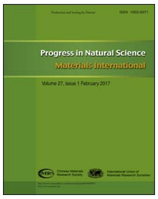
Progress in Natural Science: Materials International 27 (2017) 498–502

Contents lists available at ScienceDirect

Progress in Natural Science: Materials International

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



Original Research

Temperature-dependent optical resonance in a thin-walled tubular oxide microcavity

Yangfu Fang[a], Xianyun Lin[a], Shiwei Tang[b], Borui Xu[a], Jiao Wang[a,c], Yongfeng Mei[a,*]

[a] Department of Materials Science, Fudan University, Shanghai 200433, China
[b] Department of Physics, Faculty of Science, Ningbo University, Ningbo, Zhejiang 315211, China
[c] School of Information Science & Engineering, Fudan University, Shanghai 200433, China

ARTICLE INFO

Keywords:
Microcavities
Rolled-up
Whispering gallery mode (WGM)
Temperature-response
Mie scattering method

ABSTRACT

This work proposes a temperature-response capability of optical resonance in tubular optical oxide microcavities. The thin wall thickness with a subwavelength scale enables these microcavities to interact with the environment effectively. By optimization of the geometries and materials, the tubular microcavities can be tuned into temperature-inert in vacuum, and the experiments support this design. The experiments prove the idea of utilizing them as temperature-inert microcavities. Contrary wavelength shifts from previous studies were observed, which can be explained with the theoretical model. Furthermore, the theoretical results of the present work suggest that novel rolled-up microtubes could act as an exceptional optical microcavity for the application in temperature response.

1. Introduction

With their distinct feature of high quality factor (Q factor) and small mode volume, the optical whispering-gallery modes (WGMs) in dielectric microcavities have been extensively used in the applications such as photonics filters [1–4], cavity quantum electrodynamics [5,6], bio-molecule sensors [7], low threshold lasers [8,9] and nonlinear optics [10]. Small changes in the geometry or refractive index of the dielectric microcavity system may cause a significant resonance wavelength shift for a given WGM [9], which could be induced by thermal fluctuations from the variation of ambient temperature or the absorption of laser energy during the laser scanning or pumping, leading to thermal instability. The temperature-related shifting of WGMs in microresonators can be a help or a hindrance depending on the application [11]. For example, the ultrasensitive mode shifting in the WGM resonance to the surrounding temperature can be utilized to design high-sensitivity thermal sensor [12] or allow thermal tuning of the lasing mode [13], the thermal nonlinearity induced optical bistability can make a useful optical switch [14]. On the other hand, in label-free biological-chemical sensing the thermally induced drifting can be a source of thermal noise that needs to be reduced [15]. Moreover, strong thermo-optic effect would mask the Kerr-driven variations in the refractive index so that the observation of the Kerr effect can be restrained [16–18]. Therefore, finding a way to reduce or even cancel this thermal effect of WGMs is highly desired. A practical approach is to introduce materials with a negative thermal refraction coefficient in the vicinity of the WGM microcavities to compensate the resonance wavelength shift due to their positive thermal refraction coefficient [14,19], which, in turn, could influence the intrinsic resonance behaviors of the WGMs.

Different behaviors of resonances are shown as the temperature changes for different materials, geometry or circumstance of our self-rolled up microtubes correspondingly. We tested the resonance property of these tubular optical microcavities under various temperatures and found out the contrary mode shift directions between our work and previous work [20,21]. These structures are based on a new class of microcavities with WGMs in a tubular or hollow cylindrical geometry [1,22–24], which have been comprehensively studied in both theoretical and experimental aspects for potential applications including optofluidic devices, integrated optics and sensors in lab-on-a-chip applications [9,25,26]. Moreover, the tubular microcavities rolled up from pre-strained films have been demonstrated with superior sensing performance owing their sub-wavelength wall thickness [29–31]. For example, we take the tubular microcavities fabricated from Y_2O_3/ZrO_2 bilayer nanomembrane based on the self-rolled process with wet chemical method. To improve the Q factor, the oxide tubular microcavity arrays are uniformly coated with 50 nm alumina oxide by atomic layer deposition (ALD), as shown in Fig. 1(a). The microtube consists

---

Peer review under responsibility of Chinese Materials Research Society.

