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Review

Recent development of fiber-optic chemical sensors and biosensors: Mechanisms, materials, micro/nano-fabrications and applications

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ABSTRACT

The Internet-of-Things (IoT) has witnessed exponential growth over the past decade and will significantly reshape human life from every aspect, e.g., defense, environmental monitoring, energy, food safety, knowledge dissemination, healthcare and so on. Fiber-optic sensors, with both communication and sensing functions, have become a bridge to connect people and the whole world, so they are essential parts for accelerating the development of the IoT. Fiber-optic sensors possess the capability of translating a change of target analyte into optical signals and subsequently transmit an optical signal with target analyte information to people, machines or systems in real-time, even from a long distance. Therefore, exploration of high-performance fiber-optic chemical sensors and biosensors could significantly promote the development of the IoT. This review paper presents the foundations of fiber-optic chemical sensing or biosensing, including the sensing mechanisms of various fiber-optic sensors, sensing materials and the novel techniques for sensing materials deposition. Furthermore, recent developments on fiber-optic chemical sensors and biosensors are summarized, analyzed and discussed. Finally, the strategies and guidelines to further promote the development of fiber-optic sensors are also discussed.

Contents

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1. Introduction

Optical sensors have been recognized as a fancy and high-performance approach for the detection of various analytes [1,2]. The optical sensing mechanisms include fluorescence, absorption, colorimetry, Raman, refractive index (RI), surface plasmon resonance (SPR) and luminescence etc. For example, the colorimetric method could be utilized to detect cesium ions in domestic water using an optode membrane [3]. Due to the great progress of functional materials and manufacturing techniques, optical sensors have experienced high-speed developments. Recently, many excellent review papers have summarized and commented on the progress of optical sensors from different viewpoints [4–8]. Mahata et al. summarized the utilization of rare-earth-based MOFs as luminescent sensors to detect nitro explosives, cations, anions, small molecules, pH and temperature [7]. Zhao and his coworkers gave a comprehensive review of the on-chip biochemical sensors based on optofluidic photonic crystal cavities, sensing principles and their applications were discussed in detail [8]. Yoon's group has made great contributions to fluorescence-based optical sensors and provided an insightful view on the development of fluorescent chemosensors [4–6]. For example, they analyzed and summarized organic-dye-based near-infrared fluorescence probes for metal ion detection [6], crown ethers contained fluorescence probes for sensing [4], as well as fluorescent and colorimetric probes for the detection of reactive oxygen and nitrogen species [9]. However, a comprehensive and updated review of fiber-optic chemical sensors and biosensors has not appeared yet.

Optical fibers, as transducers for light, have been explored for their potential in optical sensing devices in the last several decades and numerous achievements have been realized in fiber-optic chemical sensing and biosensing fields [2,10–19]. Due to the demand for small-size sensors for remote and real-time monitoring, optical fibers are becoming a versatile and excellent platform for the fabrication of chemical sensors and biosensors by virtue of their distinguished advantages of cost-effectiveness, small-size, flexibility, robustness, no electromagnetic interference, chemical inertness, lightweight, remote and multiplexed detection capability, etc. [20,21]. Up until now, fiber-optic sensors have been widely studied in the areas of environmental monitoring [22], explosive gas detection [23], disease identification and development of new medicines [22,24–27], just to name a few (See Fig. 1). Compared with other types of optical sensing techniques, fiber-optic sensors offer the versatilities of multiplex detection capability and remote monitoring in human-untouchable environments, which is particularly essential for explosive detection.

It is well-known that the propagation of light in an optical fiber is confined in the core of the fiber, based on the total internal reflection (TIR) principle and has near-zero propagation loss within the cladding, which is very important for optical communications, but limits its sensing applications due to the non-interaction of light with the surroundings [18,34]. Therefore, it is essential to exploit novel fiber-optic structures to disturb the light propagation, thereby enabling the interaction of the light with the surroundings and constructing fiber-optic sensors. Until now, several methods, including polishing [35,36], chemical etching [37], tapering [34,38], bending [39], as well as femtosecond grating inscription [25,40–43], have been proposed to tailor the light propagation and prompt the interaction of light with sensing materials. In the above-mentioned fiber-optic structures, the enhanced evanescent fields can be efficiently excited to induce the light to expose to and interact with the surrounding medium. However, the fibers themselves can only sense very few kinds of analytes with low-sensitivity and zero-selectivity [44], which greatly limits their development and applications, especially for biosensors that require both high-sensitivity and high-selectivity.

To overcome the issue, an efficient way is to resort to responsive materials, which possess the ability to change their properties, such as RI, absorption, conductivity, etc., once the surrounding environments change [2,44–53]. Due to the rapid progress of functional materials in recent years, various sensing materials are available for fiber-optic chemical sensors and biosensors fabrication, including graphene [36,54], metals and metal oxides [55–58], carbon nanotubes [59,60], nanowires [61,62], nanoparticles [63], polymers [20,28,29,64], quantum dots [65,66], etc. Generally, these materials reversibly change their shape/volume upon stimulation by the surrounding environments (the target analysts), which then leads to the variation of the RI or absorption of the sensing materials. Consequently, the surrounding changes will be recorded and interrogated by the optical fibers, realizing sensing functions of the optical fibers. However, a technological gap exists between the sensing materials and optical fibers, i.e., how to