

# Fiber-taper-coupled zeolite cylindrical microcavity with hexagonal cross section

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Whispering-gallery modes (WGMs) in a zeolite cylinder have been effectively coupled with a low-loss fiber taper. The fiber transmission spectrum directly shows the WGM distribution, which agrees well with the theoretical prediction based on geometric optics. Due to other scattering and absorbing mechanisms, the measured quality factors of the WGMs are limited to approximately 800. This result shows that the fiber taper provides a powerful tool for coupling WGMs of a zeolite cylinder, and this taper-coupled zeolite can be a potential microcavity system for the cavity quantum electrodynamics and the microlaser. © 2007 Optical Society of America

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## 1. Introduction

Whispering-gallery modes (WGMs) in microcavities where light is confined inside by total internal reflection [1] are being widely used for compact low-power optoelectronic devices due to their high quality factors ( $Q$ ) and relatively small mode volumes [2]. With these WGMs, low-threshold microlaser [3], highly sensitive sensing [4], narrowband filter [5], and other passive devices [6] have been realized. Recently high- $Q$  WGMs have also been proposed for quantum information processing based on cavity quantum electrodynamics (QED) [7–9]. In general, such WGMs are usually studied in a rotational-symmetry shape, such as microdroplet [10], microsphere [3], microdisk [11], and microtoroid [12].

On the other hand, another type of WGMs has also been reported in naturally grown microcylinders in which the cross sections are hexagonal [13–15]. In [13], single-mode microlaser emission has been observed in a dye-doped zeolite cylindrical microcavity, where organic dye molecules are doped into zeolite host and pumped by a 532 nm Nd:YAG laser. In [14], visible emission from nanosized ZnO nanoneedles

has been directly observed using a spatially resolved cathodoluminescence. In [15], WGMs can be discovered inside a highly hexagonal three-dimensional (3D) symmetry of SBA-1 mesoporous silica. These experiments open the door to cavity QED research with hexagonal-cross-section microcylinders. However, to effectively excite WGMs in such a microcylinder, near-field couplers should be used for both input coupling and output coupling. In the present paper, we report an experiment, that determinately demonstrates the feasibility of a fiber-taper-coupled zeolite microcavity.

## 2. Experimental Measurement of a Taper-Coupled Zeolite Microcavity

The zeolite microcavities were  $\text{AlPO}_4\text{-5}$  crystals synthesized in a chemical way [16,17] that have natural hexagonal boundaries. Through examination under a microscope, we can pick out some smooth-boundary zeolite crystal cylinders with the size of tens of micrometers. Then the zeolite cylinders with good surface quality were manipulated and moved on a glass plate. To avoid the influence of the glass plate, which may decrease the quality factors of the WGMs in the microcylinder cavity, we carefully positioned the zeolite on the edge of the plates, and then injected a small amount of glue around the zeolites to fix them

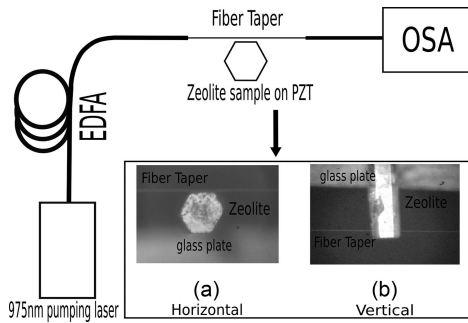


Fig. 1. Experimental setup of our taper-coupled zeolite microcavity. EDFA is the erbium-doped fiber amplifier used as a broadband light source in the experiment. OSA is the optical spectrum analyzer with resolution set to 0.2 nm. Insets (a) and (b) are pictures taken with monitoring CCD cameras horizontally and vertically, respectively.

together. As a result, the cylinder was hung in the air, so that the glass plate would not influence the zeolite taper-coupling system (see the inset in Fig. 1). To effectively couple the microcylinders in our experiment, fiber taper was pulled from a single-mode fiber by heating it with a hydrogen flame [18]. The final waist diameter was less than  $1\text{ }\mu\text{m}$  with the loss of less than 0.3 dB at 1550 nm wavelength. Our measuring setup is similar to [18], as shown in Fig. 1. The sample was placed onto a 3D piezoelectric transition (PZT) stage with a positioning precision of 20 nm, so that the gap between the fiber taper and the zeolite microcavity could be precisely adjusted. The whole experimental process was monitored by two CCD cameras horizontally and vertically. Here a broadband light source with a smooth spectrum from 1.53 to  $1.56\text{ }\mu\text{m}$  was adopted instead of a tunable laser source in other experiments [18–20], which is an erbium-doped fiber amplifier (EDFA) light source driven by a 975 nm diode laser with the output power of 300 mW. The highest power output after the fiber taper is approximately  $-27\text{ dBm}$ . All the preceding data were gathered by the optical spectrum analyzer (OSA) with a resolution set to 0.2 nm. The glass plate can be rotated so that the coupling position can