* Corresponding author.

E-mail address: yfm@fudan.edu.cn (Y. Mei).

http://dx.doi.org/10.1016/j.pnsc.2017.03.011
Received 18 January 2017; Accepted 22 March 2017

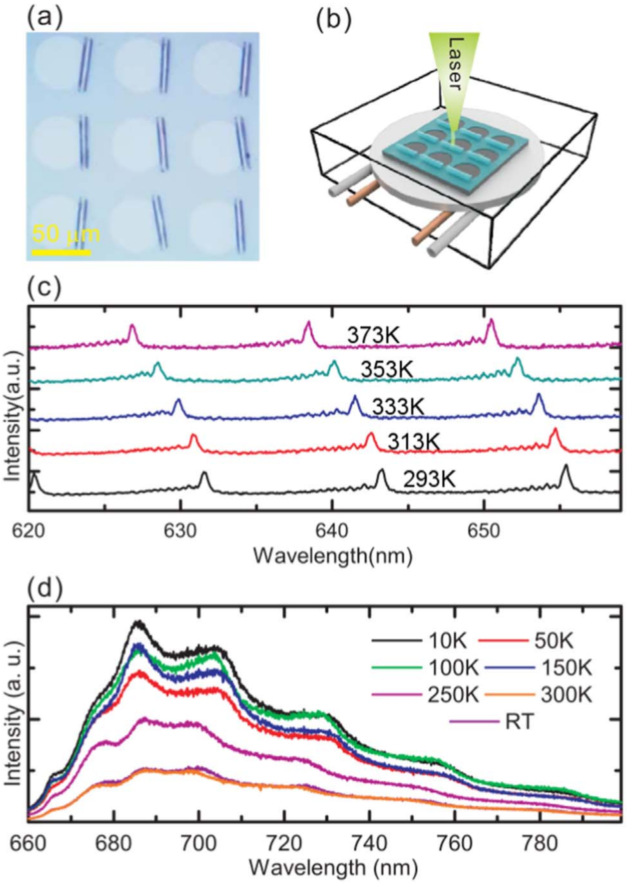


Fig. 1. (a) Optical microscopy image of oxide tubular microcavity arrays after the ALD coating. (b) Schematic diagram of μ-PL measurement under different temperature and nitrogen atmosphere. (c) The μ-PL spectra of a rolled-up microcavity under different temperature of the above Y_2O_3/ZrO_2 tube in air. (d) The μ-PL spectra of SiO/SiO_2 tubular optical microcavities in nitrogen gas.

of Y_2O_3/ZrO_2 layers wrapped by ALD for 50 nm and thicknesses of Y_2O_3/ZrO_2 are 8/24 nm, respectively. The temperature controlling device is shown in Fig. 1(b), where brown pipes with resistance wire inside heating the disk below the sample and white pipes bubble liquid nitrogen for cooling, thus we can arbitrarily control the temperature and the ambience. The optical properties of these microcavities were measured by a micro-photoluminescence (μ-PL) spectroscopy with an excitation line at 514 nm, under different measuring temperature. Fig. 1(c) indicated that the experimental thermal-induced resonance wavelength shows obvious blue shift when the temperature rises from room temperature (~ 293 K) to 373 K with the step of 20 K. In contrast, the resonance properties from the SiO/SiO_2 tubular optical microcavities fabricated by dry etching method, releasing pre-stressed SiO/SiO_2 bilayer nanomembranes from polymer sacrificial layers are also influenced by temperature, which is shown in Fig. 1(d). The resonance peaks in Fig. 1(c) presents obvious shifts compared with that in Fig. 1(d). This abnormal blue mode shift were observed in the previous experiments [20,21], which was considered resulting from dynamic desorption process of H_2O molecules when oxide terminated microtubes were heated. However, theoretical model suggests that only red shifts appear when there are only considered with geometry deformation and refractive index changing induced by thermal effect. Hence, it is demanded to establish a complete theory to describe such temperature-dependent resonance behaviors of our tubular microcavities.

