Optics Communications 285 (2012) 2189–2194

Contents lists available at SciVerse ScienceDirect

Optics Communications

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

Humidity and particulate testing of a high-Q microcavity packaging comprising a UV-curable polymer and tapered fiber coupler

Ying-Zhan Yan [a,b], Shu-Bin Yan [b,*], Zhe Ji [a], Jun Liu [b], Chen-Yang Xue [a], Wen-Dong Zhang [b], Ji-Jun Xiong [a]

[a] Key Laboratory of Instrumentation Science and Dynamic Measurement, North University of China, Taiyuan 030051, PR China
[b] Science and Technology on Electronic Test and Measurement Laboratory, North University of China, Taiyuan 030051, PR China

ARTICLE INFO

Article history:
Received 19 July 2011
Received in revised form 28 November 2011
Accepted 5 December 2011
Available online 17 December 2011

Keywords:
Optical microcavities
Quality factor
Package
Practical application

ABSTRACT

The high-Q maintenance of microcavities greatly challenges the microresonator-based practical application. In this paper, we analyze the theoretical model of the Q in the open air, indicating that the Q can be spoiled drastically in the open air. The Q spoiling factors are also demonstrated experimentally to show the Q spoiling which originated from the water and the particulate in the surroundings. Then we propose and realize the Q maintenance through constructing a sealed and packaged microcavity regime. In the packaged structure the Q decreases a little but a high Q larger than 10^6 can be achieved continuously. Moreover, the sealed structure has good performance to maintain the high Q for a long time with the standard deviation about 10^4, because the Q spoiling factors are isolated by the package layer. Additionally, the package also enhances the robustness. These merits can promote the practical application of the microcavities.

1. Introduction

Whispering gallery mode (WGM) optical microresonators [1] are widely researched for a number of passive and active devices as filters, lasers, sensors and modulators [2] due to their ultra-high quality factor (Q) values, very small volume and good compatibility with traditional fiber optics. In these applications the WGMs, which behave as resonant dips, are every important. On the one hand, the dips reveal the Q through the resonant linewidth. On the other hand, the resonant spectra are the basis of the above applications. For example, in microcavity based filter [3–6] and laser [7–10] researches, the WGMs act as the filting and the laser emission windows, respectively. Additionally, in microcavity based un-evanescent sensing applications, such as micro-optical force sensor [11–12] as well as acceleration sensor [13–14], the resonant frequency shift is used as the sensing signal normally. Thus, the device performance depends on the resonant linewidth and its stability greatly. However, the resonant linewidth (or the Q) can be disturbed easily in practical application, because the actual environment where the microcavity lies is complex and mutable, which can induce extra losses and impact the Q inevitably. This can subsequently cause errors in the above devices. Therefore, a stable Q with a steady resonant linewidth is the prerequisite for practical microcavity based devices, indicating the necessity and importance of the high-Q maintenance.

Generally speaking, there are two kinds of the Q spoiling mechanism, the absorption loss caused by the water molecules and the scattering loss induced by the micro-dust adhering to the microcavity [15]. The two Q spoiling factors are great obstacles to the development of the microcavity-based practical devices. Consequently, in practical application how to eliminate these spoiling factors to obtain the stable Q is of great significance for the microcavity-based practical device investigation. In former researches, a hermetic box is used to protect the coupling system from being polluted by the micro-dust in the air [15]. Although the contaminations can be excluded by the hermetic box effectively, the box is bulky and occupies large space, making this manner only appropriate in laboratory experiments but not applicable in practical applications. In addition, R. Grover et al. [16] bonded a microring resonator to a bus waveguide by using Benzocyclobutene (BCB) as the bonding layer with the thickness about 1–2 μm, which essentially serves to package the device. This method is effective to protect the microring resonator.

In this paper, we propose a novel method to realize the Q-maintenance for the microcavities in the open air. In this method a sealed and packaged microcavity structure is realized, in which the microcavity and the fragile taper are encapsulated wholly to isolate the microcavity–taper coupling system from the surroundings by using low refractive index (RI) ultraviolet (UV) polymer as the encapsulating material. Thus, the Q spoiling factors are eliminated ultimately. This processing method is of great significance to promote the development of the microcavity based practical devices as filters, lasers and sensors.

