Rolled-Up Vertical Microcavities
Studied by Evanescent Wave Coupling
and Photoluminescence Spectroscopy

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Abstract

Vertically rolled-up microcavities are fabricated using differentially strained nanomembranes by employing rate and temperature gradients during electron beam evaporation of SiO$_2$. The geometry of the rolled-up tubes is defined by a photo-lithographically patterned polymer sacrificial layer beneath the SiO$_2$ layers that is dissolved to start the rolling. Rolled-up tubes support resonances formed by constructive interference of light propagating along the circumference. Optical studies are performed in the visible spectral range using a micro-photoluminescence (µPL) setup to excite and detect optical modes. Record high quality factors (Q factors) of 5400 for rolled-up resonators probed in PL-emission mode are found and their limits are theoretically investigated. Axial modes can also be supported when an increased winding number in the center is realized by appropriate pattern designs. In addition, higher order radial modes can be confined when atomic layer deposition (ALD) coatings are applied. Both types of modes are identified using polarization and spatially resolved µPL maps.

Evanescent-wave coupling by tapered fibers and tubes on substrates is the second method used to study light confinement and to demonstrate frequency filtering in ALD coated rolled-up microcavities. Scans are performed by monitoring light from a tunable laser in the range of 1520–1570 nm after transmission through the tapered fiber. Dips in the spectrum are found and attributed to fundamental and axial resonant modes. Moreover, by coupling two tapered fibers to a lifted rolled-up microcavity, a four-port add-drop filter is demonstrated as a future component for vertical resonant light transfer in on-chip optical networks.

Simulations show that the subwavelength tube wall thickness limits the Q factor at infrared wavelengths and ALD coatings are necessary to enhance the light confinement. After coating, two linear polarization states are found in experiment and fundamental and axial modes can be selectively excited by coupling the fiber to different positions along the tube axis. Spatially and polarization resolved transmission maps reveal a polarization dependent axial mode distribution which is verified theoretically.

The results of this thesis are important for lab-on-chip applications where rolled-up microcavities are employed as high resolution optofluidic sensors as well as for future uses as waveguide coupled components in three-dimensional multi-level optical data processing units to provide resonant interlayer signal transfer.


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Introduction and motivation

The idea to understand and control light and its properties has always fascinated mankind and motivated numerous experiments to study methods of generation, confinement and guidance of light and corresponding applications. Consequently, the description of the laser by Nobel Prize winners Schawlow and Townes [1, 2] motivated huge efforts to create such a device that was eventually realized by Maiman [3]. Not much later, the birth of the optical fiber was triggered by a seminal paper from Kao [4] who later was also awarded by the Nobel committee [5].

In the past decades, largely scaled-down optical systems have become a new focus of research where signals are guided via micro- and nanoscale waveguides and processed by similar scaled active and passive optical devices. Such on-chip photonic systems help to meet the increasing demands of long distance data transmission and might gradually replace electrical interconnects in short distance data center communication that suffer from increasing energy consumption and scaling difficulties. Eventually, optical interconnects might even enter the field of inter- and intrachip communication in desktop computing [6–8]. To this end, microresonators are studied as important building blocks of on-chip optical networks where they serve as modulators, switches or filters for optical signals [9, 10]. However, microresonators are versatile tools that are also used to investigate nonlinear effects or light matter interactions or to be exploited as optical sensors [11–13].

Out of a huge variety of available microresonators, the rolled-up microcavity was selected for a detailed study because it can, in principle, combine many features of state-of-the-art microresonators. These features include flexible, scalable, and integratable fabrication methods, a rich selection of materials and a three dimensional tubular geometry that provides a customizable out of plane light confinement. This framework is promising to promote rolled-up microcavities for on-chip photonic applications as well as microfluidic sensing [14], especially when silicon microfabrication compatible- or non-toxic materials are used, respectively. The out of plane light confinement could
1 Introduction and motivation

particularly prove useful in future stacked photonic layers [15] that require interlayer vertical light transfer. To analyze the potential of rolled-up microcavities in detail, experimental methods including micro-photoluminescence (µPL) spectroscopy and tapered fiber based evanescent-wave coupling are used.

This thesis is structured in six chapters. The following second chapter provides a more detailed introduction into the field of microresonators with a focus on rolled-up resonators. Basic equations and the current state-of-the-art are summarized. Chapter three describes the fabrication of rolled-up microcavities using photolithography and electron beam deposition as fabrication methods. Particularly, the roll-up of silicon dioxide (SiO$_2$) layers is described that avoids the prior use of the silicon monoxide/silicon dioxide (SiO$_x$/SiO$_2$) bilayer system that suffered from absorption of SiO$_x$. Following, the experimental methods needed for characterization of the samples are described.

The main results of this thesis are presented in chapters four and five. µPL studies in chapter four reveal record high optical quality factors ($Q$ factor) in rolled-up microcavities probed in emission. Investigations of the experimental limits of the $Q$ factor follow, where interlayer voids are found to be the major limit. Additionally, the effects of atomic layer deposition coatings are analyzed by spatially and polarization resolved µPL emission maps where the evolution of initially unsupported modes is observed and verified.

In chapter five, on-chip rolled-up microcavities interfaced with tapered fibers are introduced. The setup developed to fabricate and couple tapered fibers to rolled-up tubes is described first. It is then used to show that low refractive index tubes can also support resonances at the telecommunication wavelength range at around 1545 nm. At these wavelengths the tube wall thickness becomes the limiting factor for the $Q$ factor which is confirmed by simulations. Tapered fibers are furthermore used to generate spatially and polarization resolved maps of the bottle-shaped potential well in tube resonators with axial confinement. To demonstrate the usefulness of the three dimensional resonator geometry for on-chip photonic applications, a proof-of-concept experiment is demonstrated by interfacing a rolled-up microcavity with two tapered fibers in a vertical configuration and a resonant transfer of signals between both fibers via the sandwiched tube is shown. The last chapter summarizes the results presented in this thesis and gives an outlook to potential future developments.
2 State of the art and theoretical background

Most of today’s scientific work is based on a long history of scientific discoveries and corresponding theoretical explanations. To correctly position the results of this thesis in the state-of-the-art of scientific knowledge, the following sections will describe important findings from previous research that paved the way to the experiments of this work. First, a general introduction to microresonators and their theoretical background is given including a section on evanescent coupling to excite resonances and then the main object of interest of this thesis, the rolled-up resonator, is introduced.

2.1 Optical microresonators

Optical resonators are devices to trap or confine light by guiding it along (usually) closed trajectories which can lead to highly enhanced light intensities within the resonator due to constructive interference [16]. Non-resonant light is not confined so that resonators are frequency selective components. Resonant enhancement and filtering belong to the most important features of laser systems and consequently the success of lasers used for optical data transmission or CD/DVD storage is closely related to the development of miniaturized resonators or microcavities [17]. But also in applications beyond laser systems, microcavities proved useful to explore, for example, new regimes of electromagnetic coupling of atoms or quantum dots to strongly localized and intense light fields in cavity quantum electrodynamics (cQED) [12]. In addition, the ability of resonators to filter selected frequencies is highly interesting for signaling applications, especially when the filter is tunable. Such filters can also be used to modulate light by tuning them in and out of resonance and belong to the basic building blocks of on-chip photonic data processing networks [8].
2 State of the art and theoretical background

The variety of microcavities has increased significantly over the last years to cover different geometries, fabrication techniques, materials and applications. Common microcavities include, for example, simple silica microsphere resonators that can reach ultra-high quality factors for precise sensing applications [18], tunable fiber bottle resonators [19], liquid core capillaries for refractive index sensing [20], waveguide ring resonators, microtoroids or even photonic crystal cavities [17]. Most of these resonator configurations can be used in a passive mode where resonances need to be excited externally or in an active emission mode, where emitters like quantum dots, nanocrystals or defects are embedded and activated by exploiting their photoluminescence (PL) to excite resonances. Active mode resonators have the advantage of a comparatively simple excitation scheme and allow studies on the interaction of the embedded emitters with resonant modes. On the other hand passive mode resonators are favorable for signaling applications which should not be influenced by embedded emitters, which could spoil the resonator’s quality factor ($Q$ factor) due to their absorption. More detailed comparisons of different microcavity types and applications can be found in numerous articles such as the well-known review of Vahala [17] or also Vollmer and Yang [13].

2.1.1 Resonator theory

![Figure 2.1: Schematic drawing of a Fabry-Pérot resonator with a length $d$ and confined wave with wavelength $\lambda$.](image)

In this section, the most important equations for resonators are given that are needed later in this thesis. A more extensive description can be found for example in the textbook *Fundamentals of Photonics* [21] which was also used as a source for the following description.

Probably the simplest design to create a resonator and to derive the basic equations is the *Fabry-Pérot resonator* which consists of two plane mirrors at a distance $d$ that reflect light with a wavelength of $\lambda$ to form a standing wave between the two mirrors as shown...
in Fig. 2.1. At least one of the mirrors should be partly transmissive so that light can be coupled in and out. For perfect mirrors, the transverse components of the electric field vanish at the mirror surfaces which imposes boundary conditions on the solutions of the Helmholtz equation so that only distinct wavelengths $\lambda_m$ can be confined that fulfill the basic resonator relation
\[ m \frac{\lambda_m}{2} = nd, \quad m = 1, 2, 3, \ldots, \]  
with $m$ being the mode number (in the case of Fig. 2.1 $m = 3$), $n$ the refractive index and $d$ the length of the resonator as defined in Fig. 2.1. It follows that resonant modes are separated by the free spectral range $\Delta \lambda$ approximately given by (neglecting dispersion):
\[ \Delta \lambda = \lambda_m - \lambda_{m+1} = \frac{\lambda_m^2}{2nd + \lambda_m} = \frac{\lambda_m}{m + 1}, \]
while in frequency representation resonant modes $\nu_m$ are separated by a constant difference $\Delta \nu$ with
\[ \nu_m = m \frac{c}{2nd} \quad \text{and} \quad \Delta \nu = \frac{c}{2nd}. \]

One can also derive these equations by assuming a traveling wave in a resonator that reproduces itself after one round trip which is a more intuitive approach especially when ring resonators are considered. In this case the round trip length $2d$ from the example above needs to be replaced by the appropriate value for the given geometry and additional phase shifts from mirrors (if present) need to be considered. One important example is a circular waveguide ring resonator with a diameter $D$ that guides light using total internal reflection which results in modes following
\[ m \lambda_m = n \pi D. \]

However, for such a resonator type the equation is an approximation and only valid when the curvature of the resonator can be neglected along one wavelength cycle which is true for large mode numbers $m$. When this condition is fulfilled, the light trajectory basically follows the boundary of the resonator to form whispering-gallery modes [21]. When the dimensions of the resonator are close to the wavelength of light, which is often the case for microcavities, the refractive index has to be replaced by an effective index to include the effect of transversal confinement and differently confined polarization states.
The effective refractive index can be determined from the solutions of the Helmholtz equation with appropriate boundary conditions.

**Spectral width of resonances: quality factor and finesse**

In realistic resonators, perfect mirrors are not available or partially reflecting mirrors are deliberately used to achieve efficient coupling of light into the resonator. Even in resonators based on total internal reflection such as microspheres for example, losses occur due to absorption and scattering. These losses lead to a relaxation of the frequency selectivity, and resonances possess a certain spectral width in contrast to the infinitely narrow modes that would follow from the simple theory above.

The width of the resonances, or more generally the ability of a resonator to confine light, is described by the $Q$ factor. It is defined as [21]

$$Q = \frac{\text{stored energy}}{\text{energy loss per cycle}}, \quad (2.5)$$

where *cycle* describes not one resonator round trip but one period of the electromagnetic field. For large values of $Q$ an experimentally accessible definition can be derived. In this case it is assumed that all losses are combined in a general resonator loss coefficient $\alpha$ and the loss rate per unit time is given by $c \alpha$ or equivalently, the loss rate per cycle is given by $c \alpha / \nu_m$. With Eq. (2.5) it follows that

$$Q \approx \frac{2\pi}{c \alpha / \nu_m} = 2\pi \nu_m \tau_p, \quad (2.6)$$
where $\tau_p = 1/c\alpha$ is the photon lifetime within the resonator.

For measurements in the frequency/wavelength domain it is more convenient to use the equivalent definition of the $Q$ factor

$$Q \approx \frac{\nu_m}{\delta \nu} = \frac{\lambda_m}{\delta \lambda},$$

(2.7)

where $\delta \nu$ and $\delta \lambda$ are the width of the resonance in units of frequency and wavelength, respectively. This definition is also shown in Fig. 2.2. A high $Q$ factor is consequently related to low losses and narrow resonances or according to Eq. (2.6) to a long photon lifetime which can be seen as the result of a time frequency uncertainty relation when (2.6) and (2.7) are combined resulting in $\delta \nu \cdot \tau_p = 1/2\pi$.

High $Q$ factor resonators are required in many applications including sensors and frequency filters. This follows because small shifts of resonances can only be detected when the mode peaks are sufficiently narrow. Consequently, the resolution of resonator based sensors is related to the $Q$ factor. Likewise, frequency filters achieve a higher selectivity when the resonator has narrow modes or a high $Q$ factor.

Common values for the $Q$ factor can reach $10^{11}$ in crystalline CaF$_2$ cavities [22], $3.6 \times 10^8$ in fiber bottle resonators [19] or $1.5 \times 10^5$ [23] and $5 \times 10^3$ [24] in rolled-up resonators probed in transmission or with $\mu$PL, respectively.

Another commonly used parameter to describe the quality of a resonator is the *finesse* $\mathcal{F}$ which is approximately given by the free spectral range divided by the width of a mode

$$\mathcal{F} \approx \frac{\Delta \lambda}{\delta \lambda},$$

(2.8)

and is related to the $Q$ factor via

$$Q = \frac{\lambda_m}{\Delta \lambda} \mathcal{F}.$$  

(2.9)

While in this thesis only the $Q$ factor is used to describe the fabricated microcavities, the finesse can be more suitable for some applications like enhancement resonators which is nicely compared and described by Savchenkov et al. [22].
2 State of the art and theoretical background

2.1.2 Evanescent coupling

Commonly, resonators with a high $Q$ factor are desired for efficient confinement where light cannot easily escape. As a consequence, it can be difficult to initially inject light into such structures. For example, the Fabry-Pérot resonator mentioned above requires a mirror with deliberately reduced reflection so that light can be injected via this mirror but at the same time this degrades the optical confinement and the $Q$ factor. Another approach is to directly embed light emitters into the cavity such as quantum dots or defects, both emitting PL when excited externally which in turn excites resonances in the resonator (see Sec. 3.2.1 and Chap. 4).

