The International Society for Optical Engineering

SPIE Newsroom

10.1117/2.120071.0585

Whispering-gallery modes in photonic tubes

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A new method has been developed to fabricate microtube resonators with strong whispering-gallery-mode emission and quality factors up to 3000.

Microcavity structures are designed to enhance the interaction of light with matter. Wavelength-scale structures that confine light can be used to make highly efficient micro-lasers and sensors. Planar, spherical, and cylindrical geometries have all been developed to make efficient micro-resonators.

Among these devices, the microcylindrical or microcapillary dielectric resonators have generated significant interest due to their small size and material compatibility with telecommunication optical fibers.[1] The cylindrical cavity format is also compatible with a large variety of sensing modalities such as immunoassaying and molecular diagnostic assaying. Recent efforts to develop efficient micro-tube emitters focused on optical modes that are concentrated at the surface of dielectric materials. The main physical phenomenon exploited for this development is grazing-incidence total internal reflection of light resulting in 'whispering-gallery' modes (WGMs). In these modes, light propagates in planes near the surface, with integer numbers of wavelengths along closed circumferential trajectories. The high degree of confinement of light in WGM results in a high resonance quality factor (Q).

Experimentally, the most widely-studied configuration of thin-wall microtube cavities is the microcapillary filled with a highly luminescent dye solution. Both diameter (typically 50-200μm) and wall thickness can be controlled by the etching of commercially-available glass samples in an HF-water solution.[2] However, the short-distance evanescent field in these microcavities and the limited photostability of dye molecules are retarding factors for potential applications.

In the small-size regime (with diameters less than 10μm), semiconductor microdisks of finite height—micropillars—have been widely used as a tool to control spontaneous emission and confine photons in three dimensions. The evanescent field in these photonic structures extends a few micrometers into the surroundings, thus allowing efficient coupling to an external photonic device. However, fabrication of small high-Q cylindrical semiconductor microcavities involves complex and expensive processes.[3]

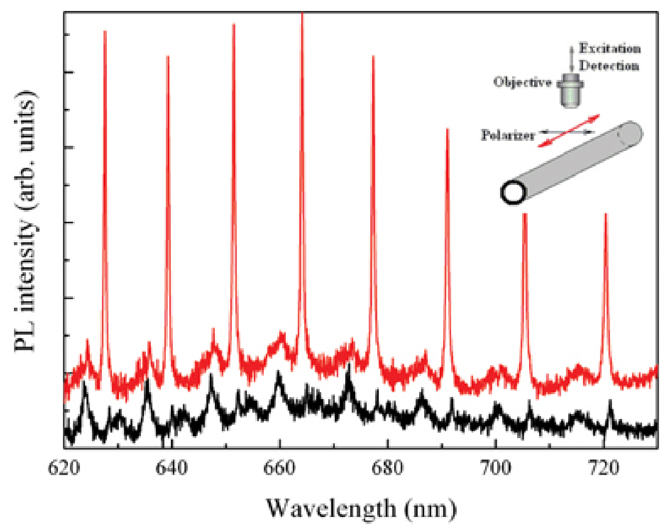

Figure 1. Room-temperature photoluminescence spectra of a single free-standing microtube recorded with polarizer orientation parallel to the microtube axis (red trace) and with polarizer rotated by 90° (black trace).

We have recently developed a simple method for fabricating highly luminescent small aluminosilicate microtubes of $\sim 7-8\mu$m diameter using sol-gel processing and a micro-channel glass membrane as a template.[4] The microtube resonators for our photonic experiments were fabricated by vacuum-assisted wetting and filtration of alumosilicate gel through a micro-channel glass matrix.

When separated from the matrix, this type of microtube is much more optically dense than its surrounding medium. Light propagating inside can therefore be spatially constrained to

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travel along the rim of its cross-section, thus becoming trapped in a WGM. The presence of sharp emission peaks in the microtube spectrum (see Figure 1) is a clear signature of this optical confinement. These peaks correspond to optical resonance locations and reflect the fact that transition probabilities are increased for emission wavelengths near resonance. Fabricated microcavities can support optical WGM at Q = 3200 which is the highest Q-factor achieved to date in the spectra of microcylinders or micro-tubes of comparable diameters. (Figure 2 shows the fluorescence lifetime of a microtube made using our technique.)

The most striking feature of the observed spectra is the strong polarization properties. Experimentally, the distinction between modes of different polarization can be determined using a polarizer inserted into the optical beam path in front of the detection system, which selects only the component of the electromagnetic field parallel to the orientation of the polarizer. The sharp peaks dominating the spectrum for a polarizer orientation parallel to the microtube axis correspond to linear polarized light with the electric vector vibrating parallel to the axis of the cylinder. Rotating the polarizer by 90° strongly quenches these WGMs, indicative of their transverse magnetic character.

It is well known that the resonant internal field of a microcavity is not completely confined to the interior of the microresonator. It was recently recognized that the partial delocalization of the resonance states is of great importance, because it implies the possibility of coherent coupling between WGMs of two adjacent microcavities with closely matched sizes.[5,6] In the case of microtube cavities, the evanescent field can be probed by analysing the integrated photoluminescence (PL) efficiency while scanning the excitation beam position in a direction perpendicular to the microtube axis. Our recent experiments show that the distance through which the evanescent field acts can be as long as 10μm away from the microtube axis.

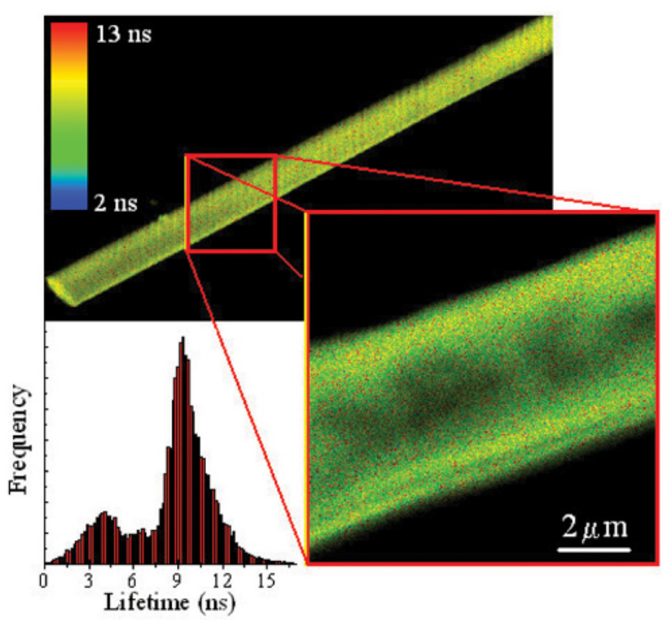

Figure 2. Fluorescence lifetime image of a single aluminosilicate microtube and corresponding lifetime histogram. The image was collected using a Microtime200 time-resolved confocal-microscopy setup. Every pixel in the lifetime image gives the lifetime at that particular position in space.

As a result of their high Q-factor and very narrow WGM peaks along with the cylindrical geometry considered useful for optical pumping, microtube cavities now represent very promising systems for the design of an optically pumped microlaser emitting at room temperature with significant potential for photonic applications. In addition, the potential to couple photonic structures through their evanescent fields opens the possibility of developing highly efficient and controllable emitters down to the single photon level.

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