2. Theoretical model

As the most important parameter, the loaded Q (Q_{tot}) of the microcavity is determined by several factors:

$$Q_{tot}^{-1} = Q_{in}^{-1} + Q_{co}^{-1} + Q_{so}^{-1}, \tag{1}$$

* Corresponding author.
E-mail address: shubin_yan@nuc.edu.cn (S.-B. Yan).

0030-4018/$ – see front matter © 2011 Published by Elsevier B.V.
doi:10.1016/j.optcom.2011.12.031

where Q_{in}, Q_{co} and Q_{so} denote the intrinsic, coupling and the external surroundings-related Q, respectively. Put simply, the Q_{in} depends on the microcavity intrinsic factors, which can be expressed as:

$$Q_{in}^{-1} = Q_{abs}^{-1} + Q_{rad}^{-1} + Q_{sca}^{-1}, \tag{2}$$

where Q_{abs}, denotes material absorption losses; Q_{rad}, intrinsic radiative (curvature) losses; Q_{sca}, scattering losses on the microcavity residual surface inhomogeneities. The Q_{co}, as frequently described, can be larger than 10^{10} by using an evanescent coupler, i.e., fiber half-block, hybrid fiber-prism or the tapered fiber [17].

When placing the microcavity-taper coupling system in ideal surroundings, such as the vacuum environment or the dust-free chamber filled with dry air, the Q_{tot} is mainly determined by the Q_{in} and the Q_{co}. The above ideal conditions are common in laboratory but greatly challenge the manipulation in practical applications. Actually, the surroundings are various and multivariate in the application. Thus, there are some other Q-spoiling factors originated from the surroundings, which are independent from Q_{in} and Q_{co}. Here, we call the surrounding-related quality factor as Q_{so}.

In practical applications, there are mainly two kinds of influencing factors on Q_{so}. One is the water in the ambient air. The water molecules would form an adsorbed water monolayer on the microcavity surface, inducing water absorption losses. In fact, for a water layer of thickness ξ with a water absorption coefficient at the testing laser waveband $\alpha(\lambda)$, we can estimate the water-related Q_{so} by $\sqrt{\pi/8n^2} \cdot D^{1/2}/(\xi\lambda^{1/2}\alpha(\lambda))$ (n and D are the RI and the diameter of the microcavity) [18]. The expression implies a greater water-related Q-spoiling for the laser with longer wavelength, because the absorption coefficient becomes larger and larger with the increasing laser wavelength, especially at the telecommunication band which is extensively used. The other influencing factor is the micro particles especially the micro-dust in the air. The micro-dust, depositing upon the microcavity surface (especially the route of the WGMs), can worsen the surface inhomogeneity and cause additional scattering losses. It should be noted that both of the intrinsic surface roughness (Q_{sca} in Q_{in}) and the micro-dust adhering to the microcavity decrease the Q in the same mechanism that we call scattering. However, there are essential differences in the causes and the controlling means between the two kinds of scattering. The Q_{sca} indicates the intrinsic surface roughness of the microcavity, and it depends on the microcavity material and the fabrication, which can't be changed after the fabrication. The micro-dust, which is irrelevant to the microcavity intrinsic characteristics, depends on the ambient air. We estimate the total surface scattering-limited Q by the following expression: $K/(1+K) \cdot [3\lambda^3(D/2)]/(8n\pi^2 B^2\sigma^2)$, where tK defines the microcavity internal reflection condition, B and σ are the correlation length and the surface roughness of the cavity, respectively [19]. The purpose for differentiating the two forms of the scattering is to clarify the Q limiting factors in practical applications. The theoretical model demonstrates that the surroundings-related Q_{so} is the only factor we can control after the construction of the microcavity coupling system. In addition, in practical application the Q_{so} is random and mutable due to the uncertainty of the Q spoiling factors. Thus, the Q_{so} is the most labile factor for Q_{tot}, which is the critical point to maintain the Q. For this purpose the Q spoiling from the water and the micro-dust in the microcavity surroundings need to be eliminated.

