analytes has significant importance within medical science, environmental monitoring, food quality, national security and defense. The opto-fluidic ring resonator (OFRR) is a relatively new solution for label-free optical sensing that is compatible with a versatile range of analytes. A capillary-based platform, the OFRR supports whispering gallery modes within its circular cross-section and conducts evanescent sensing within its hollow core. Herein, we provide an overview of the basic operation principles of the OFRR and some examples of its most important applications, including the detection of proteins, virus, DNA molecules, whole cells, vapors and pesticides.**

I. INTRODUCTION

THE opto-fluidic ring resonator (OFRR) is a unique and versatile tool for biological and chemical detection [1], which is a relatively new idea within the decades-old field of optical ring resonators. The OFRR is a glass capillary-based optical cavity. Like other optical cavities, including microspheres [2-4], microtoroids [5, 6], and planar waveguide rings [7, 8], the OFRR supports shape-dependent resonant frequencies or whispering gallery modes (WGMs) (see schematic in Fig. 1(a)). Ring resonators, which utilize evanescent fields generated by WGMs for sensing, have an advantage over traditional waveguide-based evanescent sensors. The circular confinement of light created by WGMs allows a great miniaturization of the sensors while maintaining large effective interaction lengths.

In addition to providing these advantages, the OFRR has several important characteristics that make it extremely competitive amongst other ring-resonator technologies [9]. These include high Q-factors (up to 10^7) [10], low refractive index (RI) resolutions (10^{-7} refractive index units, or RIU) [11], high RI sensitivity (up to 51.9 nm/RIU) [12], low sample volume consumption, small device footprint, and fast assay completion times. Additionally, the capillary nature of the OFRR avoids the problems typically associated with integration of optical and fluidic components.

II. PRINCIPLE OF OPERATION

The construction of the device starts with a capillary perform which is pulled under intense heat until it has an outer diameter around 100 μm and wall thickness of less than 5 μm. This process has been extensively described in the literature [1, 13]. When the wall becomes this thin, the evanescent field from the WGMs is exposed to the hollow core. At this point, the WGM becomes sensitive to the RI in the hollow core in a manner expressed by the following formula [2]:

$$\lambda = \frac{2\pi r n_{eff}}{m}, \tag{1}$$

where r is outer radius of the ring, n_{eff} is the effective RI experienced by the WGM, λ is the spectral position of the WGM, and m is an integer that describes the WGM angular momentum. Eq. 1 demonstrates the direct dependence of WGM spectral position, λ, on the effective RI experienced by the WGM, n_{eff}.

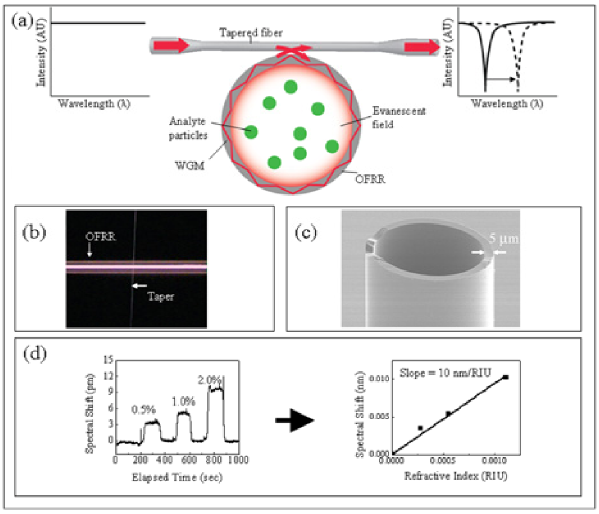

Fig. 1. Schematic of OFRR cross-section showing how optical input couples into WGMs (a). Photograph of a taper coupled to an OFRR 115 μm in diameter (reprinted with permission from [14]) (b), and an SEM of an OFRR cross-section (reprinted with permission from [15]) (c). Raw refractometric sensing data for ethanol in water (percent by volume listed) and the resulting RI sensitivity curve (d).

