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Miniature photonic crystal cavity sensor for simultaneous measurement of liquid concentration and temperature

Ya-nan Zhang[a], Yong Zhao[a,b,*], Hai-feng Hu[a]

[a] College of Information Science and Engineering, Northeastern University, Shenyang 110819, China
[b] State Key Laboratory of Synthetical Automation for Process Industries, Shenyang 110819, China

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ABSTRACT

A new method for simultaneous measurement of liquid concentration and temperature is proposed by using a miniature photonic crystal sensor, where two cascaded cavities (H0 cavity and H1 cavity) are separately located adjacent to one waveguide. The standard liquid whose concentration is fixed and known will be infiltrated in defected holes of the H1 cavity, and the measured liquid whose concentration is unknown will be infiltrated in defected holes of the H0 cavity. Both the two independent resonant dips of cascaded cavities that can be simultaneously monitored at output spectrum of the waveguide will shift with the variation of liquid concentration or ambient temperature. By using finite difference time domain (FDTD) simulation, resonant properties of the two cavities are respectively optimized, and then the linear relationships between shifts of two resonant dips and liquid concentration/temperature are calculated. Finally, according to dual-wavelength matrix method, liquid concentration measurement with a resolution of 9.4322 ppm and temperature measurement with a resolution of 0.0136 K are simultaneously realized, which can not only solve the cross-sensitivity problem between liquid concentration and temperature, but also provide a solution for two-parameter measurement in a miniaturized system.

1. Introduction

Liquid concentration, as a main physicochemical parameter of target liquid, has attracted considerable attention in the application fields of fundamental research, biochemical analysis, medical diagnosis, environmental assessment, chemical industry, and so on [1,2]. Naturally, many methods have been developed to measure this parameter [3–6]. Among them, refractive index (RI) sensor is the most popular apparatus due to that RI variation of liquid is directly related to concentration or existence of target liquid and the target liquid can be detected in its natural form without any modifications [6]. Particularly, optical RI sensor inherits the peculiar advantages of optical fiber sensing techniques, such as immunity to electromagnetic interference, safety in flammable explosive environment, rapid response speed, and the ability of remote on-line sensing [6–8]. However, now the commercially available optical RI sensors usually have a relatively large sensing probe, and thus greatly limit their applications in the case that only a limited amount of liquid sample can be supplied. Therefore, it is particular important to develop miniaturized optical RI sensor, which is beneficial in realizing portable, low cost, and low power detection of liquid concentration with rapid analysis time and reduced liquid consumption.

On the other hand, it has been demonstrated that photonic crystal (PC), which is formed by periodically arranging regularly shaped materials with different dielectric constants in a substrate, presents the capability of guiding and manipulating light at the scale of optical wavelength [9]. Besides, the periodic air hole of hole-typed PC is a natural candidate for housing target liquid, and the inner variations of holes will bring much more strong influences on propagating light. Particularly, PC cavity, which is formed by introducing some intentional point defects in the PC, exhibits strong field confinement in the defected region and has long photon lifetime (namely, high Q) [10]. These characteristics will further enhance the light-liquid interaction and give rise to an optical mode whose resonant wavelength is highly sensitive to local RI perturbations of defected holes. At present, PC cavity has been demonstrated as a promising building block for realizing miniature and high-sensitive optical RI sensor [11,12]. In addition, PC cavity with small sensing area (<10 μm^2) only requires about 1 fL target liquid [13]. Comparing with traditional optical RI sensor, the size of PC cavity

* Corresponding author at: College of Information Science and Engineering, Northeastern University, Shenyang 110819, China. Tel.: +86 13998812362.
E-mail address: zhaoyong@ise.neu.edu.cn (Y. Zhao).

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based RI sensor can be drastically reduced. Therefore, many optical RI sensors based on PC cavity have been proposed and utilized to monitor the concentration variations of NaCl solution [14], DNA biomolecule [15], Rat monoclonal Ab [16], Human Papillomavirus virus-like particles [17], avidin [18], and so on. However, all of these presented studies had not considered the influence of temperature fluctuation in practical measurements. Actually, as the RI of target liquid is also related to external temperature [19–22], the measurement accuracy of liquid concentration will be easily interrupted by temperature for individual RI sensor. Therefore, it is necessary to discriminate or compensate for the influence of temperature when the PC cavity based RI sensor is used for concentration measurement [21]. Furthermore, it is much more desirable to simultaneously measure liquid concentration and temperature in many applications [22–25]. Recently, we have demonstrated that a cascaded cavity slab can be used to simultaneously measure magnetic field and temperature with high sensitivity and small size [20], in which the two cavities were considered to be absolutely independent. Absolutely, this hypothesis is just an extreme scenario and will bring some slight measurement errors. Besides, the wavelength spacing between the two cascaded cavities is a bit narrow and the quality factors of two cavities are too low, which will limit the measurement range of sensor and even cause the crosstalk between two measured signals.