![Figure 2.3](image)

**Figure 2.3:** Coupling of light into a ring resonator by overlapping evanescent fields using (a) prism and (b) tapered fiber. Red line indicates light trajectory with indicated transversal intensity profile. (Not to scale.)

A largely different method relies on a tunneling-like effect where the evanescent field of the electromagnetic wave is exploited. When the light guiding structures become very small, as in microcavities, light is also guided outside the structure as an evanescent wave which can be used to couple a microcavity to an external light source that also features an evanescent field. Two common approaches for such light sources rely on prisms [25] or tapered fibers [26] where an evanescent field is created due to total internal reflection or due to an ultra-thin optical fiber in the micron range that is than coupled to the evanescent field of a resonant mode as shown in Fig. 2.3. For efficient evanescent coupling, the propagation constants of the exciting coupler and the resonator need to be matched and sufficient overlap of the two evanescent fields is required [27] as discussed in the following.

**Phase matching**

The experimental realization of phase matching for a resonant mode with refractive index $n_{eff}$ can be achieved in the prism configuration via the angle of the incident beam
2.1 Optical microresonators

Figure 2.4: Solid red solid line represents propagation constant $\beta$ of a tapered fiber dependent on its radius [Eq. (2.10)] while black circles show discrete values of $\beta$ for resonant modes of a rolled-up microcavity around 1550 nm for typical parameters of later used resonators [Eq. (2.11)]. (Recalculated by S. Li based on [26]).

arcsin($n_{eff}/n_{prism}$) [25] or in the tapered fiber configuration by the diameter $\rho$ of the taper [26]. Later in this thesis, fiber coupling is used and therefore appropriate parameters for this approach are presented in the following. For tapered fibers the propagation constant of the guided mode $\beta$ is given by [26]

$$\beta^2 = k^2 n^2 \left(\frac{2.405}{\rho}\right)^2,$$

where $k$ is the free-space propagation constant of the light, $n$ the refractive index (1.44), $\rho$ the radius, and 2.405 the cut-off parameter ($V$) of the fiber for single mode operation [21]. The propagation constant of a resonant mode $\lambda_m$ with mode index $m$ in a ring resonator with radius $r$ and effective refractive index $n_{eff}$ is approximately given by

$$\beta = n_{eff} \frac{2\pi}{\lambda_m}.$$

For a given resonator and wavelength range, the fiber diameter has to be selected so that both propagation constants match. For the calculations in Fig. 2.4 typical parameters for a rolled-up microcavity were used and resonant frequencies calculated by solving a numerical ring resonator model. It follows that for the given resonator radius range, the fiber radius should be just below 0.7 $\mu$m, which is within the possibilities of the fiber.
2 State of the art and theoretical background

drawing setup demonstrated later (note that the two radius axes can be shifted relatively).
As a convenient feature of tapered fibers, the radius can be easily adjusted by moving the
resonator along the taper profile.

**Coupling strength and modal overlap**

![Diagram of waveguide coupled to a ring resonator](image)

**Figure 2.5:** Waveguide coupled to a ring resonator. Electric fields are described by $E_i$, $g$ describes the coupling, $t$ the non-coupled fractions (coupling loss) and $a$ is the round trip attenuation factor.

In addition to the requirement of phase matching to excite modes in a resonator, the
efficiency of energy coupling also needs to be considered. It can be controlled by the
distance of fiber to resonator and depends on the resonator loss. Universal relations
independent on the specific resonator type have been derived by Yariv [28] and here a
similar but more intuitive description adapting [29, 30] is given.

Using the definitions from the schematic in Fig. 2.5, the electric fields are given by

\[ E_1 = i g E_0 + t E_3, \]
\[ E_2 = t E_0 + i g E_3, \]
\[ E_3 = a e^{i\theta} E_1, \]

where $g$ describes the fraction of the field coupled in and out of the ring and $t$ the fraction
that is not coupled from or to the ring ($g$ and $t$ have values between 0 and 1 and $t^2 + g^2 = 1$).
After one round trip the field acquires a phase $\theta = \frac{2\pi n D}{\lambda}$ for a ring with diameter $D$ and
refractive index $n$ and is attenuated by $a$ ($a = 1$ equals no resonator loss). By appropriate
substitution of Eqs. (2.12)–(2.14), the ratio of the output to the input field follows as

\[
\frac{E_2}{E_0} = \frac{t - ae^{i\theta}}{1 - ta e^{i\theta}},
\]

which translates to the normalized intensity transmission

\[
\left| \frac{E_2}{E_0} \right|^2 = \left| \frac{t - a e^{i\theta}}{1 - ta e^{i\theta}} \right|^2 = \frac{t^2 + a^2 - 2ta \cos \theta}{1 + t^2a^2 - 2ta \cos \theta}.
\]

On resonance \( \pi D n = m \lambda \) and \( \theta = m2\pi \) and Eq. (2.16) simplifies to

\[
\left| \frac{E_2}{E_0} \right|^2 = \frac{(t - a)^2}{(1 - ta)^2}.
\]

It follows from Eq. (2.17) that when \( a = t \), or when the attenuation in the ring equals the coupling loss, all power from the waveguide is coupled into the resonator. In this case the field coupled back from the ring into the waveguide \((gE_3)\) and the directly transmitted field through the waveguide \((tE_0)\) have the same amplitudes and interfere destructively [28].

**Figure 2.6:** Coupling regimes of waveguide to resonator coupling (diameter 17 \( \mu \)m, \( n = 1.45 \)). The selected attenuation factor is \( a = 0.98 \) in all three regimes.

Apart from this so called critical coupling, two additional regimes are possible as shown in Fig. 2.6. In the case of under coupling \((t > a)\) the directly transmitted light fraction is larger than the attenuation factor and the \( Q \) factor is mainly determined by the intrinsic resonator loss. In the second over coupling regime \((t < a)\) a large field fraction is coupled...
in and out of the resonator and light can escape to the waveguide before being lost due to resonator loss. Now, the coupling to the fiber behaves like an additional loss channel and the $Q$ factor is dominated by the coupling.

Both over- and under coupling regimes lead to a less efficient extinction of the overall transmitted power in the output waveguide compared to critical coupling because the fields $(gE_3)$ and $(tE_0)$ have different amplitudes.

Experimentally the coupling can be adjusted by varying the resonator loss, for example by an external probe [31] or by controlling the coupling coefficient $g$ for example by changing the gap between resonator and fiber or prism which determines the overlap of the evanescent fields [27].

2.2 The rolled-up resonator

Microcavities have proven to provide high $Q$ factors in small mode volumes [32, 19], outstanding optofluidic sensing abilities, and large-scale integrated fabrication on-chip [13]. However, few of the state-of-the-art microcavities are able to combine all of these features, especially when integrated fabrication is required. This challenge can, in principle, be solved by resonators based rolled-up nanotechnology which have already demonstrated their potential in many important milestone experiments as shown in this section. In the following, first a general introduction is given which is followed by the current state-of-the-art of rolled-up resonators.

2.2.1 Rolled-up nanotechnology

Rolled-up nanotechnology describes a comparatively young research field where strain is incorporated into nanomembranes to enable a self roll up into tubular structures [33, 34]. Such rolled-up tubes have found applications in a variety of fields ranging from magneto-electronics [35, 36] to photonics [37–40] and biophysics [41].

In early works, nanomembranes were fabricated by molecular beam epitaxy (MBE) and strain was incorporated by exploiting the crystal lattice mismatch between two different materials such as InGaAs and GaAs [42]. The lattice mismatch creates a differentially strained bilayer causing an up- or downwards rolling. The rolling of these nanomembranes is accomplished by stress relaxation after a MBE-grown sacrificial layer,
for example AlAs, is selectively etched as shown in Fig. 2.7. The rolling distance is controlled by the etching time of a lithographically defined sacrificial layer and the final diameter is set by the thicknesses of the nanomembranes [42, 43]. This method can also be adapted for amorphous layers but in this case the control of strain is more difficult because it depends on grain formation and deposition parameters [44] during preparation of the nanomembranes. However, for both material groups the tube diameter $D$ can be estimated when the in-plane biaxial strain between both layers $\varepsilon$ is known from the lattice mismatch or empirical studies. The diameter then follows a continuum mechanical model and is fully determined by the thicknesses $d_1, d_2$ and Poisson ratio $\mu$ of the respective nanomembranes while assuming approximately equal Young’s modules and Poisson ratios of both layers [45, 43].

$$D = \frac{1}{3\varepsilon(1+\mu)} \frac{(d_1 + d_2)^3}{d_1 d_2}. \quad (2.18)$$

A bilayer system is not necessarily required because it was already shown that also single Si films can be rolled into tubes due to a strain gradient in the Si nanomembranes [46]. A further milestone was the extension of the rolled-up technique to polymer sacrificial
layers and an even larger material selection [35] which enabled a fabrication compatible to standard silicon microfabrication methods. The roll-up using polymers and single materials films is also used in this thesis where tubes are made from SiO$_2$.

A large field that evolved out of these tubes are optical applications sometimes referred to as rolled-up photonics. Here, tubes serve as hosts for quantum wells or dots [37, 47] that are embedded into the tube walls and experience strain effects due to the roll up. Moreover, the embedded light sources quickly lead to the discovery of resonances in tubes that result from light traveling around their circumference [38, 39] which is presented in more detail in the following.

### 2.2.2 State of the art of rolled-up optical microcavities

First studies of resonant modes in rolled-up optical microcavities were reported by Kipp et al. [38] with $Q$ factors of up to 3200 for InGaAs/GaAs microtubes with embedded InAs quantum dots at cryogenic temperatures and by Songmuang et al. [39] for nontoxic SiO$_x$/Si microtubes at room temperature with Si nanoclusters or nanocrystals as light emitters formed by the SiO$_x$ layer. Not much later, a fabrication of tube resonators without sophisticated MBE techniques became possible due to a work of Mei et al. [35] who reported the roll up of a variety of nanomembrane materials including metals and oxides on polymer sacrificial layers.

Further improvements of rolled-up resonators were obtained by novel designs of their roll up patterns. For example, the U-shaped pattern Kipp et al. [38] is a beautiful demonstration how simple two-dimensional patterns can be rolled-up into sophisticated three-dimensional bridge-like tubes. The elevated central tube area avoids a contact of the resonator to the substrate to reduce optical losses. Axial light confinement was realized by adding a lobe to the U-shape pattern [48, 24] or by using circular shaped roll up patterns [49] both causing a locally increased (effective) refractive index due to additional windings in the central part of the tube. Figure 2.8 shows a schematic of a tube rolled from a U-shaped pattern featuring a lobe. This lobe creates an optical potential well comparable to the confinement in magnetic bottles [50] and can optically be detected as new set of spatially distributed modes along the tube axis. The U-shape pattern is described in more detail in Sec. 3.1.1.

Along with additional improvements to increase the optical quality factor as discussed later and investigations on resonance tuning by atomic layer deposition [51], ample
2.2 The rolled-up resonator

![Figure 2.8](image)

Figure 2.8: Rolled-up tube with lobe structure for additional windings to increase the effective refractive index of the subwavelength thick wall. The U-shaped pattern leads to a bridge-like structure avoiding optical losses [48].

Applications for rolled-up resonators were developed over the past years. Practical uses often rely on the subwavelength thick wall, one of the key features of these structures. It causes an extended evanescent field of the guided light which can be exploited for energy coupling from the outside while the field in the hollow core is used for sensing. A refractometric sensor based on the sensing ability has been demonstrated by Bernardi et al. [52] which triggered further works on optofluidic sensing [14] and even biosensing [53]. All these sensing applications are part of a larger lab-in-a-tube concept [54] where also non-optical applications of tubes are included.

Apart from sensing applications, rolled-up microcavities were also used in proof-of-principle experiments for on-chip photonic networks in transmission configurations. For example, InGaAs/GaAs tubes were manually transferred and coupled to waveguides [23, 55] and fibers [56] to serve as on-chip optical frequency filters or modulators. However, the strained nanomembrane growth was based on epitaxial methods which make an integrated fabrication of tubes on waveguides challenging. Such incompatibilities are much less prominent for SiO$_x$/SiO$_2$ based tube resonators so that they provide a promising system for a direct and scalable fabrication on on-chip waveguides without requiring a manual transfer. To demonstrate the potential of low refractive index single layer SiO$_2$ tubes for silicon photonics, results are presented in Chap. 5 where tubes are interfaced with optical fibers to serve as rolled-up add-drop filters. This vertical resonator device is promising for future multi-level optical data processing units where signals need to be transported and filtered between stacked photonic layers.
3 Methods of fabrication and characterization of rolled-up microcavities

Towards the detailed investigation of resonances and their applications in the cavities that are presented in later chapters, here the development and optimization of structural parameters and fabrication methods of rolled-up tubes based on the prior state-of-the-art are described. These optimizations first focused on the increase of the optical quality factor while keeping the existing compatibility with industry standard integrated silicon microfabrication methods, and were later focused on the development of a geometry suitable for on-chip waveguide coupling.

The chosen material system to fabricate rolled-up microcavities is based on non-toxic silicon monoxide and silicon dioxide (SiO$_x$ and SiO$_2$) which is in accordance with above mentioned industrial compatibility and does not require complex molecular beam epitaxial (MBE) methods. A fabrication method to roll up tubes using oxides on polymers was initially developed by Mei et al. [35] who investigated possibilities to create strain gradients by exploiting thermal expansion coefficients or suitable deposition parameters. However, the resonators fabricated using this approach did not provide a high optical quality factor ($Q$ factor) with sharp and narrow resonant peaks and therefore could not compete with high refractive index MBE grown semiconductor tube resonators. This limited the practical use of oxide resonators in experiments and applications.

Using the methods presented in this chapter it became possible to improve the $Q$ factor to a record value for actively emitting rolled-up resonators as described in Chap. 4 that is even higher than high refractive index semiconductor tubes. Only for tubes interfaced with waveguides higher values were reported [23] but not reproduced up to this day.

In the following, the required techniques to fabricate rolled-up microcavities with high
3 Methods of fabrication and characterization of rolled-up microcavities

$Q$ factors are shown, starting with the design of the resonator geometry by photolithography and followed by the methods and parameters used for thin-film deposition and subsequent roll up. Different approaches for the characterization of the resulting tubes are only briefly described here and more detailed explanations are given in Chap. 4 and 5.

