Optical Fiber Technology 45 (2018) 244–249

Contents lists available at ScienceDirect

Optical Fiber Technology

journal homepage: www.elsevier.com/locate/yofte

Investigation of fused tapering with inner pressurized air for microcapillary-based optical sensor

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ARTICLE INFO

Keywords:
Fiber optical sensor
Capillary
Tapering
Whispering gallery mode
Refractive index sensing

ABSTRACT

To fabricate thin-wall and large radius microcapillary-based optical sensor with high sensitivity and Q factor, a fused tapering process with inner pressurized air is modelled. The influence of the fabrication condition on the structural parameters of microcapillary is investigated. A microcapillary with large outer radius of 37.34 µm and thin wall of 1.52 µm is realized, and its refractive index sensitivity reaches 1126.67 nm/RIU. This provides the potential to microcapillary-based optical sensor application.

1. Introduction

Recent years, microcapillary-based optical sensor has attracted a lot of attentions, such as optical ring resonating sensor based on whispering gallery mode (WGM) mechanism [1,2] and optical sensor based on anti-resonant reflecting guidance mechanism [3]. The cross section of the microcapillary can be used as a WGM ring resonator, which has high quality factor and small mode volume [4,5] and can be applied in various fields, such as physical parameters sensing [6–8] and label free biochemical sensing [9–11]. Besides being used as sensor, microcapillary-based WGM ring resonator is also applied in low threshold laser [12,13] and optomechanics [14,15].

For a microcapillary-based sensor, the thickness of the wall and the radius of the microcapillary are critical parameters because they determine the strength of interactions between light and the analyte. In order to obtain the microcapillary with the desired wall thickness, the fused silica capillary tapering method is frequently used to decrease the wall thickness to a certain value and further etched with low concentration of hydrofluoric acid ($<10\%$) [16]. However, the chemical etching will rough the surface and reduce the quality factor of the resonator. The limit of hydrofluoric acid concentration also prolongs the process time to several hours. Another method that rolling up SiOx/Si layers into microtubes on a Si substrate and form a thin-wall resonator is also proposed [17], but the process is complicated and the excitation of the WGM is difficult since the light wavelength is larger than the sub-micro scale perimeter of the microtube.

Providing air pressure to the microcapillary during the drawing process can make the microcapillary expanding, enlarge the radius and decrease its wall thickness simultaneously. Furthermore, this method will keep the smooth of the wall to avoid the deterioration of the quality factor. In addition, the process time can be shorten to a few minutes. The pressurized drawing technology based on drawing tower and graphite furnace heating has been used for hollow Bragg fiber and tubular fiber fabrication [18–20]. But the 20–30 cm heating zone length of graphite furnace and 200–300 m drawing length are too large for microcapillary resonator. Pressurized tapering technology under the heating of oxyhydrogen flame [21] confines the heating zone in several millimeters, and after processing the resonator wall thickness can reduce to submicron, which is appropriate for high sensitivity detection application. However, how the fabrication parameters, such as pressure and elongated length, affect the structure parameters of the processed microcapillary haven't been studied in detail, which is important to obtain a resonator with desired structure parameters.

In this paper, a pressurized microcapillary tapering model is established and the effects of applied pressure and elongated length on radius and wall thickness are studied. The model is applied to direct the

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https://doi.org/10.1016/j.yofte.2018.07.025
Received 24 April 2018; Received in revised form 14 June 2018; Accepted 19 July 2018
1068-5200/

fabrication of ultra-thin silica microcapillary WGM resonator with large radius, which has promising prospect in liquid sample sensing application. A microcapillary ring resonator with the outer radius of 37.34 μm and the wall thickness of 1.52 μm is fabricated successfully. To our best knowledge, it has the minimal wall thickness among the microcapillary resonator sensors with an outer radius larger than 35 μm. The refractive index sensitivity of this microcapillary resonator sensor is 1126.67 nm/RIU, which is close to the theoretical limit.

2. Theory

2.1. Effect of wall thickness and radius of microcapillary on sensitivity

The radial distribution of the WGM electrical field of a capillary is governed by [22]:

$$E_{m,l}(r) = \begin{cases} AJ_m(n_1 k_0^{(l)} r), & r \leqslant r_1 \\ [BJ_m(n_2 k_0^{(l)} r) + CH_m^{(1)}(n_2 k_0^{(l)} r)], & r_1 \leqslant r \leqslant r_2 \\ DH_m^{(1)}(n_3 k_0^{(l)} r), & r \geqslant r_2 \end{cases} \quad (1)$$

where J_m and $H_m^{(1)}$ are the mth Bessel function and mth Hankel function of the first kind respectively. n_1, n_2 and n_3 are the refractive index of the sample core, the silica wall and the surrounding medium air. r_1 and r_2 represent the inner and outer radius of the microcapillary, respectively. By solving Eq. (1), we can get the relationship between radius, wall thickness and the RI sensitivity under different radial mode.