Fig. 1(a) shows how this WGM can be traced over time when monitored in transmission mode through an optical fiber coupler. The specific spectral position of the OFRR's WGMs provides a quantitative signal which may be leveraged for refractometric or absorption-based sensing applications. Typically, the optical input is from a tunable laser, and the transmission is monitored at the fiber output in real time. In transmission mode, the WGMs appear as dips

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in the transmission spectrum due to coupling loss. The evanescent field extends approximately 100 nm into the fluid core. Fig. 1(b) shows a picture taken of an OFRR positioned with its optical fiber. Fig. 1(c) shows an SEM image of a cross-section of an OFRR with a 5 µm wall. Fig. 1(d) shows how bulk refractometric sensing can be used to estimate the bulk RI sensitivity, or BRIS. The BRIS shown in Fig. 1(d) is 10 nm/RIU, although values up to 51.9 nm/RIU have been observed by etching the capillary wall with HF until it is very small [12].

III. SENSING APPLICATIONS

To date, OFRR sensors have been utilized for the detection of both chemical and biological reagents. These may be grouped into categories of aqueous chemical sensing [14, 16], vapor chemical sensing [17-20], and aqueous biomolecule sensing [1, 10, 12, 13, 21-26]. Many of these projects, with their published LODs, are listed in Table 1.

TABLE I
DETECTION LIMITS FOR BIOLOGICAL AND CHEMICAL ANALYTES

Analyte	Limit of Detection	Reference
Bulk solution RI	10^{-7} RIU	[11]
DNA	10 pM	[23]
Methylated DNA	5 nM	[12]
Virus particles	1000 particles/mL	[22]
Protein (BSA)	1 pg/mm^2, 3 pM	[13]
Pesticide	0.038 nM	[15]
DNT vapor	200 pg	[17]
Ethanol vapor	200 ppm, 1 ng	[18]
CD4+ lymphocytes	200 cells/µL	[26]

Aqueous chemical and biological sensing operate in very similar manners. In order to assure specificity, affinity chemistries are used to target the chemical or biological species of interest. In the case of many biological analytes, including whole cell [27] and virus [23] detection, this may be accomplished by immobilizing select antibodies to the interior surface of the OFRR via covalent surface chemistries. DNA detection can be accomplished by hybridizing target strands to immobilized complementary probes [24]. In another demonstration, it was demonstrated that capillary electrophoresis could also be used in the OFRR to separate and assay analytes in solution [14].

Vapor sensing requires a much different approach, involving the use of polymer coatings which have unique and recognizable reactions to gas absorption [17, 18]. Alternatively, polymer layers can be used to separate mixed gas species, providing a micro gas chromatography function [20].

In characterizing the performance of the OFRR for these various applications, the limit of detection (LOD) is a good way to assess the sensor's ability to detect a given target. Table 1 shows the LOD values for a number of important analytes. These LOD values demonstrate the ability of the OFRR to detect very small concentrations of a wide variety of different analytes. It can be observed that the LODs are typically recorded in three types of formats: surface concentration (number of analyte molecules or particles per unit area), bulk concentration (molarity or ppm), and absolute detectable mass. It is typically very easy to estimate bulk analyte concentrations, however surface densities must be derived from their known excess polarizabilities. The theoretical models for surface densities are geometry dependent, and are available in the literature [13, 28].

IV. CONCLUSION

The OFRR technology platform is an emerging technology within the category of label-free ring resonator sensors. In the preceding text, we have covered the principle of operation of the device as well as its most important applications. Interest in label-free optical sensing systems has grown consistently in recent years, driving creative innovations in opto-fluidics and giving the OFRR a special niche. Given the tremendous potential for applying the OFRR to integrated lab-on-a-chip systems and the large body of work demonstrating its versatility, we expect it to lead to commercially available devices.

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