3.1 Methods of fabrication

The preparation of rolled-up microcavities relies on standard optical lithography equipment and simple electron beam evaporation and the roll up into tubes is accomplished by a removal of the sacrificial layer using organic solvents. Optionally, atomic layer deposition can be included to the fabrication to enhance the structural integrity or the optical confinement. The details of all fabrication methods are described in the following.

3.1.1 Mask design for elevated cavities featuring axial confinement

A striking feature of rolled-up nanotechnology is the possibility to easily create sophisticated three-dimensional tubular structures out of planar lithographically patterned membranes. Except for the diameter and the direction of roll up which are set by the following nanomembrane deposition, almost all geometrical parameters including the length of the tube, the number of rotations along the axis and a partial lift up from the substrate can be defined by lithography. In some special cases even the direction of roll up can be set by the pattern geometry [57, 58].

An example how the pattern influences the tube geometry can be seen by comparing the effects of rectangular and circular patterns. The first shape leads to tubes with a constant number of rotations along the axis with a length defined by one edge of the rectangle. The second example, a circular or also an elliptical pattern, leads to a tube with a maximum winding number in the tube center and is then gradually decreasing in both directions of the axis. These very simple patterns can already cause interesting optical effects when the tube wall thickness is smaller than the wavelength of light because the effective refractive index is strongly influenced by the number of rotations in this case. In tubes rolled-up from circular patterns this effect has been exploited to create an optical potential well along the axis with a minimum in the center [48].

A partial lift-up from the substrate is favorable to reduce optical leakage of resonant modes to the substrate [49]. This lift-up is naturally present at the two ends of a tube.
when circular patterns are used because the tube is only attached to the substrate at its thicker middle part [60, 61]. To achieve a lift up of the optically interesting central tube part, U-shaped patterns were introduced by Strelow et al. [48] that can also include additional features such as a lobe structure for axial confinement. This geometry was adapted for this work because it allows a tuning of the lift-up height which is important for later waveguide coupling. Two versions of the designed U-shaped patterns are shown in Fig. 3.1 both including a central lobe to gradually increase the winding number for axial confinement. When such a pattern is rolled towards the open side of the “U” as indicated by the arrows, a bridge-like tube is created that is elevated in the central part due to the additional windings from the “legs” of the U-shape, as schematically shown in Fig. 3.2. The lift-up height is further determined by the sacrificial layer thickness of 2–3 µm that leads to vertical edges of the deposited thin film at the pattern boundaries. A fine tuning is possible by adding additional windings set by the rolling length which is limited by the two half circles that stabilize the tube in its final position.

In first experiments the design in Fig. 3.1(a) was used that features a tapered geometry

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**Figure 3.1:** Mask design used for lithography: (a) Initial version with tapered legs designed with S. Harazim [59] and (b) improved version for larger tube diameters and straight legs for simplified roll up.
3 Methods of fabrication and characterization of rolled-up microcavities

Figure 3.2: Rolled-up tube according to the pattern in Fig. 3.1(b). The distance to an embedded waveguide (red) can be tuned by the rolling length and the sacrificial layer thickness. Central axial confinement is exaggerated for visibility.

of the two legs or supporting structures to enhance the rolling process. It was however found that this idea did not lead to significant changes and was therefore dismissed to simplify the structure. The improved straight design (b) was developed as a successor that features a longer and wider rolling pattern for larger tube diameters. Furthermore, to simplify optical investigations of single tubes and allow interfacing by fibers as described in section 5.2.1 the pattern arrays were changed. The initial design (a) was aligned in an 18 × 18 array (including one alignment mark) optimized for big 10 × 10 mm² substrates with 323 patterns, while the design (b) used a widely spaced array of only 7 × 7 optimized for 5 × 5 mm² substrates. The wide spacing of tubes greatly simplified a pick-up of tubes by fibers as described in Sec. 5.2.1.

3.1.2 Photolithography

The pattern described in the previous section was written into a chromium mask to be used in a standard mask aligner located in a clean room environment. No special lithography equipment was needed because the minimum feature size of the patterns is comparatively large. Although the process is compatible with standard large scale fabrication, all samples were prepared manually to maintain a flexible fabrication process that is described in the following.

Substrate preparation

The demands on the substrate material are not very critical because only chemical stability concerning the photoresist and organic solvents used during preparation are necessary. Possible materials include for example Si wafers, cover slips or silicon-on-insulator (SOI) wafers with embedded on-chip optical waveguides. The latter was demonstrated in a
preliminary work of Smith [62] and proves that even rough substrates with additional structures can be used.

Substrates were made from 4 inch silicon wafers cut into squares of $11 \times 11 \text{ mm}^2$ or later also $5 \times 5 \text{ mm}^2$ because Si wafers were readily available and the small size was convenient to handle. To avoid a contamination during cutting, a protective resist coating was applied. Therefore, sample fabrication always started with a cleaning procedure to remove the resist. First, every substrate was cleaned with acetone in an ultrasonic bath and then rinsed with isopropanol and subsequently dried using a nitrogen flow. A final bake-out at $120 \, ^\circ \text{C}$ for 10 minutes on a hotplate was applied to remove residual water.

**Spin-coating and patterning of sacrificial layer**

The sacrificial layer as well as an adhesion promoter, were deposited by spin coating and dried by baking on a hotplate. The adhesion promoter was used to avoid a possible delamination of the photoresist from the substrate during development. Parameters for spin coating and baking were slightly varied during this work to adapt for different substrate dimensions or not optimal environmental conditions. On smaller square shaped substrates it becomes increasingly difficult to obtain uniform layers which was accounted for with higher spin speeds. Standard parameters for the adhesion promoter *TI-Prime* were spin-coating at a speed of 3500 rpm for $11 \times 11 \text{ mm}^2$ substrates and 6000 rpm for $5 \times 5 \text{ mm}^2$ substrates and hotplate baking for 120 s at $120 \, ^\circ \text{C}$. The positive photoresist *AR-P 3510* was spin coated at a speed of 3500–4500 rpm and dried on a hot plate at $90 \, ^\circ \text{C}$ for 120 s. The resist thickness range for the given spin speed range was 2.1–2.5 µm.

For lithography of the U-shaped patterns a mask aligner was used to expose the resist through a mask to UV light for 7 to 9 s. The exposed areas were subsequently removed by a 1:1 dilution of developer *AR 300-35* and deionized water. The development was stopped by rinsing the samples in pure deionized water and drying in a nitrogen flow. A schematic representation of the spin coated and patterned sample fabrication steps is shown in Fig. 3.3.
3 Methods of fabrication and characterization of rolled-up microcavities

![Figure 3.3](image)

**Figure 3.3:** First steps of sample preparation with top and side view, respectively: (a) spin-coated photoresist as sacrificial layer on a silicon wafer and (b) developed U-shaped patterns after lithography (not to scale, substrates usually contain more patterns).

### 3.1.3 Electron-beam evaporation

As demonstrated by Mei et al. [35], electron beam (e-beam) evaporation can be used to create differentially strained nanomembranes that roll up into microtubes. E-beam evaporation is a variant of physical vapor deposition where a material condenses on a sample after being heated up in a crucible by electron bombardment. The electrons stem from a heated filament (Edison effect) and are accelerated until they collide with the material filled into the crucible. To heat up a larger volume in the crucible a magnetic field is usually used to periodically change the position of the electron beam. This modulation and the intensity of the beam determine the deposition rate and the latter is regulated by the current flowing through the filament that serves as a cathode. The deposition in an e-beam evaporator is directional so that only surfaces in the line-of-sight of the crucible are coated. This is even true for samples facing the crucible at an angle, so that thick patterns create shadows as shown in Fig. 3.4. These openings in the thin film can be exploited to define the start of the roll up because the membrane can easily detach here during etching of the sacrificial layer.

In this work an e-beam evaporator was used at a vacuum pressure of approximately $5 \times 10^{-6}$ mBar. For the deposition of SiO$_2$, an oxygen background was added to increase the pressure to $1 \times 10^{-4}$ mBar while SiO$_x$ was deposited at vacuum pressure without oxygen. Two switch materials without opening the machine a water cooled crucible with four holders was available of which two were filled with 1–6 mm pieces of SiO$_2$ or SiO$_x$, respectively with a purity of 99.99%. Samples were placed at an angle of 30° with regard to

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$d$DREVA OPT 400 – VTD Vakuumtechnik Dresden GmbH.

$e$Purchased from Kurt J. Lesker Company.
3.1 Methods of fabrication

(a) (b)

Figure 3.4: Angled deposition of two layers (a) and (b) onto patterned photoresist (red) shown in top and side view. Arrows indicate directional deposition creating shadows (white) at the straight edges of the U-shaped patterns.

the beam direction to create a shadow along the rectangular part of the U-shaped pattern (shown in Fig. 3.4 as white areas). The deposition on top of the photoresist patterns was then performed in a two-step process to create differentially strained nanomembranes. The two steps were used to deposit different materials or to change deposition parameters for single material evaporation as explained in Sec. 3.3.1. Operations were performed at room temperature to protect the heat sensitive photoresist. Sample heating during the deposition was tested only for evaluations of temperature influences on the rolling efficiency and details can be found Sec. 3.3 and in the thesis of Trommer [63]. The results did however not justify the extended cooling times that are not needed with the rate gradient method.

3.1.4 Sacrificial layer etching for roll up

After deposition of the gradually strained nanomembrane, samples were ready to be rolled up. To start this process, the resist layer was dissolved by immersing the whole sample in organic solvents such as acetone, isopropanol or N-Methyl-2-pyrrolidone (NMP). NMP is a standard solvent for the removal of photoresist and was found to be ideal for the roll up of tubes because of its very low vapor pressure compared to acetone. Acetone starts to dissolve the resist even before the sample is fully immersed which presumably affects reproducibility negatively.

When the sample was fully immersed in NMP, the membranes started to roll from the previously defined shadow edge as shown in Fig. 3.5(a) while the edges perpendicular to the rolling direction had to be ripped off during the process. It follows that the number of
such edges should not be too high because it might complicate the roll up process. The rolling of the U-shape pattern was especially challenging due to its large number of edges. To compensate for this difficulty, the width of the legs of the U-shape was increased in the second mask as comparatively shown in Fig. 3.1 (a) and (b). When acetone was used the rolling could be observed via a microscope and was usually finished within one minute. In most cases NMP was used which has a refractive index comparable to SiO$_2$ making it difficult to judge the status of the rolling process using microscopy. To still ensure a full roll up, the samples were left in the solvent for several minutes up to several hours. As a last step the samples were immersed in acetone for additional cleaning and as a necessary preparation for the following drying step.

Drying took place in a critical point dryer (CPD) where the acetone was replaced by liquid CO$_2$ at 10 °C and 50 Bar, then heated up to 40 °C while reaching a pressure of 80 Bar where CO$_2$ becomes supercritical. The fluid was then slowly released and the sample was dried without crossing the liquid-gas transition to prevent the tubes from collapsing. An scanning electron microscopic image of a rolled-up tube is shown later in Chap. 4.

![Figure 3.5: (a) Rolled-up tubes after removal of the photoresist and critical point drying. (b) Thickness enhancement by atomic layer deposition.](image)

### 3.1.5 Post processing with atomic layer deposition

Atomic layer deposition (ALD) was used when the wall thickness or the refractive index needed to be increased as schematically shown in Fig. 3.5(b). This was necessary to support the confinement of long wavelength infrared light as discussed in Sec. 5.2.3 or to simply mechanically enhance the tubes. Materials used were HfO$_2$ (hafnium(IV) oxide) and Al$_2$O$_3$ (aluminum(III) oxide). Only standard deposition recipes were used and can be found in the thesis of Jens Trommer [63], for example. ALD deposits material at the
in- and outside of tubes which largely affect the effective refractive index of rolled-up microcavities causing a significant mode shift and can even lead to additional mode peaks. Both effects are studied optically in Sec. 4.2.2.

3.2 Methods of characterization

The fabrication of tubes was a significant part of this work because the material system was changed from SiO$_x$/SiO$_2$ to single material SiO$_2$ nanomembranes which required a new set of fabrication parameters. The prepared samples where then tested on their ability to confine light by the methods described in this section. First as a coarse test, each sample was investigated using light microscopy to find damaged or preferable rolled-up tubes for a further detailed analysis.

![Figure 3.6: Samples after critical point drying using (a) mask version one and (b) mask version two as described in section 3.1.1. Some tubes did not roll to the end due to the lobe structure. Scale bars are 200 µm. High resolution zoomed-in views on single tubes can be found in Chap. 4 and 5.](image)

Figures 3.6(a) and (b) show arrays of SiO$_2$ tubes fabricated using the two different U-shape mask versions, respectively. In Fig. 3.6(b) every pattern except the second row in the second column would be interesting for further analysis although not all tubes rolled the desired final position. The quality of the fabrication was then determined by counting the number of optically interesting tubes. Tubes that rolled far enough to provide a detached central lobe region were useful for further optical tests even when they did not roll to their intended final position because they provided sufficient distance to the substrate. With further optimizations the yield of tubes that roll to the end should increase which was demonstrated already for SiO$_x$/SiO$_2$ tubes rolled from rectangular
patterns by Harazim et al. [43] who reported a yield of almost 100% using this well-known material system.

The preselected tubes were tested on their ability to confine light by probing possible resonances. Two completely different methods were used and are schematically shown in Fig. 3.7. The first method is based on the photoluminescence (PL) emission properties of the microcavities so that a standard micro-PL (µPL) setup could be used to quickly check tubes for optical resonances to estimate a Q factor. This method originates from the first rolled-up photonics experiments that investigated the emission of rolled-up quantum wells [37] and became therefore a standard tool to investigate the later discovered resonances in tubes [38, 39]. Such a µPL setup is described in Sec. 3.2.1.

The second method used in this work is based on a transmission configuration in which fibers are coupled to the microcavities to directly excite resonances. This approach is motivated by the optical resonator community where resonators commonly do not feature emission detectable by µPL. A transmission setup is not commercially available and so it was developed and customized for rolled-up resonators and is described in detail in Chap. 5. This transmission configuration of tube resonators is highly interesting since it can demonstrate possible applications in silicon photonics. Fiber coupling is therefore an important milestone on the way to integration of rolled-up microcavities with on-chip waveguides. As a proof of concept, a simple frequency filter and an add-drop filter based on a fiber interfaced rolled-up microcavity is presented in Sec. 5.2.2 and 5.4.

