Chapter 7
Light Confinement in Microtubes

Tobias Kipp, Christian Strelow, and Detlef Heitmann

Abstract We review recent developments in the field of light confinement in semiconductor microtube resonators fabricated by utilizing the self-rolling mechanism of strained bilayers. We discuss resonant optical modes in the framework of a waveguide model that naturally explains the occurrence of two-dimensional ring modes by constructive interference of light azimuthally guided by the tube wall. Experiments show that diverse geometries of a microtube have strong impact on the emission properties, including preferential and directional emission, as well as on a three-dimensional light confinement. We show that by lithographically structuring the microtube, it is possible to reach a three-dimensional confinement in a fully controlled way. The evolving confined modes can be described by an intuitive model using an expanded waveguide approach together with an adiabatic separation of the circulating and the axial light propagation.

7.1 Introduction

Semiconductor microcavities are optical devices in which light is spatially confined on a scale of its wavelength. These cavities gained considerable interest in the last years because, on the one hand, they offer the possibility to study fundamental interaction effects between light and matter, and on the other hand, they might be applicable in new and superior optoelectronic devices [1]. Pioneering works, for example, demonstrated the Purcell effect, i.e., the modification of the spontaneous emission rate, of quantum dot (QD) emitters embedded in microcavities [2,3]. Later, it was shown that one can even reach the strong coupling regime between QDs and cavity modes, proven by the so-called vacuum Rabi splitting [4–6]. Prerequisites for such experiments are high quality factors and low mode volumes inside the microcavities. Concerning possible applications, microcavities might lead to superior lasers with low or even no threshold [7–9] or to single-photon sources applicable in quantum cryptography [10,11]. Furthermore, their use in possible quantum computers are discussed [12].
Three different kinds of semiconductor microcavities have been intensively investigated: (1) Micropillars, (2) two-dimensional photonic-crystal microcavities, and (3) microdisks. Micropillars result from lateral structuring of vertically arranged Bragg reflectors. The periodic modulation of the refractive index inside the Bragg mirrors leads to a strong light confinement between the mirrors in vertical direction. In lateral direction, the confinement is caused by the large difference in refractive index between semiconductor material and air. In two-dimensional photonic-crystal microcavities, the periodic modulation of the refractive index of a thin semiconductor membrane leads to a strong lateral light confinement, whereas the vertical confinement is caused again by the difference in refractive index between semiconductor and air. Microdisks consist of circular semiconductor slabs centered on a thin semiconductor post. Here, light confinement is caused by internal total reflection at the border of the disk.

Optical microtube resonators form a new class of microcavities, firstly demonstrated in the year 2006 [13]. The basis for their fabrication is the self-rolling mechanism of strained layer systems lifted-off from their substrate [14, 15] together with its full lithographic control [16]. For further reading, this book’s chapter by Peters, Mendach, and Hansen, especially the section “The Basic Principle Behind ‘Rolled-Up Nanotech,’” is recommended. This basis is used to fabricate self-supported microtube bridges in which optical emitters like QDs serve as internal emitters. Typical dimensions of these microtubes are 5 μm for diameter, 100–200 nm for the wall thickness, and 10–50 μm for the length. The tubes’ walls serve as waveguides for the luminescence light of the internal emitters. The azimuthally guided light interferes after a round trip along the circumference of the tube, which leads to optical modes for constructive interference. Microtubes resonators exhibit the striking features of a nearly perfect overlap between embedded emitters and the intensity maximum of the optical modes as well as low surface scattering rates. The strong evanescent fields of the optical eigenmodes should enable a good coupling to optical networks by waveguides or to emitters brought in the vicinity of the thin walls.

In the last years, optical microtube resonators have been extensively studied [13, 17–27]. These studies deal with different material systems – based on, e.g., InGaAlAs [13, 17, 19, 20, 22, 23, 27] or Si [18, 24–26] – different emitters – like QDs [13, 17, 20, 21, 23] or quantum wells (QWs) [19, 22] – and different possible applications, e.g., as lab-on-chip refractometers [24].

The main topics of our work on microtube resonators so far [13, 19–22] were the demonstration, understanding, modeling, and exact tailoring of three-dimensionally confined optical modes in microtube resonators. The ringlike, cross-sectional shape of a microtube of course has the strongest impact on the optical modes since it ensures confinement of light in azimuthal direction. However, in order to achieve a real three-dimensional confinement of light, confinement mechanisms along the axis of the microtube are of great importance. In this review, we want to carry together selected results concerning the three-dimensional light confinement in microtubes. Our experimental results were obtained on systems based on InGaAlAs microtubes, but they are not restricted to this material system.