3. Fabrication

According to the theoretical model introduced above, the Q_{tot} is unstable and can be spoiled easily by the water and the micro-dust in the open environment. In this paper, we eliminate the above Q spoiling factors by encapsulating the microcavity-taper coupling system wholly to fabricate a sealed and packaged structure to isolate the microcavity-taper coupling system from the surroundings. Here, the microspheres are used to illustrate the package process. And the fiber taper coupler is used to excite and probe the microsphere WGMs evanescently. The method introduced here is not just for the microsphere. All other kinds of WGM microresonators (microdisks, microtoioids, and bottle microcavity et.al.) are still applicable.

3.1. Construction of the coupling system

In this paper, we have fabricated microspheres with D ranging from 180 μm to 620 μm. The microspheres are fabricated by using thermal melting method [20]. Depending on the surface tension, it is easy to obtain spheres with smooth surface. The tapered fiber is fabricated by using the thermal stretching technique with low insertion loss (less than 5%), in which the fiber is stretched while being heated by oxy-hydrogen flame. A tunable laser (1550 nm wavelength band, linewidth<300 kHz) is used to explore the WGMs. The transmission spectra are collected by a photoreceptor and displayed on a digital oscilloscope. The diagrammatic sketch of the experimental setup is shown in Fig. 1(a). *3D* X–Y–Z stages with 20 nm resolution are used for controlling the air gap between the two parts to adjust the coupling strength. Fig. 1(b) is an experimental photo of the testing system. Fig. 1(c) shows a typical microsphere resonant dip. The dip reveals two pieces of important information, the coupling efficiency about 11db and the high Q about 4.8×10^7. It is worth noting that, during experiments a protective covering is used to protect the coupling system. The following section introduces a novel method to maintain the Q by isolating the coupling system in an encapsulating manner. The encapsulated structure is independent and irrelevant to the surroundings.

3.2. Packaging experiment

It is a feasible way to maintain the Q in practical applications by isolating the microsphere–taper coupling system from the outside. A sealed and packaged structure in which the microsphere–taper coupling system is embedded deeply and isolated wholly from the surroundings can be realized in a capsulation manner by using the low RI (1.35) solidifiable UV polymer. Two important factors should be considered when selecting the polymer. One is that the RI must be lower than that of the microsphere, because low RI makes the optical energy confined in microresonators. The other is that the absorption coefficient of the polymer at the working wavelength should be as low as possible, because the absorption loss induced by the packaged body can decrease the loaded Q.

The packaged structure has been introduced for the first time in our former researches [21]. Here we improve the packaging technology to realize a sealed and packaged structure, in which the microsphere and the taper are wholly encapsulated and embedded deeply in the package body to realize an integrated bulk, as shown in Fig. 2(a). Briefly, there are five steps to perform the package. First, we need to obtain an effective coupling between the microsphere and the taper in the air before the package, as shown in Fig. 2(b1). The effective coupling is confirmed through the resonant dips with a large coupling strength and a narrow linewidth. Then, as illustrated in Fig. 2(b2), the UV polymer is coated on the coupling system in a dropping manner. Afterward, as shown in Fig. 2(b3) an ultraviolet lamp is used to irradiate the capsulated structure to solidify the UV polymer. The microsphere–taper coupling system here is capsulated by the solidified UV polymer. In the fourth step, the microsphere stem, mounted on the *3D* stages, is truncated by using a heat burning manner. Then the microsphere coupling system is independent of the *3D* stages and can be moved freely, as shown in Fig. 2(b4) and (c1). Finally, similar to the potted circuit module we further package the structure by using a designed slot as the mold to package the fragile taper totally. Fig. 2(c2) shows the semi-finished products of the sealed and packaged microcavity unit. Fig. 2(c3) shows a typical