### 3.2.1 Setup to observe resonances excited via photoluminescence

A convenient feature of rolled-up microcavities is their PL emission due to intrinsic emitters. These emitters can be easily excited and emit broadband light in the range of 450–700 nm within the walls of the cavity itself. This emitted light is “captured” by the resonances which can be detected as regular spaced narrow peaks on top of the broadband emission. The exact origin of the emission is still unclear but was explained earlier as defects in the SiO$_x$ layers or residual photoresist [64, 60, 65].

Excitation and detection was performed with a commercial µPL setup that features a HeCd laser at 442 nm, a spectrometer with 1200 blz/mm and 2400 blz/mm gratings and an electrically cooled charge coupled device (CCD) camera. The laser beam could be focused onto single tube resonators by a 50X objective and the PL emission was collected.

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*Renishaw inVia*
Figure 3.7: Two methods of optical characterization of resonances used in this work: excitation and spectroscopic detection of resonances via μPL (a) and resonant excitation using fiber coupling in transmission configuration (b).

by the same objective and guided to the spectrometer where the light was spectrally analyzed. Automatic spatial sample mappings were possible with a lateral resolution of 1 μm. In addition, semi-automatic polarization mappings were possible by installing a rotatable half-wave plate and a fixed polarizer mounted between the objective and the spectrometer.

3.2.2 Transmission studies of fiber-coupled rolled-up microcavities

Fiber coupling to rolled-up microcavities is a passive approach meaning that no intrinsic emitters are needed. This enables measurements at, in principle, any wavelength range where the resonator shows the best performance for specific applications. Especially interesting is the spatially and spectrally selective excitation of single optical modes and the investigation of light trajectories within the tube which is not possible with the broadband excitation in μPL setups.

The basic principle of this technique is a simple wavelength and polarization dependent transmission measurement of an optical fiber connected to either a broad band source and a spectrometer or a tunable laser and a photodiode. In the latter case the resolution is much higher and comparable to the line width of the laser. When a resonator is evanescently coupled to the fiber the transmission spectrum changes and resonances can be detected as dips in the transmission as theoretically described in Sec. 2.1.2. Standard optical fibers confine light very efficiently and a thinned or tapered fiber is required to achieve a coupling with the resonator. The necessary fiber diameters are in the range of sub micron to around 3 μm depending on the wavelength and resonator geometry [26]
3 Methods of fabrication and characterization of rolled-up microcavities

(see Sec. 2.1.2). The evanescent light field of such a tapered fiber can then overlap with a microcavity mode and couple to it. In Chap. 5 the developed setup for fabrication and coupling of such tapered fibers to rolled-up microcavities is explained in detail.

3.3 Strain creation in SiO$_2$ nanomembranes

At the beginning of this work, non-MBE-grown tube resonators were commonly fabricated using SiO$_x$/SiO$_2$ bilayers [51, 66, 67, 61, 53]. However, the deposition of SiO$_x$ using e-beam evaporation can be challenging and the material adds losses to the resonators [68] so a SiO$_x$-free rolling was investigated. As a result of this material exchange high Q factors were obtained as discussed in Chap. 4. Here, the method to achieve a roll up using SiO$_2$ is investigated first.

From [35] it was known already that rate and temperature gradients can be used to roll up tubes but an adaption for SiO$_2$ was still necessary. To accomplish this task a Diplomarbeit (master’s thesis project) as a subproject of this thesis was initiated after the first promising results of pure SiO$_2$ rolling were obtained. Parts of this work were repeated or completely carried out (temperature effects) by Jens Trommer [63]. In both of the following studies of strain creation, the efficiency was evaluated based on the total pattern number of 323 and then all patterns were counted where a tube had formed disregarding its actual optical Q factor. The Q factor of rolled-up microcavities depends on many factors that were beyond the scope of this efficiency evaluation but a detailed investigation follows in Chap. 4. The yield of high Q factor tubes is presumably much smaller than the yield of rolled tubes on the samples presented in the following, especially for temperature gradient induced roll up where maximum Q factors of 450 were obtained. For later samples, rolled up using rate gradients, high Q factor tubes with ratios of 4–10% were common.

3.3.1 Strain creation by deposition rate gradients

Strain can be incorporated into amorphous films by varying deposition parameters or by exploiting different thermal expansion coefficients of thin films and substrates [44, 35]. However, to achieve a roll up instead of wrinkled or shrunken films, a strain gradient within the film or a differential strain of subsequent layers is necessary. Such an effect can be obtained in two common ways [35]: when a bilayer material system is used differentially
strain results almost automatically due to different material properties such as thermal expansion coefficients, when single material films are needed, strain gradients within the layer can be created by varying parameters during the deposition of the films. The latter method was adapted to fabricate the SiO$_2$ tubes that are used in the following. Strain was created by varying deposition rates and temperatures during the thin film fabrication. To evaluate which method is more suitable, first the influence of the deposition rate is analyzed which was the mainly used technique and later the effect of temperature is discussed. Both effects were studied separately but since heating processes are difficult to avoid in an intense electron beam, their influence cannot be ruled out completely, especially at high deposition rates.

![Figure 3.8](image)

**Figure 3.8:** Tube rolling efficiency depending on the deposition rate using acetone or NMP to dissolve the sacrificial layer. Each sample contained 323 patterns that were counted to evaluate the efficiency (lines are a guide for the eye).

To estimate the optimal deposition rate, SiO$_2$ membranes were deposited in a two-step process. First a thin layer of 15 nm was deposited at a high rate between 1 Å/s and 15 Å/s and then a 45 nm layer was added at a constant rate of 0.7 Å/s. Both layers were deposited in an e-beam chamber with a vacuum pressure of approximately $5 \times 10^{-6}$ mBar that was increased to $1 \times 10^{-4}$ mBar by adding an O$_2$ background. The slow rate for the thick second layer was chosen to achieve an optimal film quality. Deposition was performed onto U-shaped photoresist patterns on a Si substrate where the small, first version U-shape structure was used (see Fig. 3.1) and patterns were aligned in an array of 323 patterns (18
by 18 subtracting 1 alignment mark). For each deposition parameter set, two samples were fabricated so that the suitability of acetone and NMP to dissolve the sacrificial layer could be evaluated at the same time. As the last step, all samples were immersed in acetone and dried using a critical point dryer.

The results of this study are shown in Fig. 3.8. The start-to-roll-efficiency was estimated based on the total pattern number of 323 by counting all patterns where a tube had formed disregarding its actual optical $Q$ factor. An increase of the rolling efficiency with increasing rate can be seen that seems to reach a saturation at around 8 Å/s. Such rates are much larger than standard machine parameters of below 1 Å/s and could lead to rate fluctuations of 1–2 Å/s. To still ensure a sufficiently high rate, a value of 10–12 Å/s was chosen as the standard deposition parameter for SiO$_2$ roll up. At even higher rates the thickness control became difficult as the deposition had to be stopped manually which complicates a precise thickness control. For low rates or no rate difference for both layers, the efficiency drops down rapidly and only very few patterns roll. In this case roll up occurs probably due to thermal effects during machine operation. Similar results were also obtained in the work of Trommer [63] who repeated the investigation of strain gradients.

Another interesting detail is the different efficiency of the acetone and NMP. Both solvents show a similar trend with increasing deposition rate but acetone is shifted towards lower efficiency values. A possible explanation was found in the high vapor pressure of acetone that presumably starts to attack the sacrificial layer before the sample is completely immersed making a controlled start of the roll up difficult. NMP on the other hand has a 2–3 orders of magnitude lower vapor pressure which is also the reason why NMP is a suggested stripper for photoresist films. In addition, it was observed that the rolling process starts slightly delayed by a couple of seconds so that turbulences in the solvent can settle down before the tubes roll up. The delayed undisturbed rolling presumably improves the efficiency.

### 3.3.2 Strain creation by temperature gradients

Rolling up nanomembranes by exploiting thermal effects was reported previously by Mei et al. [35] and was extended to e-beam deposited SiO$_2$ in the final year project (Diplomarbeit).

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8Acetone: 246 mbar, NMP: 0.32 mBar. Vapor pressure at 20 °C (GESTIS-Stoffdatenbank).

beit) of Jens Trommer [63] that is summarized here. In these experiments fabrication steps where identical to the description given directly above except the following: the deposition rate was kept constant at 0.7 Å/s for both layers and the deposition of the first layer was performed at elevated temperatures of nominal\(^1\) 100 °C, 120 °C, 140 °C, and at 25 °C as a reference for no temperature gradient. After the first deposition step of 15 nm the samples remained in the chamber to cool down to room temperature (25 °C) before the second layer with 45 nm was deposited. These fabrication steps were chosen because it was expected that the polymer sacrificial layer, with a large thermal expansion coefficient, would cause a compressive strain in the first SiO\(_2\) layer when cooled down [35]. The second layer deposited at room temperature would not experience this effect resulting in an effective differential strain in the SiO\(_2\) nanomembrane.

![Graph showing results of temperature induced rolling](image)

**Figure 3.9:** Results from temperature induced rolling. The classifications “damaged” and “no rolling” describe not rolled-up patterns and “start to roll”, “freestanding”, and “rolled until the end” describe patterns where tubes were formed according to the definition used in previous section. (Adapted from Trommer [63].)

Results of the investigation are shown in Fig. 3.9 and support assumption from above.

\(^1\)Set values at controller. Actual temperature is presumably lower due to air gap between heater and sample.
The 25 °C reference deposition resulted mainly in damaged/not rolled patterns and shows a rolling efficiency of less than 10%. Samples prepared at 100 °C and 120 °C show a rolling efficiency of 80% (including “start to roll”, “freestanding”, and “rolled until the end” patterns) with a slightly larger efficiency at 120 °C where a higher fraction of tubes is freestanding or rolled even to the end. Tube diameters on the 120 °C sample were also smaller than on the 100 °C sample with is consistent with the assumption of a temperature dependent strain. The efficiency of this sample is close to the best result obtained from the rate gradient method. Temperatures of 140 °C presumably damage the heat sensitive photoresist layer and obviously prevent rolling. The results confirm that a temperature gradient generally supports rolling but compared to the roll up by the deposition rate gradients the method is less convenient because substrate heating and cooling takes several hours and includes the possibility of thermal damages to the resist.
4 Optical modes in rolled-up optical microcavities excited by photoluminescence

The first method used to investigate resonances in rolled-up microcavities was micro-photoluminescence (µPL) spectroscopy [38, 39] which is still a standard tool to conveniently probe the optical quality of rolled-up tubes in the visible wavelength range. Photoluminescence emission is a very helpful feature present in most rolled-up resonators where it serves as a build-in light source to excite optical resonances from within the resonator. The exact origin of the light emission is still an ongoing discussion in literature and common explanations include material defects [64], nanoclusters [61] or residual photoresist [65] that are present in the tube’s walls.

This chapter focuses on investigations of the optical quality factor (Q factor) of rolled-up SiO$_2$ resonators without additional coating. It is shown that these resonators can support record Q factors when probed in emission mode. To understand this result an investigation was performed to identify the limits of the Q factor using experimental and theoretical methods. The tube resonators used in this chapter were rolled up from differentially strained SiO$_2$ nanomembranes where strain is created by the deposition gradient method presented in Sec. 3.3.1. The Q factor investigations are based on µPL single point measurements that were performed at positions close to the central area of tubes where the structure is optimized for light confinement and thus best results can be expected.

In the second part of this chapter axial confinement in rolled-up tube resonators is addressed experimentally by performing µPL line mappings along the resonator axis. These maps demonstrate the spatial distribution of axial modes that appear as additional peaks in the spectra shown in the first part of this chapter. In the last section the radial
confinement of atomic layer deposition (ALD) coated tube resonators is probed by the combination of single position and map scans including polarization resolved µPL scans. Using this combination, the evolution of higher order radial modes is observed.

The results presented in this chapter have been partly published in Böttner et al. [24] and Trommer et al. [69] and theoretical models were developed by Shilong Li if no other references are given.

4.1 High optical quality factors and corresponding limits in rolled-up microcavities

The rolled-up microcavity that is investigated in this section was fabricated with the methods described in Chap. 3. The thickness of the SiO$_2$ nanomembrane was 60 nm and strain was incorporated using varying deposition rates. To define the geometry of the tube, the first pattern version shown in Fig. 3.1(a) was used resulting in a tube with a diameter of 11 µm, 3.3 windings and 200 nm average wall thickness in the center. A scanning electron microscopy (SEM) image of a similar SiO$_2$ tube is shown in Fig. 4.1 with the U-shaped pattern visible in the background.

To judge about the usefulness of such a rolled-up tube as a resonator, the $Q$ factor is commonly used. It was introduced already in Sec. 2.1.1 as an important value to describe
4.1 High optical quality factors and corresponding limits in rolled-up microcavities

the quality of resonators and is defined as

\[ Q = \frac{\lambda_m}{\delta\lambda} \]  

with the width \( \delta\lambda \) of a resonance at the spectral position \( \lambda_m \). To obtain these values experimentally, \( \mu \)PL was used to excite and study resonances. An extended \( \mu \)PL spectrum, typical for this type of rolled-up resonator, is shown in Fig. 4.2(a), where a broad background emission from 450 nm to 750 nm is visible from intrinsic light sources that are excited by a 442 nm HeCd laser. Sharp additional peaks are visible on top of this background which are shown in detail in the zoomed view in Fig. 4.2(b). The spectrum in Fig. 4.2(b) shows two groups of azimuthal modes that consist of one fundamental mode (or zero order axial mode) at 611 and 619 nm, respectively. These peaks are followed by additional 13 (higher order) axial modes at shorter wavelengths with lower intensities that appear due to the axial confinement generated by the lobe structure described in Sec. 3.1.1.

The correct identification of the fundamental modes is confirmed by the relation for resonances in a ring cavity given by \( m\lambda = \pi nD \) (Sec. 2.1.1) where \( m \) is the azimuthal mode number, \( \lambda \) the wavelength, \( n \) the refractive index and \( D \) the tube diameter. The identification of axial modes is slightly more challenging. These modes also cycle along the circumference and consequently follow the same resonance condition for their az-
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imimuthal \( k \) vector components. However, because they also propagate along the axis, their \( k \) vector possesses additional axial components that lead to blue shifted mode peaks depending on the magnitude of the axial components [70]. The estimation of these components requires more advanced theoretical models as presented later. A more intuitive experimental identification is possible by probing the spatial distribution of axial modes with the help of spatially resolved \( \mu PL \) maps along the axis as presented in Sec. 4.2.1 and also by fiber transmission experiments in Chap. 5.

