Sensors and Actuators B 238 (2017) 98–104

Contents lists available at ScienceDirect

Sensors and Actuators B: Chemical

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

Laser-tuned whispering gallery modes in a silica-based microsphere resonator integrated with ethyl-orange-doped polyvinyl alcohol coating

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ARTICLE INFO

Article history:
Received 11 May 2016
Received in revised form 7 July 2016
Accepted 12 July 2016
Available online 13 July 2016

Keywords:
Microsphere resonator
Whispering gallery mode (WGM)
Laser tuning
Ethyl orange (EO)
Polyvinyl alcohol (PVA)
Functional coating

ABSTRACT

A laser-tuned whispering gallery modes (WGMs) microsphere resonator integrated with ethyl-orange-(EO-) doped polyvinyl alcohol (PVA) coating has been proposed and experimentally demonstrated. Owing to the photo-induced isomerization feature of the azo-doped coating, the WGM resonance wavelength could be tuned by adjusting the 532 nm excitation laser power density based on a lateral pumping scheme. The WGM tuning principle of the proposed microresonator has been investigated, which is in accordance with our experimental observation results. Experimental results indicate that the proposed functionalized microsphere has a fully linear WGM resonance wavelength tunability up to 0.158 nm/(mW mm^{-2}). Further experimental study shows nonlinear WGM resonance wavelength shift respectively dependent on EO weight percentage and pump laser power densities, which is in agreement with our theoretical analysis. Moreover, our proposed microresonator also exhibits good spectral reversibility as well as dynamic temporal response, which ensures its potential applications in optical modulation and future all-optical networking systems.

1. Introduction

Due to their desirable advantages such as compact size, high quality factor, and small mode volume, whispering gallery mode (WGM) microresonators have attracted growing research interests in recent years. And owing to their perfect geometrical symmetry that helps significantly enhance the quality factor, many efforts have been made to develop microsphere-resonator-based photonic devices. With the progress in material sciences, different kinds of functional materials have been developed and employed to functionalize microsphere resonators for photo-thermal [1–3], bio-sensing [4,5], environmental humidity monitoring [6–8] and optical networking applications [9,10]. Particularly, the great demands in high-speed communications capacity make all-optical networking, such as optical switching, optical routing and optical signal transforming, a promising method to take the place of conventional networking approach based on electrical instruments. Various photosensitive materials have been investigated for developing all-optical functional devices, amongst which azobenzene materials have become the subjects of numerous studies in the past decades. The unique photosensitive feature of azobenzene materials could date back to G. S.'s et al. intriguing discovery in 1937 [11], which indicates that the photo-isomerization-based geometric transition between *trans* and *cis* azo molecules under excitation laser with proper wavelength would make them exhibit distinctive optical properties. In 1998, Lagugné et al. fabricated an optically controlled azo-based birefringence grating and investigated the birefringence property of azobenzene materials [12]. Besides the light-tuning feature, in 1999C. Wang et al. achieved reversible optical storage by using liquid-crystalline azobenzene side-chain [13]. And S'heeren further discovered and investigated the nonlinear optics property of azobenzene materials in 1993 [14]. Following this work, Rangel-Rojo et al. investigated the third-order nonlinearity of functionalized azobenzene film [15]. And Ouazzani et al. also fabricated novel azobenzene polymer based on push-pull nonlinearities in 2011 [16]. In successive years, this type of functional materials have been widely studied for applications in optical storage [17,18], optical modulation [19,20], optical switching [17], optical sensing [21,22] and laser tuning [23,24].

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http://dx.doi.org/10.1016/j.snb.2016.07.044
0925-4005/