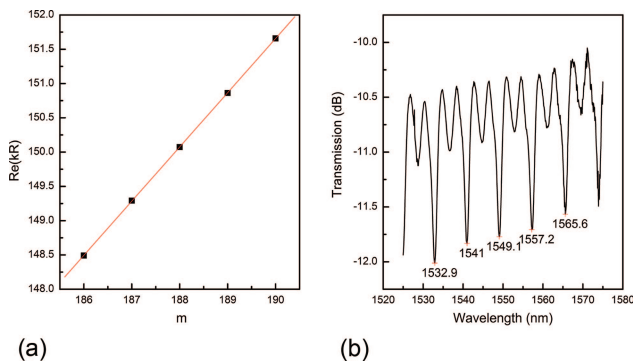


Fig. 2. (Color online) (a) Linear fitting of the resonant  $\text{Re}(kR)$  versus mode number with  $\text{Re}(kR) = \nu(m + m_0)$ . Here  $\nu = 0.795$ ,  $m_0 = 1.855$ . (b) Transmission spectrum. The dips representing WG modes are marked on it.  $Q \approx 775$ ,  $R = 37\text{ }\mu\text{m}$ .

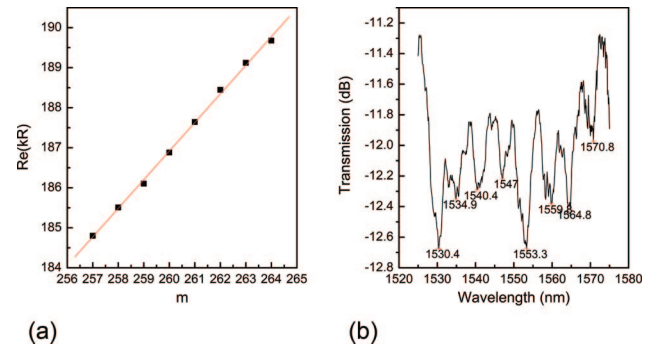


Fig. 3. (Color online) (a) Linear fitting of the resonant  $\text{Re}(kR)$  versus mode number with  $\text{Re}(kR) = \nu(m + m_0)$ . Here  $\nu = 0.714$ ,  $m_0 = 1.639$ . (b) Transmission spectrum. The dips representing WG modes are marked on it.  $Q \approx 450$ ,  $R = 46\text{ }\mu\text{m}$ .

be chosen in our experimental setup. In practice, we found that a coupling taper at the facet of the zeolite cylinder was much more efficient than at the corner, because the coupling region is obviously larger at the facet from the electromagnetic field distribution of the hexagonal cavity calculated in [21]. Therefore in this paper the taper was designedly chosen to be coupled at the facet of the zeolite. The fiber transmission spectrum was recorded by the OSA. The normalized transmission spectrum can be numerically achieved by subtracting the background signal when the fiber is not coupled with the zeolite, which is shown in Figs. 2 and 3.

### 3. Theoretical Analysis

The modes in the hexagonal microcavity have been studied with the plane wave expansion method [22], which can give a geometric optical explanation. Later a more accurate numerical simulation based on the boundary element method (BEM) [23] has been developed. The geometric optical method is proved to be an approximation of BEM theory when mode number  $m$  is large ( $\text{Re}(kR) \rightarrow \infty$ ) after introducing emission mechanisms [21]. Theoretically, by defining a complex dimensionless wavenumber  $kR_{\text{mode}} \approx kR - i\Gamma/2$  ( $k$  is the free-space wavenumber of the mode,  $R$  is cavity side length,  $\Gamma$  is the width of the mode. Subscript “mode” is omitted in what follows), it is proved that the real part of  $kR$ , i.e., the mode frequency, is linear with the mode number,