To focus first only on the fundamental modes, the \( Q \) factor was calculated according to Eq. (4.1). Both modes at 611 and 619 nm reach a value of 5400 which is a record for rolled-up microcavities probed in emission and is even higher than reported for high refractive index InGaAs/GaAs tubes [71] (for transmission see [23]). An explanation for the record \( Q \) factor of the fundamental modes can presumably be found in the low loss SiO\(_2\) membrane that does not contain silicon monoxide and the optimized bridge-like structure resulting from the U-shape lithography pattern which avoids substrate losses. The fabrication of such high \( Q \) resonators was repeated several times [63, 14], so that good reproducibility can be claimed.

To further investigate what influences the \( Q \) factor, several possible loss contributions were analyzed experimentally and theoretically. The resulting maximum \( Q \) factors of the respective loss contributions can later be added up reciprocally to estimate the overall limit [18]. First, limits were estimated that directly follow from measurements of the material absorption (\( Q_{\text{abs.}} \)) and surface roughness (\( Q_{\text{rough.}} \)). Second, contributions that are not directly accessible were studied by calculations based on a modeled structure with input from experimentally known parameters. In all estimated values, an enhancement factor of 2.54 was added that was calculated by Sumetsky [72] for the effect of axial confinement on the \( Q \) factor in cylindrical microresonators. Without this confinement circulating light beams are lost along the axis and the \( Q \) factor is decreased.

4.1.1 Material absorption and surface roughness

The rolled-up resonators were fabricated using SiO\(_2\) which has a well-known absorption due to its wide spread use in optical fibers. To confirm that the electron-beam evaporated SiO\(_2\) films also have a low absorption, and to calculate a corresponding \( Q \) factor limit, ellipsometric measurements were performed. A 60 nm thick SiO\(_2\) nanomembrane deposited with the same parameters as for tubes, but without a photoresist layer, was
4.1 High optical quality factors and corresponding limits in rolled-up microcavities

used to determine its refractive index \( n \) and extinction coefficient \( \kappa \). The results of the measurement are shown in Fig. 4.3(a) and confirm the low loss of SiO\(_2\) which is below the detection limit of the system. To still calculate a resulting \( Q \) factor limit, a literature value for the absorption \( \alpha = 4\pi \kappa / \lambda \) was taken from Gorodetsky et al. [18] who calculated the limit for \( Q_{\text{abs.}} \), using similar material parameters in microspheres at a wavelength of \( \lambda = 633 \) nm, a refractive index \( n = 1.46 \) and an absorption coefficient \( \alpha \approx 2 \) dB/km, and found the upper limit

\[
Q_{\text{abs.}} = 2.54 \frac{2\pi n}{\alpha \lambda} \approx 10^{10}.
\]  

(4.2)

Absorption can therefore be neglected for rolled-up resonators.

Another possible contribution to losses in microresonators is light scattering due to rough surfaces. An estimation of this roughness is possible by atomic force microscopy (AFM) measurements of the resonator surfaces. For rolled-up resonators two surfaces are in question. These are first the outside wall of the tube whose roughness was measured directly with the AFM tip on top of a rolled-up tube and second the inside wall whose roughness was probed on an unrolled part of the membrane close to the tube. Low (root-mean-squared) roughnesses of \( R_q = 0.80 \) nm (outside) and \( R_q = 1.37 \) nm (inside) were detected as shown in Fig. 4.3(b) leading to a limit in the range of \( Q_{\text{rough.}} = 10^7 - 10^8 \).
that is calculated using the equation [18]:

\[ Q_{\text{rough}} = 2.54 \frac{\lambda^2 D}{2\pi^2 R^2 B} \]  

(4.3)

where \( D \) is the tube diameter and \( B \approx 8 \text{ nm} \) the correlation length of the surface inhomogeneities estimated from the AFM scans of the inside wall.

### 4.1.2 Radiative losses from curvature

The curvature of thin walled microcavities can add significant radiative losses similar to bending losses in optical fibers. The amount of these losses depends on the wall thickness, the refractive index and the diameter of the microcavities. In addition, the spiral structure of tubes is important which causes a nonuniform wall thickness when the number of rotations is not an integer. To take this into account, the structure was split up into a thin and a thick ring resonator with radii \( R_1, R_2 \) and thicknesses \( t_1, t_2 \), respectively, as illustrated in Fig. 4.4. The loss was then calculated separately for each ring and added in a weighted sum.

![Figure 4.4:](image)

**Figure 4.4:** (a) Schematic cross section of a rolled-up microcavity (unscaled). The radii \( R_1, R_2 \) and wall thicknesses \( t_1, t_2 \) are indicated. (b) Simplified structures to calculate radiative losses weighted by their sizes and field distribution (see text). (Published in Böttner et al. [24])

For the simplified dielectric ring structure the two dimensional Helmholtz equation depends only on the radius and the azimuthal coordinate. It was solved using a MATLAB code developed by our group (more details are published in [73] or [74]). The result
4.1 High optical quality factors and corresponding limits in rolled-up microcavities

contained the complex wave vectors \( k = \omega/c \) of all modes in the selected wavelength range which translate to a maximum \( Q \) factor according to the definition:

\[
Q = \frac{\text{Re}(\omega)}{2\text{Im}(\omega)}.
\]  

(4.4)

The smaller value of the thin and thick ring could already serve as an upper limit but to include the effect of the non-integer winding number the two values were combined by weighting them with the respective length of the ring segment given by the number of rotations. This was done using a model that approximates tubes as rolled-up waveguides \[71\]. For an arbitrary fractional number of rotations it is possible to perform a weighted sum of both \( Q \) factors by taking the length of the thin and thick segment \( (L_1, L_2 \text{ see Fig. 4.5}) \) and their effective refractive indexes \( (n_{\text{eff},1}, n_{\text{eff},2}) \) into account. First the number of modes \( m \) is split in two values \( m_1, m_2 \) that represent the respective circle segments using

\[
m\lambda = n_{\text{eff},1}L_1 + n_{\text{eff},2}L_2 \\
= m_1\lambda + m_2\lambda,
\]

(4.5)

and the weighted \( Q \) factor is calculated with

\[
\frac{m}{Q_{\text{rad}}} = \frac{m_1}{Q_1} + \frac{m_2}{Q_2},
\]

(4.6)

leading to a final radiative limited \( Q \) factor of \( Q_{\text{rad}} > 10^5 \) that is also far from the experimental result of \( 10^3 \).

4.1.3 Scattering losses from steps along the circumference

The spiral shape of the resonators does not only lead to a varying thickness but also to steps at the transitions between thick and thin parts that scatter light and decrease the \( Q \) factor. To calculate this effect separately from other effects such as curvature losses, a straight waveguide structure was assumed as shown in Fig. 4.5 which was further simplified by assuming a single vertically symmetric step instead of the two asymmetric steps in the real spiral structure. The estimated value for the symmetric step was then doubled. With this simplification the theory from Marcuse \[75\] can be applied who investigated steps in dielectric waveguides to calculate the loss coefficient when a wave
is traveling along such a waveguide. These calculations are based on solving Maxwell’s
equation in dielectric structures and can be found in standard textbooks. The derivation
of a $Q$ factor from such results is less known and is shown in the following.

$$P_j = P_0 (1 - \alpha)^j.$$  

Replacing $j$ with the passed time $t = j mT$ yields

$$P(t) = P_0 (1 - \alpha)^\frac{t}{mT} = P_0 \exp \left( - \frac{t}{\tau} \right),$$

where the photon lifetime $\tau = -mT/\ln(1 - \alpha)$ was defined in the last step. When $\tau$
is inserted into the definition of the $Q$ factor from Eq. (2.6), it follows for $Q_{\text{step}}$:

$$Q_{\text{step}} = 2.54 \frac{2\pi \tau}{T} = -2.54 \frac{2\pi m}{\ln(1 - \alpha)} \approx 2.54 \frac{2\pi m}{\alpha}, \quad (4.7)$$

where also the axial confinement factor of 2.54 is included. The loss coefficient calculated
using MATLAB code according to [75] is $\alpha = 2 \times 0.006$ (factor of 2 for both steps) and
results, with Eq. (4.7), in $Q_{\text{step}} \approx 10^5$. The non-continuous surface of the spiral resonators
is surprisingly not a major $Q$ factor limit which can be understood by comparing the
4.1 High optical quality factors and corresponding limits in rolled-up microcavities

A small step size of 60 nm with the wavelength of light which is one order of magnitude larger. All calculated $Q$ factor limits are well below the experimental value of 5400 so the most significant limit was not yet found and is presented in the following.

4.1.4 Interlayer voids as a source for major losses

All possible $Q$ factor limits in the previous sections neglected the effect of imperfections during the roll up process. Such imperfections have been reported earlier to be interlayer voids, for example. They have been discovered using cross sectional transmission electron microscopy [39] and their influence on the $Q$ factor has been exploited for sensing applications [53]. A quantitative analysis has however not been reported and is demonstrated here.

![Cross sectional focused ion beam cut (FIB) of a SiO$_x$ / SiO$_2$ microtube showing a Gaussian-shaped interlayer void (red line). Image provided by L. B. Ma, FIB cut by S. Baunack.](image)

The analysis is based on focused ion beam cuts of silicon oxide microcavities performed by L. B. Ma as shown in Fig. 4.6. To model these voids theoretically, their shape was assumed as Gaussian-curve-like where initial size parameters were taken from the FIB cut data. Then, a model was designed to calculate the influence of such voids on the $Q$ factor by finite difference time domain simulations. To exclude other influences such as the curvature or the spiral shape, a simple straight waveguide was assumed. This waveguide is split up symmetrically by a void as shown in the inset in Fig. 4.7. When light is passing through this structure, part of it is scattered out and lost depending on the size of the void which was varied for the simulation while keeping its width constant. The result for different void heights is shown in Fig. 4.7.
Figure 4.7: Rapid drop of the quality factor $Q_{\text{void}}$ with increasing void height was simulated by assuming Gaussian shaped voids that symmetrically split-up the waveguide structure. The enhancement factor of 2.54 for axial confinement is included. The inset shows the simulated scattering of the electric field at a void height of 0.45 µm. (Simulation performed by S. Li, published in Böttner et al. [24])

It is obvious that the $Q$ factor is largely affected by such a void and rapidly drops down for increasing void size. A minimum value is reached at 450 nm void size where light is most efficiently scattered by the split waveguide. For increasing sizes the bend upper waveguide part presumably loses its influence and the $Q$ factor slightly recovers. As a comparison with the experimental result a void of only 200 nm would be enough to limit the $Q$ factor to the experimentally found record of 5400 when all other loss channels are neglected. It can therefore be concluded that voids occurring during roll up are the most significant obstacle on the way to higher $Q$ factors. Strain engineering by appropriate roll up pattern geometry could be a promising way to avoid these “wrinkles” and first steps were already taken by theoretical studies on the effect of pattern size on rolling by Cendula [58] (see also [76]).

4.2 Spatial and polarization dependent $\mu$PL maps

Single position $\mu$PL scans can quickly reveal values like the optical $Q$ factor but cannot be used to safely identify specific modes in more complicated spectra. Additional modes arise, for example, by axial confinement which can be nicely visualized by spatially re-
solved µPL mappings. In addition, when tube resonators are coated using ALD to improve their structural stability also their optical properties are changed and more optical modes are supported. For example a second polarization state can be confined as reported by Bolaños Quiñones et al. [51]. For thicker coatings even higher order radial modes can be supported and µPL spectra become increasingly crowded. To experimentally verify the origin of each mode in such a complicated spectrum, spatial mappings combined with polarization resolved mappings are helpful. In the following the mode distribution in a high quality uncoated SiO$_2$ microcavity is investigated by a spatial mapping to confirm the previous statements on the existence of axial modes. Later polarization maps are added and combined with spatial maps to investigate an ALD coated tube. This tube supports a rich variety of modes that are identified as differently polarized modes, axial modes and higher order radial modes.

### 4.2.1 Axial mode detection via spatial µPL mappings

µPL measurements performed at several positions on a sample can be used to create emission maps to reveal interesting details of resonant modes in rolled-up microcavities. This technique was used extensively to investigate the optical confinement by specially designed lobe structures by Strelow et al. [71]. Here it is used to confirm the finding of axial modes that where shown in Fig. 4.2(b) but until this section not yet verified experimentally.

In Fig. 4.8 a µPL map of a high Q factor tube rolled-up from a 60 nm SiO$_2$ membrane using the small U-shape pattern [Fig. 3.1(a)] is shown. The tube had a diameter of 15 µm, 2.44 rotations and 146 nm average wall thickness in the center of the lobe. Spectra were taken along the axis of the tube in the central area and no background subtraction or normalization was performed. However, the intensity scale was changed to improve the visibility of weaker axial modes to highlight their characteristic spatial distribution. Position 0 corresponds approximately to the center of the lobe structure where intense fundamental modes can be seen at 582, 587, 593 and 598 nm that are followed by axial modes at shorter wavelengths and different axial positions. The fundamental modes show only one intensity peak along the axis, as expected. Peaks of the axial modes are visible at the edges of the optical confinement at ±10 µm but corresponding intermediate peaks in the central region are difficult to resolve and appear only as weak and almost continuous peaks along the axis. The different spatial distribution of axial modes is however clearly
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Figure 4.8: µPL map along the axis of a rolled-up microcavity. Four azimuthal mode groups can be seen each consisting of a high intensity fundamental mode at a position around 0 µm followed by weaker axial modes at shorter wavelengths that are spread along the axis.

visibly and confirms the previous statement about modes at smaller wavelengths being axial modes in Fig. 4.2(b).

In addition, it can be observed that the fundamental mode is shifted from the center of the lobe and also the first order axial mode has an asymmetric intensity distribution with a bright antinode around 4 µm and a corresponding weak one at −2 µm. This shift presumably results from an asymmetric optical potential well created by a nonuniform diameter along the axis. The strong influence of such asymmetries on spatial mode position was already found in [49] to explain shifted resonances in tubes. In addition, a pinning of modes by small potential undulations created by defects from the roll up might locally shift the optical modes as reported in [77]. Asymmetric spectra were observed frequently during this work and are addressed again in Chap. 5 when the optical confinement is probed using coupled fibers.