Fig. 1 shows the simulation result of the refractive index sensitivity of the 1st, 2nd and 3rd order (l = 1, 2, 3 refers to the radial mode number) WGM TM-mode of ring resonator under different radiuses and wall thicknesses. It shows that the refractive index (RI) sensitivity increases significantly with the radius of ring resonator under the same wall thickness and radial mode number. Comparing Fig. 1(a) with Fig. 1(b), we can see that the resonator shows a higher sensitivity under a smaller wall thickness. The sensitivity is also related to the radial mode number. Based on the analysis, for the structural parameter of a microcapillary ring resonator, a thin wall and a large radius are both important to the RI sensing application. Therefore, to fabricate a microcapillary-based optical sensor with high sensitivity, in addition to the wall thickness that people usually focus on, the radius also needs to be taken into consideration.

2.2. Drawing model of microcapillary with inner pressurized air

To better build a drawing model for the microcapillary sensor, the drawing process is divided into two steps. The first step considers the shape change of microcapillary during drawing, especially the variation of the radius and wall thickness with the elongation length. The second step considers the expanding or shrinking process under the effect of internal air pressure.

The first step is similar to the drawing process of fiber taper. For a fiber taper, suppose the length of heated area as L_0, the initial radius as r_0 and the elongation length as x. As shown in Fig. 2, the radius of taper waist changes from r_0 to r_w during drawing. The relationship between taper waist radius and the elongation length is as follows [23]:

$$r_w(x) = r_0 \exp(-x/2L_0) \quad (2)$$

We assume the shape change of microcapillary during drawing process also obeys Eq. (2). The initial outer radius and inner radius of capillary are r_{out0} and $r_{in\,0}$, then the taper waist outer radius r_{out1} and inner radius $r_{in\,1}$ can be expressed as:

$$r_{out1}(x) = r_{out0} \exp(-x/2L_0) \quad (3)$$

$$r_{in1}(x) = r_{in0} \exp(-x/2L_0) \quad (4)$$

The wall thickness W of the microcapillary taper waist can be expressed as:

$$W = (r_{out0} - r_{in0}) \exp(-x/2L_0) \quad (5)$$

The sectional area S of microcapillary waist can be obtained as:

$$S = \pi \cdot [r_{out1}^2(x) - r_{in1}^2(x)] = \pi \cdot [r_{out0}^2 \exp(-x/L_0) - r_{in0}^2 \exp(-x/L_0)] = \pi \cdot (r_{out0}^2 - r_{in\,0}^2) \exp(-x/L_0) \quad (6)$$

The second step is only influenced by pressures, including the excess hydrostatic pressure P_{st} and the internal pressure P. The excess hydrostatic pressure P_{st} is an additional stress caused by surface tension based on the melting of materials [24]. Under the effect of P_{st}, the microcapillary turns to shrink in the process of drawing. In order to resist P_{st}, the pressurized air is injected into the microcapillary with the pressure of P, and how the shape is changed depends on the combination of the excess hydrostatic pressure P_{st} and the internal pressure P. It is foreseeable that the microcapillary will expand when P is greater than P_{st}, otherwise shrink. The expansion process is decided by the internal pressure P and the drawing time t. We further describe the expansion process of microcapillary by using the parameter of radius increment speed V(P). V(P) is a function of P and can be obtained from experimental measurement result. The increment of taper waist outer radius r_{out2} will be:

$$r_{out2}(x, P) = r_{out1} \int_0^t V(P)dt \quad (7)$$

Then the final taper waist outer radius r_{out} can be expressed as:

$$r_{out}(x, P) = r_{out1}(x) + r_{out2}(x) = r_{out0} \exp(-x/2L_0) \times \left[1 + \int_0^t V(P)dt\right] \quad (8)$$

The silica is an incompressible viscous and the sectional area of waist will not change. As a result, we can figure out the wall thickness

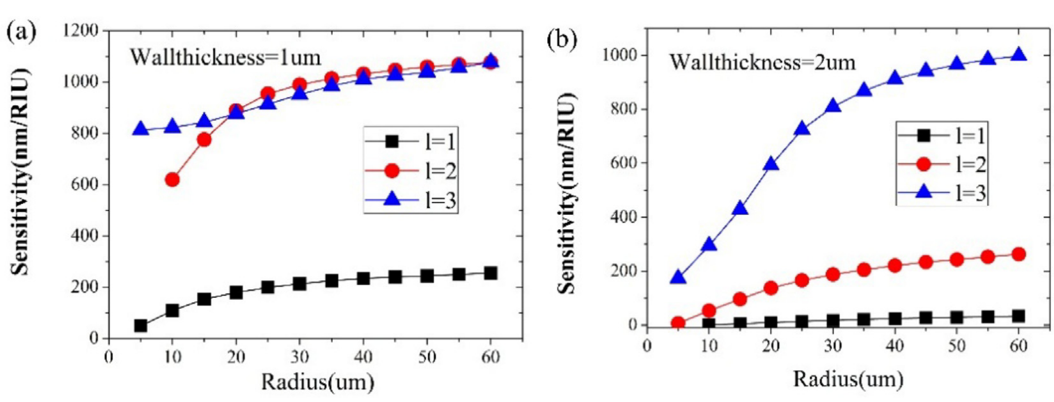

Fig. 1. The refractive index sensitivity of the 1st, 2nd and 3rd order (l = 1, 2, 3 refers to the radial mode number) WGM TM-mode of ring resonator under different radiuses. (a) The wall thickness of ring resonator is 1 μm (b) The wall thickness of ring resonator is 2 μm.