$$\text{Re}(kR) = \nu(m + m_0), \quad (1)$$

where  $m$  represents the mode number, while  $\nu$  and  $m_0$  are constants that are related to the material index. In geometric optical approximation  $\nu = 2\pi/3\sqrt{3}n$ . Dissipation mechanisms can be divided into two parts: boundary-wave leakage and psudeointegerable leakage. By considering these two dissipations as the origination of the imaginary part of  $kR$ , it is proved  $\text{Im}(kR)$  is related to the refractive index  $n$ :

$$\text{Re}(kR)\text{Im}(kR) = f(n). \quad (2)$$

Here  $f(n) = f_{bw}(n) + f_p(n)$  with  $f_{bw}$  and  $f_p(n)$  representing the two dissipations, respectively. To date, there are two experimental results that can support the theory. In the zeolite laser experiment [13], the  $Q$  factor is calculated from the linewidth of the laser emission of the doped zeolite, which is an indirect measurement of zeolite cylinder microcavity. However, since the laser is single mode, this experiment is not capable of exhibiting more information about this type of microcavity, such as the distributions of WGMs in zeolite. The other experimental verification is carried out in a ZnO nanosized hexagonal cavity [14]. By selecting the position of the exciting point on the nanoneedle, the size of the hexagonal cavity is changed, so that the peaks of the cathode luminescent (CL) spectra are shifted. Eventually the resonant  $\text{Re}(kR)$  is obtained and analyzed with the theory [24], which is also an indirect measurement of WGMs distribution. Our experimental results of transmission spectrums (Figs. 2 and 3) can give us a direct illustration of WGMs in a zeolite microcavity. As there are multiple modes in one transmission spectrum, it is possible to fit these dips with theory.

In this paper, since large size zeolite samples are chosen and  $\text{Re}(kR) > 150$ , the geometric optical method is adopted in the following discussion. In the theory above, for zeolite with refraction index  $n = 1.466$ , constants are  $\nu \approx 0.8248$ ,  $m_0 \approx 1.562$ . In our experiment, for the sample with  $R = 37 \mu\text{m}$  in Fig. 2(b), the free spectrum in the experiment is  $\Delta\lambda = 8.5 \text{ nm}$ , which is agreed with the theory  $\Delta\lambda = \nu\lambda_0^2/2\pi R \approx 8.1 \text{ nm}$ . From FWHM of the dips, the  $Q$  factor is estimated to be 775 for this sample. All the resonant wavelengths in Fig. 2(b) are fitted with Eq. (1) as shown in Fig. 2(a), which gives us values of  $\nu = 0.795$ ,  $m_0 = 1.855$  very close to the theoretical ones. Figure 3(b) is the transmission spectrum for another sample with size  $R = 46 \mu\text{m}$ . The free spectrum range is also satisfied with the theoretical prediction. The  $Q$  factor of this zeolite is 450.  $\text{Re}(kR)$  in resonance is linearly fitted with mode number  $m$  in Fig. 3(a) and  $\nu = 0.714$ ,  $m_0 = 1.639$ . The small variances from theory in  $\nu$  for both samples might be originated from the deviation of the shape from a perfect hexagonal resonator for our samples and inaccuracy in measuring  $R$ 's.

The measured  $Q$  factors in this experiment did not reach the prediction of Eq. (2). This might have resulted from the same effects that affect the  $Q$  factor in the microsphere and other microcavities [1]. Besides the radiation loss (which is dependent on the size of the cross section), dissipation in this type of microcylinder also includes surface scattering, material absorption, contamination, and especially water absorption induced by the glue for preparing the samples. In addition, the cross sections are usually deformed; such deformation on the boundaries may cause violation of the total internal reflection condition. Coupling with fiber taper may also introduce extra loss to zeolite cavities.

We focus on the long-lived modes in zeolite cavity in all our discussions. However in practice there are likely to be many families or resonances with different mode distribution, e.g., the triangular modes mentioned in [21]. The  $Q$  factors of those modes are usually very low, whose FWHMs are far beyond the linewidth of our EDFA source. So in our experiment, they are observed to be overlapped with each other and cause a total decrease of light intensity in the transmission spectrum.

#### 4. Conclusion

In the present experiment, WGM distributions in zeolite microcavities have been measured with a fiber taper, which are consistent with the prediction of geometric optical theory. This experiment is a direct exhibition of the WGMs in cylindrical microcavities. From the transmission dips, the loaded  $Q$  factors can be as high as 800. The quality factors are predominantly affected by the surface diffraction, contamination, and absorption of water introduced when preparing the sample. Fiber taper coupling could be a powerful technique for implementing microlasers in zeolite microcavities.

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