4.2.2 Identification of optical modes with polarization and spatial µPL maps

For most µPL investigations in this work uncoated SiO₂ tubes were used. However, for the later presented infrared experiments as well as for many µPL based applications
such as microfluidics, a coating is necessary to mechanically strengthen the structures or to enhance confinement for long wavelength light. ALD coatings can largely influence the optical properties and have been used to tune resonances of rolled-up resonators by Bolaños Quiñones et al. [51]. However, comparatively thin coatings were used that lead to broad optical modes. In the following, the effect of coatings on the optical properties is investigated in detail by a stepwise coating process that also includes especially thick coatings up to $2 \times 80$ nm (in- and outside tube walls). For such coating thicknesses new modes appeared in $\mu$PL spectra which were identified by combining different $\mu$PL analysis techniques such as spatial and polarization resolved mappings. The identification leads to the finding of a second polarization state and a higher order radial mode where especially the latter one is interesting for improved sensitivity when rolled-up resonators are used as sensors. This larger sensitivity is related to the increased extended evanescent field of higher order radial modes [78].

The experimental work presented in this section was partly performed during the final year project of Jens Trommer who prepared the sample tube and performed ALD coating and the corresponding single position $\mu$PL scans. Further contributions are indicated in the figure captions and all results were published by Trommer, Böttner, Li et al. in [69].

The rolled-up microcavity used for the following analysis was rolled-up from a 70 nm thick SiO$_2$ nanomembrane into a tube with a diameter of 15.3 $\mu$m with 2.4 rotations and an average wall thickness of 167 nm in the center. An SEM image of the tube is shown in Fig. 4.9. Fabrication was performed as described previously in Chap. 3 and strain was incorporated by the rate gradient method. The sacrificial layer was patterned prior to the nanomembrane deposition using the small U-shape mask described in Fig. 3.1(a). ALD coating with Al$_2$O$_3$ was performed in steps of 10 nm on the inner and outer wall of the tube leading to a total thickness increase of 20 nm after each step. A $\mu$PL spectra was taken after each coating step as shown in Fig. 4.10.

The notation used to describe the modes are: TM for the transverse magnetic polarization state which is aligned parallel to the tube axis (or in plane) and TE for the transverse electric state which is aligned perpendicular (or out of plane). To differentiate fundamental and higher order radial modes a subscript is added where “0” stands for fundamental and “1” for the first order radial mode.

The initial “as-fabricated” spectrum in Fig. 4.10 shows the known peaks of a rolled-up microcavity with axial confinement [48, 24] similar to the one shown previously in Fig. 4.2. Three groups of azimuthal modes are visible with mode numbers from 107 to
All groups show axial modes (diamonds) at the short wavelength side of a respective fundamental mode (triangles) both belonging to the TM polarization state. Modes from a TE polarization state are not visible because they are subject to higher losses due to the non-continuous electric field at the wall-air interface [71]. Also, radial modes (TM\(_1\)) are not visible due to the thin wall.

Coating of the tube with Al\(_2\)O\(_3\) increases the effective refractive index and the thickness of the tube wall which leads to a red-shift of the resonances [51]. As visible from the indicated mode numbers \(m\) in the first two spectra, the shift is so large, that it is not possible to observe the evolution of one specific mode throughout the whole coating process but the behavior of the resonator in a given wavelength range can be observed. The mode numbers are only calculated in approximation because the position of the resonances are very sensitive to the wall thickness and tube diameter both determined experimentally. It is therefore not possible to safely distinguish different mode types based on calculations only, but experimentally an identification is possible. Following the spectra for increasing coating thickness, it can be seen that the modes become broader, start to overlap and the axial modes decrease in number until they can hardly be identified at a coating thickness of 30–40 nm. This effect can be explained by a decreasing significance of the lobe whose thickness stays constant while the overall wall thickness is increased. This loss of optical
4.2 Spatial and polarization dependent µPL maps

Figure 4.10: Evolution of the µPL emission signal of the rolled-up microcavity shown in Fig. 4.9 as a function of ALD layer thickness. TM polarized azimuthal modes split up into a set of higher order axial modes (diamonds) and corresponding lowest order axial modes (triangles) are marked in the initial spectrum with respective azimuthal mode number $m$. In the spectrum from the most thickly coated resonator $\text{TM}_0$ (triangles) and $\text{TM}_1$ (stars) radial modes as well as TE polarized modes (circles) are visible. As they do not necessarily belong to the same azimuthal mode number, values for $m$ are indicated only for $\text{TM}_0$. $Q_{\text{max}}$ denotes the highest measured quality-factor for each mode spectrum. (Published in [69].)
confinement reduces also the $Q$ factor [72] as visible in Fig. 4.10.

When the coating process is continued, the increasing wall thickness leads to a gradually improved radial confinement so that the $Q$ factor increases again and higher order radial modes and a perpendicular polarization state can be confined. In 4.10 this can be seen for the spectra between 30 nm and 80 nm coating, where first new broad modes (circles) and then additional narrow peaks (stars) start to appear. The broad modes are identified later as the TE polarization state ($\text{TE}_0$) and the narrow modes as higher order radial modes of the initially supported polarization state ($\text{TM}_1$).

![Polarization resolved µPL map of an ALD coated rolled-up microcavity showing modes of two polarization states (TE/TM) and a higher order radial mode (TM$_1$).](image)

**Figure 4.11:** Polarization resolved µPL map of an ALD coated rolled-up microcavity showing modes of two polarization states (TE/TM) and a higher order radial mode (TM$_1$). (Published in [69].)

To simplify the identification of all modes, the coating is continued until the peaks are clearly separated. This is possible because the electric field distributions of different mode types are not equal (see Fig. 4.13) which influences the amount of red shift due to the coating process. As an example, for the spectra at 40 nm it is difficult to find the broad peaks that were visible at 30 nm coating thickness at wavelengths around 596, 602, and 607 nm while for the final spectrum at 80 nm coating it is possible to label even three different types of modes. The two sharp intense peaks at the 80 nm spectrum labeled with triangles and stars have $Q$ factors of 3300 and 2200. These comparatively high values can be explained by the above mentioned increase in radial confinement due to the larger effective refractive index of 1.58 after 80 nm coating compared to 1.41 for the uncoated
4.2 Spatial and polarization dependent μPL maps

resonator. This effect seems to be stronger than the loss of axial confinement and was not observed for thin ALD coatings in [51].

To first prove the existence of a second polarization state in the final spectrum of Fig. 4.10 (circles) a polarization resolved map of the μPL emission was performed and is shown in Fig. 4.11. The two sharp modes labeled with TM_{0,1} obviously belong to the same linear polarization state because they appear at 0°, 180° and 360°. The modes labeled with TE_0 appear at perpendicular angles at 90° and 270°. From this mapping experiment it becomes therefore clear that the appearing second sharp mode at 80 nm coating cannot be explained to originate from a different polarization state, only the broad peak can be identified as TE polarized.

![Figure 4.12: Spatial μPL map of an ALD coated rolled-up microcavity showing axial modes and fundamental and higher order radial modes (TM_0/TM_1). (Published in [69].)](image)

In a next step, the rolled-up microcavity was investigated using a spatially resolved μPL mapping as explained in Sec. 4.2.1. The polarization selection of the μPL setup was set to the TM state to identify the two strong peaks from the 80 nm spectra in Fig. 4.10. The result is shown in Fig. 4.12. Comparable to the map in Fig. 4.8, the characteristic signature of axial modes is visible in contrast to the 80 nm single position spectra in Fig. 4.10. Axial modes are much weaker in this map scan compared to the result in Sec. 4.2.1 because of the smoothed axial confinement and a lower Q factor of the resonances. Also, similar to Fig. 4.8, an asymmetric spatial distribution of the axial modes is apparent, presumably due to a slightly asymmetric roll up [49]. The two intense TM_0 and TM_1 modes appear
at the center of the lobe at around 20 µm away from the starting position (see Fig. 4.9). However, the spacing of the two modes is larger than the free spectral range of the axial modes, which suggests that the TM₁ labeled peak is not merely another TM₀ axial mode but genuinely a higher order radial mode which also explains the relative shift compared to the TM₀ mode during coating. The spatial map therefore helps to identify the remaining unknown peak by ruling out other possibilities.

One additional finding is revealed by the spatial map: A bright peak at an off-centered position of 30 µm. This peak seems to be independent from all other peaks in the map and does only appear when it is directly excited and not in Fig. 4.10. An explanation could be a second local optical confinement at this position due to possible corrugations in the tube wall that spatially pin resonances as reported by Strelow et al. [77].

![Figure 4.13: Electric field distribution (squared) of TM₀, TM₁ and TE₀ modes in a coated tube resonator wall (black vertical lines). Calculations are based on parameters similar to the investigated tube resonator. The large evanescent field of the TM₁ mode is related to a large optical sensitivity [78, 79]. (Calculations provided by S. Li.)](image)

To support the initial statement of the usefulness of TM₁ modes for sensing, the electric field profile was calculated using geometrical parameters similar to the tube resonator shown in Fig. 4.9. The (squared) field profiles for TM₀, TM₁, and TE₀ modes guided by a coated tube resonator, are plotted in Fig. 4.13. It can easily be seen that the TM₁ mode has a larger evanescent field in the tube core compared to TM₀ and TE₀. The sensitivity S is proportional to the energy fraction \( \eta_{\text{core}} \) guided by the evanescent field in the core and is given by [78]

\[
S = \frac{\lambda}{n} \eta_{\text{core}} \tag{4.8}
\]

where \( n \) is the refractive index of the resonator wall and the energy fraction \( \eta_{\text{core}} \) is the light energy in the core normalized to the total light energy guided by the resonator which
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can be calculated from the field profiles (see [78] for details). As a result $\eta_{\text{core}}$ values are 0.76% for $\text{TM}_0$, 5.7% for $\text{TM}_1$, and 2.2% for $\text{TE}_0$ so that the higher order radial mode has a much higher sensitivity than the fundamental $\text{TM}_0$ mode and a by a factor 2.6 larger sensitivity than the $\text{TE}_0$ mode. The large sensitivity of the higher order radial mode is especially interesting because it has a distinctly higher $Q$ factor (2200) than the $\text{TE}_0$ mode which is important for the sensing resolution that relies on the narrowness of resonances.

In conclusion it has been shown that a certain minimum coating thickness should be reached for rolled-up resonators to overcome low $Q$ factors and more importantly to reach a thickness where higher order radial modes are supported to exploit their superior sensitivity.
5 Fiber interfaced rolled-up microcavities

Free space micro-photoluminescence (µPL) based excitation of resonances in rolled-up microcavities is a convenient tool to investigate optical properties and has been used in numerous experiments starting with Kipp et al. [38] and Songmuang et al. [39]. However, µPL cannot be used to explore the features of the resonators in the highly interesting field of integrated optics where transmission configurations are required. Here, signals are transported via on-chip waveguides to which resonators are coupled to act, for example, as frequency filters or modulators. Rolled-up microcavities are a possible candidate for these applications as the fabrication of SiO$_2$ tubes is fully compatible with silicon microfabrication techniques. It is therefore a logical step to develop waveguide coupling to investigate the performance of the microcavities in such a transmission configuration.

For the results presented in this chapter, optical fibers were used as waveguides as part of a transmission setup. This setup was especially developed for the requirements of rolled-up microcavities and is explained in the first section followed by results of the transmission experiments. Most measurements were performed on-chip on as-rolled microcavities to prove their ability to operate without a pick-up from their substrate. This is in contrast to previous reports for InGaAs/GaAs tube resonators which required a manual transfer of the tubes to waveguides or fibers [56, 23].

In the following, fiber interfaced tubes are used to investigate general resonance filter properties as well as more detailed analyses of the spatial distribution of resonant modes. Moreover, as a proof of principle, a vertical add-drop filter based on a rolled-up microcavity was designed and tested to highlight the potential of tubes in silicon photonic optical networks. The contents of this chapter were published in Böttner et al. [80, 81] and here a more detailed description is given.
Coupling of microcavities with waveguides is usually achieved by overlapping the evanescent fields of both light confining components to facilitate a tunneling of light from one to the other which was theoretically described in Sec. 2.1.2. To make the evanescent field accessible a light confining structure needs to be as small as the wavelength of light. For optical fibers, diameters around 1 µm are required\[26\] that can be achieved by applying the heat and pull technique to commercially available fibers with larger diameters of commonly 125 µm. In this method a length of a couple of millimeters of the fiber is softened by a heat source and then stretched so that taper profiles with sub-micron diameters can be created that keep their initial geometry at the in- and output as shown in Fig. 5.1. When the transition from thick to thin part of the fiber is sufficiently smooth or adiabatic, a high fraction of the light energy can be transmitted and optical signals do not experience major losses. The various fabrication methods and applications of tapered fibers is nicely described in a review of Brambilla\[82\] so that only topics relevant to this work are described here.

![Figure 5.1: Schematic of a tapered fiber (not to scale).](image)

Taper profiles with almost arbitrarily shaped transitions from thick to thin parts can, in principle, be created according to the methods presented by Birks and Li\[83\]. However, sophisticated setups with computer controlled movable heat sources and pulling stages are required. In this thesis a configuration with a fixed heat source is used where only the drawing speed and distance need to be adjusted. Still, high quality tapered fibers with a transmission of 99.8 % can be created as shown in Fig. 5.3.

The setup that was used is schematically shown in Fig. 5.2. Light from a fiber coupled external cavity diode laser\(^a\) (ECDL) tunable from 1520–1570 nm is sent via a collimated beam through an attenuator and an achromatic half-wave plate and then coupled to a bare fiber that is to be tapered. The comparatively large scanning range of the laser was chosen because the small diameters of rolled-up microcavities lead to free spectral ranges

\(^a\)New Focus TLB-6728-P-D.
5.1 Transmission setup and tapered fibers

of 20–50 nm. The output signal of the fiber was detected by an InGaAs photodetector\(^b\) and read out and stored by an oscilloscope. Synchronously, the wavelength of the laser was monitored by the same device to eventually create transmission versus wavelength graphs. The normalized transmission was obtained by dividing the signal by the recorded reference transmission (e. g. signal without a sample) to eliminate changes in the laser power and varying efficiency of the fiber incoupling optics.

Standard bare telecommunications single-mode fiber (comparable with Corning\(^b\) SMF-28\(^{TM}\)) with an acrylate coating but without an additional protective jacket was used for tapering. The coating was removed at a length of a few centimeters by softening with acetone and subsequent mechanical stripping. The fiber was mounted on two motorized translation stages\(^c\) for symmetric drawing. To soften the SiO\(_2\) fiber it was inserted into a microfurnace that was constructed from a slitted ceramic tube that was heated by a

\(^b\)Thorlabs PDA20CS-EC InGaAs switchable gain detector, 800–1800 nm.
\(^c\)Physik Instrumente (PI) M-404.2DG.
butane torch. This design was inspired by a setup used in [84] where the heat of a CO$_2$-laser was distributed by a sapphire tube. In this work the ceramic tube protected the fiber from a direct impact of the torch which would break the taper otherwise. The flame width of approximately 8 mm and the indirect heating lead to comparatively long tapers of 1–2 cm which are useful to achieve coupling to on-chip rolled-up resonators while keeping a sufficient distance to the substrate. Otherwise, the 125 µm diameter of the untapered regions would make a coupling impossible for straight fibers.