In this paper, a novel cascaded PC cavity sensor with wider wavelength spacing is proposed. Besides, this miniaturized and high-sensitive sensor can be well used for simultaneous measurement of liquid concentration and temperature. Taking NaCl-H_2O solution as an example, the measurement principle with considering the cross influences of two cavities is described, and the structural design of two PC cavities are explained. Finally, the sensing properties of the proposed cascaded PC cavity are analyzed.

2. System design and working principle

A schematic configuration of the proposed PC cavity sensor is shown in Fig. 1(a). Here, the light source is an amplified spontaneous emission (ASE) with central wavelength of 1550 nm, spectral width of 100 nm, and output power of 30 mW. After light beam went through the cascaded PC cavity, it will be transmitted into an optical spectrum analyzer (OSA) to monitor transmission spectrum of the PC cavity. Besides, all of these optical instruments are linked by single mode fiber (SMF). Fig. 1(b) presents the specific structure of PC cavity, where one H0 cavity (on the right) and one H1 cavity (on the left) are located adjacent to one waveguide to form a cascaded cavity on one PC slab. The standard liquid whose concentration is fixed and known will be infiltrated in some holes around H1 cavity, and the measured liquid whose concentration is needed to be measured will be infiltrated in some holes around H0 cavity. Thus, the transmission spectrum of the proposed cascaded PC cavity exhibits two dips at corresponding resonant wavelengths of two different cavities.

In this work, the basic measurement principle is that the RI n of liquid that infiltrated in the air holes of PC cavity is a function of its concentration C and ambient temperature T [22,25]. When C or T changes, the RI n will also change and can be expressed as [25]:

$$\Delta n = \frac{\partial n}{\partial C}\Delta C + \frac{\partial n}{\partial T}\Delta T = K_C \Delta C + K_T \Delta T \quad (1)$$

where $K_C = \partial n/\partial C$ and $K_T = \partial n/\partial T$ represent the RI sensitivities of liquid to the concentration and temperature, respectively. According to the past studies on the relation between the RI of liquid and its concentration, K_C is a fixed value for certain liquid under different temperatures, and so does K_T for certain liquid under different liquid concentrations. Namely, the values of K_C and K_T are only related to the type of liquid, and they are fixed once the type of liquid is definite.

For the standard liquid that infiltrated in the H1 cavity, its RI variation Δn_1 is only related to the disturbance of ambient temperature ΔT. While for the measured liquid that infiltrated in the H0 cavity, its RI variation Δn_0 is related to both the concentration change of measured liquid ΔC and the disturbance of ambient

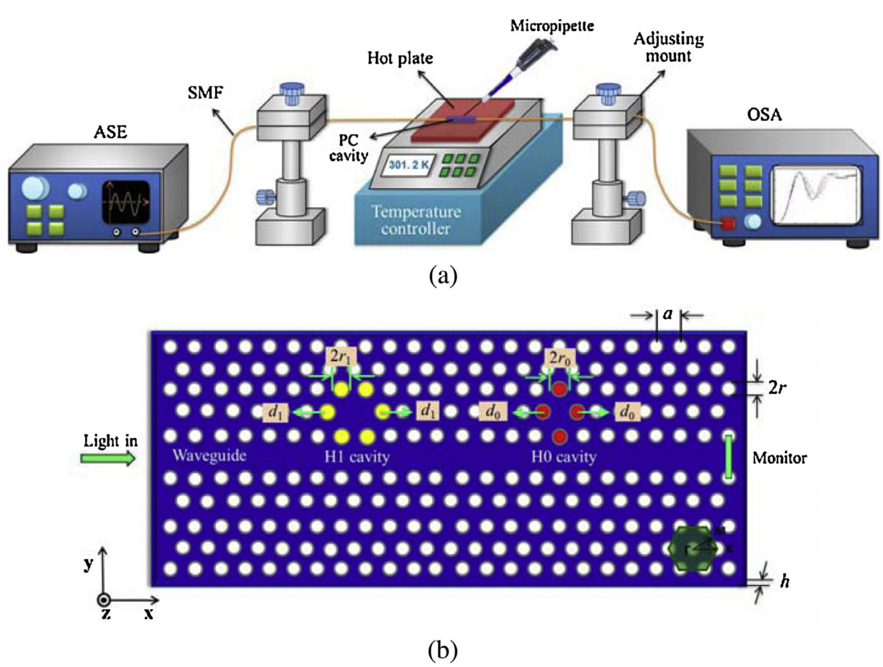

Fig. 1. (a) Schematic structure of liquid concentration/temperature sensor based on PC cavity; (b) specific structure of PC slab, where one H0 cavity and one H1 cavity are cascaded together.