In this work, the thermal stability and sensing capability of these rolled-up tubular microcavities are both theoretically and experimentally investigated. A theory is established to describe the resonance wavelength shifts behaviors of the tubular microcavities. The theoretical result shows that, the tubular microcavities are potential to be fabricated temperature-inert in vacuum or temperature-sensitive in liquid media. To confirm this theory, a temperature-inert tubular microcavity is detected, which is different from the unstable tubular microcavities we mentioned above and is in good agreement with the theoretical results. These theoretically and experimentally results indicate that the WGMs in such rolled-up microcavities are expected to be less sensitive to the refractive index of the tube wall materials.

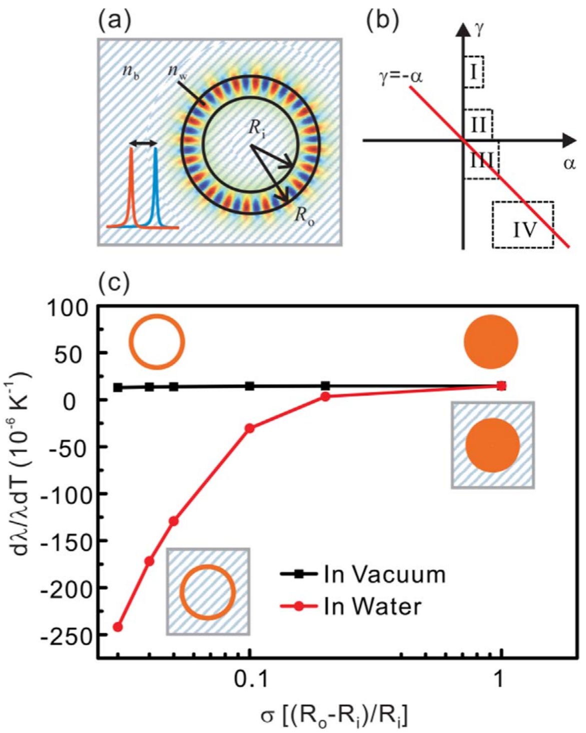


Fig. 2. (a) Sketch of a tubular microcavity. The inset in the left bottom corner exhibits wavelength shift when background refractive index n_b changes. (b) Materials map for thermal response in $\gamma-\alpha$ plane. I: semiconductors like Si, Ge; II: oxides like SiO_2, TiO_2; III: halides like CaF_2; IV: polymers like PS and PMMA. (c) Thermal response of microtubes made up with Al_2O_3 In vacuum and water. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article).

2. Theoretical model

As discussed above, the tubular microcavities with different structure, materials and circumstances have different behaviors of temperature-response. As a result, a complete theory system should be established to describe such behaviors of temperature-response of the tubular microcavities. In a realistic rolled-up microtube, the cross section of the tube is in a spiral shape, which could lead to the mode splitting and Q spoiling compared to an ideal tubular geometry [27,28]. For a simple one-layered microtube with an outer radius R_o and an inner radius R_i as shown in Fig. 2(a), we use $\sigma = (R_o - R_i)/R_i$ to identify its thickness. Combining the self-rolled-up technique with a following atomic layer deposition process of oxides, it can be well tuned with $0.01 < \sigma < 0.05$ in experiments [29,31,32]. It is worth to note that σ does not change with temperature (i.e. $d\sigma/dT = 0$) as the microtube is expanding uniformly. In addition, thermal expansion coefficient (CTE) of the microtube materials is represented by α, and we use the relative refractive index change (γ) to describe the thermo-optic effect (i.e. the refractive index of the tube wall material $n = n_0(1 + \gamma \Delta T)$, where n_0 is a constant coefficient and ΔT the temperature variation). Typical materials are selected in the γ-α plane of Fig. 2(b). For examples, Region I: some semiconductors like Si, Ge; Region II: oxides like SiO_2, TiO_2; Region III: halides like CaF_2; Region IV: polymers like PS and PMMA.