The transmission of the fiber was monitored during fabrication and revealed strong intensity oscillations when the fiber undergoes a transition from being initially single-mode to multi-mode and single-mode again. This occurs because the light confinement in the core vanishes with decreasing core size and the light is increasingly guided in the large diameter cladding until even this guidance becomes single-mode when the diameter further decreases. During the multi-mode behavior the whole taper acts like a Mach-Zehnder interferometer with varying arm lengths while the fiber is stretched. This evolution has been analyzed in detail in [85]. In this work the end of the multi-mode interference served as a stop signal for the tapering process that repeatably lead to taper diameters of about 1 µm and a transmission of 99.8 % as shown in Fig. 5.3. The stretching length was about 12 mm in each direction at a speed of 0.02 mm/s (per stage). Oscillations of the transmission in the spectra result from Fabry-Pérot interferences due
5.2 Rolled-up resonant frequency filters

5.2.1 Fiber coupling and sample cleanup

The coupling of on-chip rolled-up microcavities requires a flexible sample movement to align the fiber parallel to the substrate to avoid any contact of fiber and the high refractive index silicon substrate. For this reason a sample holder was mounted instead of the butane torch in Fig. 5.2. This holder consists of an xyz flexure stage for vertical and horizontal movements by piezo actuators or manual adjustment and a kinematic platform\(^d\) for angular movements around the fiber axis and perpendicular to it (pitch and roll). The position of the fiber or the sample was monitored by a CCD camera through a 50X objective that was freely movable in xyz directions with respect to the fixed fiber.

To couple light into a rolled-up microcavity using a fiber a direct contact or a gap of not more than a few 100 nm is required while the tapered fiber should not touch any other objects on the substrate. A small area substrate or a long taper is therefore needed when objects smaller than half the untapered fiber diameter are to be interfaced which is commonly the case considering an average tube diameter of 10–20 µm. In addition, a rolled-up tube is usually part of an array with many neighboring tubes complicating specific coupling.

\(^d\)Thorlabs MAX311 and KM100B
Figure 5.4: Sample clean-up by pick and place of tubes. Removal was achieved by inserting fiber taper into tube and lifting it up (a-c). After detachment even electrostatic forces are sufficient to attach tube to fiber. Placed tubes in corner of substrate for later use (d). Scale bars are 50 μm.

To facilitate coupling under these constraints, the substrate size was decreased to 5×5 mm$^2$ that fits well below the relatively long taper of about 44 mm (including increasing diameter in transition regions). In addition, all neighboring tubes of the selected resonator were removed so that a maximum of one tube per column remained. This clean-up was achieved by a pick and place process by removing tubes with a half taper that was inserted into the tube to lift it up and move it to a different area on the substrate. The half taper was created by manually drawing a fiber with a tweezer and a butane torch to a diameter that provided sufficient stability but was still smaller than the tube diameter. For precise movements the half taper was attached to an xyz-stage. The process is shown in the images in Fig. 5.4.

After the sample was sufficiently cleaned the rolled-up resonator of interest could be interfaced by the fiber as shown in Fig. 5.5. The coupling efficiency was optimized by
5.2 Rolled-up resonant frequency filters

moving the tube along the fiber, that varied in diameter and therefore caused different phase matching conditions [26]. In most measurements tube and fiber were in direct contact to improve stability.

![Diagram](image.png)

**Figure 5.5:** Rolled-up microcavity coupled to tapered fiber. U-shape pattern with lobe is partially visible in the background. Red color results from an additional Al₂O₃ coating to enhance the tube wall thickness. (Compositional image of multiple micrographs taken at different focus depths. Published in Böttner et al. [80])

### 5.2.2 Transmission of fiber interfaced rolled-up microcavities

Figure 5.6 shows the transmission spectrum for a fiber interfaced rolled-up microcavity. The tube has a diameter of 24 µm and a total SiO₂ wall thickness of 235 nm, estimated from the measured diameter and the number of windings derived from the rolling length. The large U-shape pattern design described in section 3.1.1 was used resulting in a bottle microcavity after roll up. Atomic layer deposition was used to coat the tube with aluminum oxide (Al₂O₃) to a total wall thickness of 650 nm. When the fiber was coupled to the central part of the tube as exemplarily shown in Fig. 5.5, two perpendicular states of polarization can be excited when the half-wave plate is rotated by 45° and both states show two sets of modes split up into axial modes due to the axial potential in the microcavity. The respective lowest order (or fundamental) axial mode appears at the long wavelength side of each group of modes. Its theoretical position (only for parallel polarization) is indicated by the black triangles that were calculated by solving the Helmholtz equation in a waveguide ring resonator with thick and thin parts [86].

To clearly identify the polarization, a reference resonator would be required, because the fiber can, in principle, change the known polarization state at the fiber input to any arbitrary state before the light reaches the tube. Still, statements can be made based
5 Fiber interfaced rolled-up microcavities

Figure 5.6: Transmission signals of a fiber interfaced rolled-up microcavity. Two polarization states can be excited. Black triangles mark calculated mode positions. (Published in Böttner et al. [80])

on the following analysis. Before the spectra were taken, first a fundamental mode was identified \((m = 60)\) while the input polarization was aligned roughly parallel to the tube axis and then the polarization was changed until this mode vanished. This reference position was labeled as the perpendicular state relative to the tube axis or 90°. Then a maximum mode visibility for both states at 0° and 90° was confirmed. The spectra with the black solid line corresponds to the parallel or 0° state at the fiber input and the blue dashed spectrum to the perpendicular or 90° state. Since the modes completely disappear after a respective 90° rotation a negligible ellipticity of the light in the fiber can be assumed. The only remaining uncertainty would be a full rotation by multiples of 90° of the linear polarization state due to the fiber. However, this possibility was ruled out later by an indirect identification method based on a spatial mapping of the optical modes which is dependent on polarization as presented in Sec. 5.3.

5.2.3 Effect of the tube wall thickness on resonances in rolled-up microcavities

The microcavities used for the transmission experiments were chosen after quick µPL measurements to ensure the presence of optical resonances before the more sophisticated
5.2 Rolled-up resonant frequency filters

fiber setup was used. Despite this selection, no clear modes were initially visible when the selected tubes were coupled to fibers. Only after coating the microcavities with Al₂O₃ using ALD to increase the initial 235 nm thin tube wall to a total wall thickness of 650 nm, results like shown in Fig. 5.6 became possible. The need for a thicker wall results from the big change of the investigated wavelength range that increased from about 600 nm to 1550 nm. Under these conditions the evanescent field becomes much larger and optical modes suffer from increased losses due to curvature and surface roughness.

Figure 5.7: Predicted effect of increasing the wall thickness on Q factor for a SiO₂ rolled-up microcavity with Q-limiting defects. The Q factors of simulated peaks located around 1550 nm were determined in a tube that initially had a wall thickness of 235 nm and diameter of 24 µm. Details of the modeled tube geometry, including void and step defects, are shown in the inset. (Published in Böttner et al. [80])

To confirm this assumption, the microcavities were modeled in a simulation to calculate the effect of increasing wall thickness on the Q factor at around 1550 nm. The assumed model geometry is shown in the inset in Fig. 5.7. The parameters for the spiral geometry were based on experimental values with a SiO₂ wall thickness of 235 nm and a diameter of 24 µm. Also included are step and interlayer void defects based on the findings of their strong effect on the Q factor as discussed in Sec. 4.1.4. Again Gaussian shaped voids were assumed and their size was adjusted so that the theoretical result matched the experimentally obtained Q factor in the coated microcavity. For this structure the Al₂O₃ coating thickness was then varied and the Q factor simulated as shown in Fig. 5.7. It can be seen that the predicted Q factor rises from 100 to over 1000 with increasing
5 Fiber interfaced rolled-up microcavities

thickness before the effect saturates and defects become again the main limit similar to the previous calculations at around 600 nm. For thin resonator walls as found in tubes without coating, bend losses are dominating (see 4.1.2) and lead to $Q$ factors that could not be detected in this setup. However, thickness enhanced tubes show clear optical modes and demonstrate how rolled-up microcavities could prove useful as resonant components in integrated optical networks at telecommunication wavelengths.

5.3 Near field mapping of resonant modes

In this section the characterization of rolled-up microcavities is extended to mappings of the resonant modes dependent on the degree of polarization and spatial position along the tube axis. Especially the latter is important to understand why the cavities can also be called bottle microcavities. It is furthermore shown that simple single position measurements are incomplete with regard to axial modes because a much richer spectrum is revealed when resonances are excited at different positions along the axial potential well. The experiments and results described and illustrated in this section were published in Böttner et al. [81].

![Figure 5.8: Scanning electron microscopic image of a rolled-up bottle resonator where axial confinement is generated by a lobe structure. U-shaped pattern leads to a lift up of the central lobe section. Inset shows lobe area with indicated mapped region (dotted line). (Published in Böttner et al. [81])](image)

The transmission setup as described previously (Sec. 5.1) with an additional in-line fiber polarization controller is used. This device consists of a single-mode fiber wound
5.3 Near field mapping of resonant modes

around three paddles that can be rotated around the fiber input axis. By moving the paddles, strain is induced on the fiber that causes an adjustable birefringence that in turn influences the polarization state. The fiber connectors of this device were coupled to the free space laser path and the bare fiber shown in Fig. 5.2. The controller was used to optimize the visibility of the resonant modes of a rolled-up microcavity for a given taper and then fixed so that the polarization could be controlled by the half-wave plate which is easier to handle. In principle this device can be used to compensate for possible polarization changes caused by the fiber that could lead to elliptical polarization states. However, in this work no significant improvements of the mode spectra were detected.

The rolled-up microcavity used in this section was fabricated from an 87 nm thick SiO$_2$ membrane deposited on a U-shaped patterned structure according to the geometry described in Sec. 3.1.1 and shown in Fig. 5.8(b). The resulting tube had a diameter of 21.6 µm with three windings and a wall thickness of 261 nm at the central tube part. In addition, the tube was coated using ALD with Al$_2$O$_3$ by 210 nm on each side to enable light confinement at around 1550 nm as described in Sec. 5.2.3. During the lithography process the lobe structure shrinks by about 10% in length and width with respect to the design. This shrinkage is accounted for later in the calculations.

5.3.1 Polarization mapping

As an extension of the brief discussion in Sec. 5.2.1 a full polarization scan is shown here to prove the existence of linear polarization states in the thin-walled microcavities. Here, also the three paddle controller (or bat-ear controller) was used to optimize the visibility of resonant modes for both polarization states. And the half-wave plate was calibrated as before.

Fig. 5.9 shows a full polarization map for a 180° rotation of the half-wave plate. The fiber was always in contact with the tube and transmission scans from 1520 to 1570 nm were taken after every 1° increment of the waveplate. Reference spectra without tube were taken afterwards at 10° intervals and used multiple times, respectively. The larger steps were sufficient due to a low polarization dependence of the setup without a coupled resonator.

Two sets of modes are visible and show a clear linear polarization behavior. Bright fundamental and axial modes are visible for the parallel and perpendicular state. Using the spatial mapping discussed in the following section, the modes at 0° and 180° can be
5 Fiber interfaced rolled-up microcavities

Figure 5.9: Polarization map of rolled-up bottle microcavity. The fiber was coupled to the position corresponding to the center of the axial confinement. Bright areas correspond to dips in fiber transmission spectrum and reveal two linear polarization states. Smoothed by 5 point running average along pol. axis. (Published in Böttner et al. [81])

identified as polarized perpendicular to the tube axis while the modes at 90° and 270° are polarized parallel to the tube axis. This result is important for the following analysis as it simplifies the identification of modes in the spectra.

5.3.2 Spatial mapping

Light confinement in microcavities with axial potential shows analogies to particles trapped in a magnetic bottle potential which lead to the term optical bottle microcavities for this group of resonators [50, 87]. These bottle cavities do not only guide “simple” resonances with circular trajectories along the circumference but also modes that have spiral like trajectories that form modes with several antinodes along the axis as shown in Fig. 5.10. These spiral or axial modes are distributed over a larger area and possess two turning points at the caustics of the resonator. The turning points are useful to couple light in and out of the cavity at different axial positions to create add-drop filters [88]. Moreover, the bottle shape confines and localizes resonances which enhances the Q factor [72] and allows to selectively couple light to specific trajectories as shown in the following in rolled-up bottle resonators.

Earlier experiments that investigated axial confinement in rolled-up microcavities have
5.3 Near field mapping of resonant modes

mainly used far-field collection methods based on µPL spectroscopy [71, 60]. However, these techniques rely and are limited by the presence and performance of optical emitters at the spectral range of interest. More importantly as previously mentioned, to explore the capabilities of the cavities as components in on-chip photonic networks as modulators or filters a transmission configuration is required.

Resonant coupling of fibers in a single-point coupling experiment has already been described in the previous section including the observation of axial modes. However, only a systematic mapping of the modes along the axis can prove their spatial distribution. To perform this mapping, the initially described rolled-up microcavity was again coupled in direct contact to a tapered fiber and the setup was calibrated and compensated with regard to polarization as described in 5.3.1. A spatial mapping was performed by measuring the transmission from 1520 nm to 1570 nm at different coupling positions along the tube axis with steps of 0.5 µm. At each position both perpendicular polarization states were probed to allow a direct comparison of their axial extension. While the tube was moved, the fiber was uncoupled to prevent it from bending that would influence the coupling position accuracy and at the same time an uncoupled reference spectra could be taken.

Fig. 5.11 shows two maps of the taken spectra. A five point running average was performed along the position axis to smooth out varying coupling efficiency for increased clarity of the mapping. It can nicely be seen how the fiber excites different modes depending on its position. In total two to three azimuthal modes in the range of 1520 nm–1570 nm were observed that consisted of up to 11 visible axial modes at shorter wavelengths. It

Figure 5.10: Schematic of microcavity with axial confinement generated by a bottle-like refractive index gradient. Simulated electric field profile of an axial mode is shown excited by the off-center coupled fiber. (Published in Böttner et al. [81])
Figure 5.11: Spatial near field maps of a rolled-up bottle microcavity. The maps are composed from transmission spectra at different positions along the tube axis for both TM polarization (left) and TE (right). Definition of TM/TE notation according to the schematics at the top. (Published in Böttner et al. [81])
can be seen that the intensity of the axial modes becomes weaker with increasing order and eventually overlaps with the next azimuthal mode group. The strongest antinodes can always be found at the maximum spatial extend of each mode and mark the boundaries of the optical confinement as discussed later. At these turning points of the bottle microcavity the propagation direction or the wave vector of the light is perpendicular to the tube’s axis and the overlap with the wave vector of the light in the fiber is maximized, greatly improving the coupling efficiency in contrast to more central positions [50].