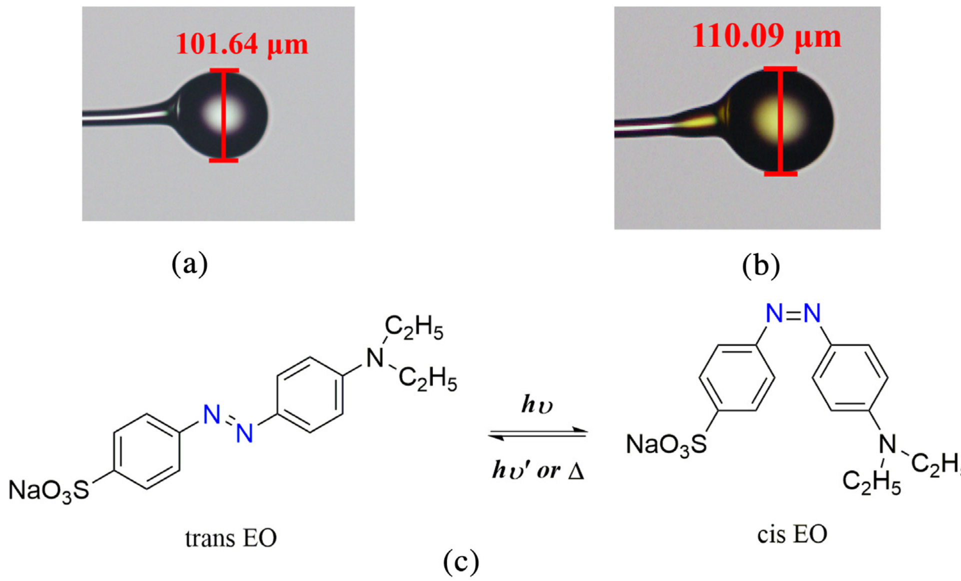

Fig. 1. (a) and (b) Micrographs of fabricated microsphere before and after integration with 2 wt% EO-doped PVA coating. (c) Schematic illustration of the reversible photo-isomerization process for EO molecule.

In our previous study, we have developed a microfiber-assisted Mach-Zehnder fiber interferometer by employing ethyl orange (EO) solution as the functional material [25]. And in this paper, we propose a laser-tuned microsphere resonator integrated with EO-doped polyvinyl alcohol (PVA) coating based on lateral pumping scheme under 532 nm laser illumination. The WGM spectral characteristics of the proposed microresonator have been investigated from theoretical as well as experimental perspectives, and the WGM spectral dependence on 532 nm laser power density has also been experimentally studied, which is in accordance with our theoretical analysis. The influence of EO weight percentage of the mixture coating has been investigated and laser-power-dependent interim wavelength shift from linear to nonlinear regions is experimentally acquired, which could be attributed to laser-induced thermal effect when the EO weight percentage exceeds some critical level. Further experiment indicates that our microsphere resonator possesses a good spectral reversibility and satisfying dynamic response features for slow signal modulation application. Our proposed microresonator integrated with EO-doped coating (MIEOC) has such desirable merits as all-optical tuning, ease of fabrication, simple structure and compactness, which make it a promising candidate for potential applications in future all-optical networking systems.

2. Operation principle and experimental setup

Compared with WGM resonators with other geometric structures, microspheres are one kind of WGM resonators with ultrahigh Q factors, which have been employed in various applications from narrow linewidth filtering [26,27], frequency combing [28], tunable laser [27], high-speed modulator [29] to nonlinearity carrier [30].

The microsphere resonators utilized in our experiment are fabricated by cutting off a tapered fiber with a waist diameter of 33 μm at the center point of its tapering segment and then applying arc discharges on fiber tip through a fusion splicer (S178A, produced by Furukawa Electric Co., Ltd., Japan). By precisely adjusting the splicing parameters, a silica-based microsphere could be fabricated from the fused fiber tip, as shown in Fig. 1(a).

EO is one kind of azobenzene materials with double nitrogen bond linking with two benzene rings to activate the intriguing photo-isomerization process. In normal cases, most of the azo molecules stay in the trans state. Through laser excitation with proper wavelength, the trans EO molecules would gradually transform into their cis counterparts and hence to induce the variation in material refractive index (RI). This molecular transition is reversible when the azo materials are exposed to thermal perturbation or laser illumination with particular wavelength. Fig. 1(c) shows the schematic illustration of the reversible photo-isomerization process for EO molecule. In our experiment, PVA is employed as the carrier medium to realize the integration of EO materials with the microsphere resonator. PVA powder is firstly dissolved into distilled water and then EO is added into the PVA solution at 80 °C. The weight percentage of EO could be controlled by adjusting the amount of EO added into the PVA solution. By immersing the microsphere into the mixture solution, EO/PVA compound could be deposited onto the microsphere surface, and the mixture coating would gradually form after being dried in an airtight box for 24 h. The microsphere resonators after integration with 2 wt% EO-doped coating are shown in Fig. 1(b). From this figure it could be seen that the coating thickness is around 5 μm.

Fig. 2 shows the schematic diagram of the WGM excitation and test system for our proposed laser-tuned MIEOC. The microsphere is placed in contact with a microfiber of 1.23 μm in diameter fabricated from a standard single-mode fiber (SMF) by using a fiber tapering machine (produced by E-Otron, China) [31]. The transmission spectrum of the microfiber is monitored by using an Agilent transmission loss test system consisting of a tunable laser (TL, 8164B produced by Keysight Technologies, US) with an operation wavelength range of 1540 nm–1560 nm and a wavelength sweep rate of 20 nm/s, a polarization controller (PC, N7786B produced by Keysight Technologies, US) and an optical power meter (OPM, N7744A produced by Keysight Technologies, US). And in the meanwhile, the spectral information is transferred to a laptop for data processing. The MIEOC with fiber stem is fixed onto a 3-dimension fiber stage to precisely adjust its distance to the transmission microfiber. Due to the total internal reflection mechanism fulfilled by the refractive index contrast between the resonator and its surrounding environment, WGM light is well confined inside the microsphere resonator. A 532 nm laser (MPL-N-532-1W, produced by Changchun New Industries Optoelectronics Tech Co., Ltd., China)