When comparing the maps for the two polarization states in Fig. 5.11 one can also see a different spatial extension and a different free spectral range of the axial modes as highlighted by the non-parallel white lines. This can be explained by considering the effective refractive index: The out of plane polarized modes (TE) have a non-continuous electric field at the tube/air interface and consequently a larger part of the mode is guided outside the tube wall. This is not the case for in plane polarized modes (TM) which experience a tighter confinement. In total this leads to a lower effective refractive index for TE modes than for TM modes, causing a narrower spatial confinement and a larger spectral axial mode spacing. This intuitive explanation is expanded by a more detailed theoretical investigation below.

It is important to note, that by selecting an appropriate set of wavelength, polarization and position of the fiber, selective excitation of one specific mode is possible in contrast to µPL where all modes are excited simultaneously. At the same time this selectivity could lead to a wrong interpretation of results when such a cavity is only probed at a single position as the mode spectrum would be incomplete. The polarization map in Fig. 5.9 is a good example because the fiber was coupled to the central part at $\delta = 0$, only. At this position only modes with a central antinode were excited and every second axial mode not excited and missed. In the worst case the free spectral range of axial modes could be wrongly estimated and conclusions on the axial potential width would be incorrect. Or when the fiber is slightly misaligned, different axial mode orders could be excited with varying efficiency and result in non-uniformly spaced modes.

Analysis of different axial confinement of TE and TM modes

The intuitive explanation for the differing potential well widths found in the spatial mapping (Fig. 5.11) are now be supported by a simple theoretical analysis that is based on a model published by Strelow et al. [71] and extended by Shilong Li. When linear
polarization states can be assumed it is not necessary to solve the full vectorial wave equation. Instead, the scalar Helmholtz equation

$$\nabla^2 F + n^2 k^2 F = 0 \quad (5.1)$$

is solved for both polarization states in a bottle shaped coupled thick and thin ring resonator geometry. $F$ is a scalar field, $n$ the refractive index, and $k$ the wave vector in vacuum. To solve (5.1), $F$ can be separated according to the adiabatic approximation as

$$F(r, \varphi, z) = \Phi(r, \varphi; z)\Psi(z), \quad (5.2)$$

where $\Psi(z)$ describes the axial field distribution along the tube's axis $z$, and $\Phi(r, \varphi; z)$ describes the field distribution of the fast circumferential dynamics in the radius, and azimuthal ($r$ and $\varphi$) plane. After inserting (5.2) into (5.1) the Helmholtz equation separates into

$$-\frac{1}{n^2(r, \varphi; z)} \nabla^2_{r, \varphi} \Phi(r, \varphi; z) = k_{\text{circ}}^2 \Phi(r, \varphi; z) \quad (5.3)$$

and

$$\left[-\frac{1}{n^2(z)} \frac{\partial^2}{\partial z^2} + k_{\text{circ}}^2(z)\right] \Psi(z) = k^2 \Psi(z). \quad (5.4)$$

The new term $k_{\text{circ}}(z)$ denotes the wave vector at each position $z$ along the axis and couples equations (5.3) and (5.4). It is obtained from Eq. (5.3) and describes the optical potential or confinement generated by the variation of the tube geometry along the axis. Each polarization state is solved separately by replacing $F$ by the respective field component $E_z$ or $H_z$ for TM and TE modes, respectively while assuming appropriate boundary conditions. To compare the calculation results with the experiment, the data shown in Fig. 5.11 is rearranged into an intensity versus position representation by summing over the respective wavelength range of each mode. The result, including the theoretical data is shown in Fig. 5.12.

A fit of the theoretical model to the experimental data was performed with the aim to obtain a good agreement between the spectral position of theory and experiment. A refractive index of 1.45 for SiO$_2$ and 1.66 for Al$_2$O$_3$ was assumed and the best fit was
5.3 Near field mapping of resonant modes

Figure 5.12: Intensity distribution of resonant modes along the rolled-up bottle microcavity axis for TE and TM polarization states, respectively. The bottle-like potential energy well is drawn with a black line. Crossed symbols represent experimental data and solid colored lines calculated data. The baselines of the distributions indicate the energies of the respective mode while peaks represent scaled intensities. (Published in Böttner et al. [81])

achieved for a slightly larger tube diameter of 24.4 µm with a conical shaped asymmetry of 0.1 % that causes a small shift of the potential compared to the center of the lobe. To achieve a good agreement of TE and TM modes at the same time the ALD thickness was reduced by 2 % in the calculations. For the axial mode fit the radius of curvature at the end of the lobe was varied to 14.4 µm (4 % decrease).

Despite the fitting of the theoretical and experimentally obtained spectral mode positions there is still a discrepancy of the spatial distribution, especially for TE modes. This difference has not been reported in previous works based on µPL where excellent agreement was achieved [71]. Two potential solutions are available. First the convolution of the evanescent field of fiber and resonator due to the finite diameter of the fiber could
cause a deviation as reported in a microsphere mapping experiment [89]. Second, since rolled-up microcavities are sensitive to refractive index changes in their environment the effect could be caused by the fiber that is “sensed” by the resonator which causes a local shift of the optical confinement. This has been reported before and was used to selectively influence axial modes of rolled-up resonators [90]. The sensing effect is supposed to be larger for TE modes due to the non-continuous electric field and the larger evanescent field which would explain the larger discrepancy for the TE mode fit. The simple analytical model presented here cannot account for both contributions because it does not include the presence of the fiber. Still, the model is sufficient to qualitatively support the observation of different axial confinement widths for TM and TE modes which is important for possible future applications where waveguides need to be coupled to the correct axial position.

5.4 Rolled-up add-drop filters

In the previous sections, rolled-up microcavities have already demonstrated their capability as frequency selective filters with potential for later on-chip integration. Here another application is presented, where the tubes act as vertical add-drop filters that route signals between initially independent optical fibers.

In this experiment a thickness enhanced HfO$_2$ coated tube is picked up from the substrate with the method described in Sec. 5.2.1 and then transferred to a tapered “through fiber”. A second tapered “drop fiber” that was previously prepared and glued at its thicker parts to a metallic holder was then also coupled to the picked-up tube in a way that the tube was sandwiched between the two fibers as shown in the schematic in Fig. 5.13(a). The through fiber was connected to the transmission setup as explained before (see Fig. 5.2) and the drop fiber was connected to a second infrared detector but not to any light source. When the wavelength of the input light was scanned from 1520 nm to 1570 nm the signal of both detectors was recorded in parallel.

The result is shown in Fig. 5.13(b), where the through fiber signal is represented by the black solid line and the output of the drop fiber by the red dashed line. The through signal shows three clear resonances that correspond well to the three peaks in the drop spectrum demonstrating that the rolled-up microcavity resonantly transfers light between both fibers. Axial modes are not clearly visible in the spectra which is likely due to the lift-
5.4 Rolled-up add-drop filters

Figure 5.13: (a) Schematic image of a lifted rolled-up microcavity sandwiched between two tapered fibers (red). (b) Transmission spectrum of through fiber (black solid line) and drop fiber (red dotted line). (Adapted from Böttner et al. [80])

An interesting feature of this add-drop configuration for future investigations is the high signal to noise ratio in the initially dark drop fiber that could be useful to detect weak modes which might be otherwise hidden in a noisy through signal. Moreover, from an application point of view, the vertical geometry of the resonator is highly interesting since it is in general difficult to transfer light out of the plane of an on-chip photonic net-
work. Planar add-drop configurations for on-chip applications are abundantly available. For example, microtoroids [91] or silicon ring resonators [92] have been used but these geometries support only in plane light routing. Vertical add-drop filters for out of plane light routing have only been demonstrated in non integratable approaches until now, including microspheres [93] or fiber bottle resonators [94]. Only the vertically rolled-up add-drop filter presented here, combines out of plane light routing and compatibility with large scale integrated silicon microfabrication technologies and is therefore a promising geometry for future three-dimensional multi level optical data processing units. Especially when the axial distribution of modes that was explored in the previous section is combined with the out of plane routing, a highly interesting three dimensional light routing geometry that could even be used for wavelength division multiplexing (WDM) when multiple waveguides are coupled along the axis.
6 Conclusion and outlook

6.1 Conclusion

Rolled-up technology provides a versatile platform to fabricate microcavities and has been used in numerous experimental and theoretical studies. The principle of rolling planar, photolithographically patterned nanomembranes into sophisticated three-dimensional objects renders these structures a promising alternative to previous state-of-the-art integratable resonator designs including planar Si ring resonators. By adapting this fabrication method, it was shown that vertically rolled-up microcavities can be made using low loss SiO$_2$ nanomembranes by exploiting deposition rate gradients [35] during preparation in an electron beam evaporation system. Optical modes in tube resonators can be excited non-resonantly by a free space laser beam at a wavelength of 442 nm that triggers photoluminescence (PL) emission. The broadband PL emission as well as resonances can be detected with a micro-photoluminescence (µPL) spectroscopy setup. It was found that SiO$_2$ rolled-up tubes support sharp resonances with high optical quality factors (Q factors) of 5400 at around 600 nm exceeding values of high refractive index InGaAs/GaAs rolled-up resonators probed in emission. The limits of the Q factor were analyzed experimentally and theoretically to evaluate potential further improvements. It was found that interlayer voids, presumably due to a competition of rolling and wrinkling [76], are the main limits and effects like steps from the spiral geometry have a comparatively small influence.

In addition to single position measurements, spatially and polarization resolved µPL emission maps were acquired. These maps were used to identify different groups of resonant modes including fundamental and axial modes. The latter occur due to an axial confinement in the tube resonators which was created by a varying winding number along the tube's axis. This effect is caused by an extra lobe structure [48] in the patterned nanomembrane. µPL maps proved also useful in studies of atomic layer deposition (ALD)
coated rolled-up resonators. Coatings increase the tube wall thickness so that additional radial modes can be observed and µPL maps help to differentiate the new peaks from axial modes.

To further study light confinement in rolled-up microcavities, and to demonstrate possible applications in optical data processing, a fiber based evanescent-wave coupling setup was developed. Using this approach resonant excitation of modes is possible and experiments are not bound to the spectral emission range of embedded emitters. The development of this setup included the possibility to interface rolled-up resonators directly on their substrates after neighboring tubes were removed by a pick and place process and stored for later use. Optical frequency filtering using fiber interfaced rolled-up microcavities was then shown and, by lifting up a tube and coupling it to two tapered fibers, an add-drop configuration was demonstrated. This vertically aligned rolled-up add-drop filter might serve as an out-of-plane light transfer and filter element in future three-dimensional multi-level optical data processing units [15] which became subject of patent application [95].

It was also shown that tapered fibers can be used to create near-field maps of the electric field of resonances in rolled-up microcavities by coupling the fiber to different position along the axis of a tube. Resonant modes are selectively excited when the evanescent field of the tapered fiber overlaps with the respective field of such a mode so that the spatial mode distribution can be visualized and studied. A polarization dependent axial confinement in the resonators was observed that was further analyzed and explained by a theoretical model. The exact knowledge of the field distribution is important for future waveguide coupling where tubes are directly fabricated on substrates with embedded waveguides.

6.2 Outlook

A plethora of experiments have been demonstrated with rolled-up microresonators up to this date, but still many important aspects are left for further studies. For example, the $Q$ factor can presumably further increase when the formation of interlayer voids is completely understood and avoided using appropriate strain engineering techniques. Extensive theoretical and experimental studies were performed already [96, 57, 58, 76] and need to be applied to the fabrication of SiO$_2$ based rolled-up resonators.
A second example concerns optical interfacing. Tapered fiber and waveguide coupling are well-known techniques to study microcavities, but were only introduced recently to rolled-up microresonators [56, 23, 80]. The implementation of both coupling techniques in tube based sensing applications [14] is highly required to replace free space laser excitation and bulky spectroscopy setups. Fiber coupling could serve as a flexible approach for first demonstrations but in the long run the fabrication of rolled-up tubes on chips with embedded waveguides needs to take over. This evolution is critical to enable large scale fabrication processes that are especially important for on-chip optical data processing applications.

Moreover, a flexible resonance tuning of rolled-up microcavities is of great significance for optical data processing. In this field, many on-chip optical components, including switches or modulators, rely on an active and fast tunability of a resonant element. First approaches to develop such a tunable rolled-up microresonator certainly include all-optical methods, embedded liquid crystals and tuning via carrier injection.

In addition to the topics covered in this thesis, many more promising studies were proposed or are already in progress and require further attention. To mention only two examples, rolled-up photonic crystals [40] and rolled-up metamaterials [97] were introduced recently to enter novel fields of tube based applications. In conclusion, applied and basic research on rolled-up microcavities has the potential to cover an even broader range of topics in future investigations. Especially optical data processing applications, as illustrated in Fig. 6.1, seem appealing due to the unique vertical geometry of rolled-up microcavities and their compatibility with standard Si microfabrication techniques.

Figure 6.1: Artistic view on the future of rolled-up microcavities: rolled-up microresonators coupled to on-chip waveguides for vertical interlayer signal transmission.
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- Poster award at NTT-BRL School, 26.11.2013.
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The end of the trip: Shilong and me at Noordwijk, Netherlands.
We made it!
Selbständigkeitsklärung

Hiermit erkläre ich an Eides statt, dass ich die am heutigen Tag eingereichte Dissertation zum Thema „Rolled-Up Vertical Microcavities Studied by Evanescent Wave Coupling and Photoluminescence Spectroscopy“ unter der Betreuung von Herrn Prof. Dr. Oliver G. Schmidt selbständig erarbeitet, verfasst und Zitate kenntlich gemacht habe. Andere als die angegebenen Hilfsmittel wurden von mir nicht benutzt.

Die Dissertation wurde in dieser oder ähnlicher Form an keiner anderen Stelle zum Zwecke eines Promotionsverfahrens eingereicht. Es wurde von mir bisher kein Promotionsverfahren an anderer Stelle beantragt.

Chemnitz, 22. Januar 2015

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Curriculum vitae

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