Dynamical thermal effects in InGaAsP microtubes at telecom wavelengths

Zhaobing Tian,1,∗ Pablo Bianucci,1,2 Philip J. R. Roche,1 M. Hadi Tavakoli Dastjerdi,1 Zetian Mi,1 Philip J. Poole,1 Andrew G. Kirk,1 and David V. Plant1

1Department of Electrical and Computer Engineering, McGill University, Montreal, Quebec H3A 2A7, Canada
2Department of Engineering Physics, École Polytechnique de Montréal, Montreal, Quebec H3C 3A7, Canada

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We report on the observation of a dynamical thermal effect in InGaAsP microtubes at telecom wavelengths. Rolled-up semiconductor microtubes have been of great interest for photonic integrated circuits due to their simple fabrication method [1], ideal mode confinement, and excellent optical properties. Most previous studies have characterized these microtubes by measuring the emission from the embedded active media (i.e., quantum dots) when pumped by a short wavelength laser. Various effects, including photoluminescence [2–4], Raman scattering [5], lasing [6], and strain effects [7], have been reported using this method. The characterization of these microtubes has typically been limited to the wafer-level, and the measured emission wavelengths have been shorter than telecom wavelengths. Recently, we have proposed a transfer method [8] using abruptly tapered optical fibers to reposition microtubes, allowing characterization at telecom wavelengths by means of evanescent mode excitation. This technique allowed studies of the highest cold cavity Q-factor [9] and selective mode excitation [10] in microtubes. To date, however, no dynamical nonlinearities have been demonstrated in microtubes at telecom wavelengths. Of all the nonlinear dynamical effects observed in microresonators, thermal non-linearities [11] are the ones usually observed first. Nevertheless, even though thermal effects have been used to implement a cross-wavelength modulation in a microtube [9], this dynamical thermal effect has remained unexplored. This effect needs to be considered in microtube applications. It is important to avoid it in passive devices, or it can be exploited in active applications. In this Letter, we demonstrate this dynamical thermal behavior in InGaAsP microtubes with embedded InAs quantum dots at telecom wavelengths.

The bilayers (bottom: 38 nm thick In0.37Ga0.63As0.41P0.59; top: 15 nm thick In0.68Ga0.32As0.41P0.59) used for the fabrication of the microtubes were grown on a semi-insulating InP (001) substrate using chemical beam epitaxy. Two layers of InAs quantum dots were embedded in the bottom layer as the active medium. Figure 1 shows the photoluminescence spectrum of the bilayer pumped by a 636 nm laser with peak emission at 1455 nm. U-shaped patterns are defined on the bilayer using lithographic processes. By selectively etching the InP layer using HCl:H2O (2:1) over 15 minutes, the bilayer rolls up due to the release of stress. The middle section of a microtube, showing surface modifications that provide three-dimensional (3D) confinement [4,12], is shown in the inset in Fig. 1. Microtubes have a diameter of 4–5 μm, a wall thickness of 50–100 nm, and a length of 50–150 μm.

An optical fiber was abruptly tapered down through a splicer machine to a tip diameter of 1 μm and a tapered length of approximately 300 μm. This abrupt taper was used as a transfer probe [8] to transfer the InGaAsP microtubes. After the microtube was picked up, an adiabatic tapered fiber was used to couple the light into the microtube, as shown in Fig. 2. The adiabatic taper fiber was fabricated by using a butane flame, having a waist diameter of 1 μm and a tapered length of around 2 cm. After its fabrication, the adiabatic taper was fixed on a glass slide by using wax on the nontapered regions at both ends. The coupling between the microtube and adiabatic taper was controlled by adjusting the microtube in X, Y, Z planes and an axial rotation. To explore the coupling positions, an erbium-doped fiber amplifier

Fig. 1. (Color online) Photoluminescence spectrum from the quantum dots embedded in the as-grown semiconductor bilayer pumped by a 636 nm laser (inset is a SEM image of an InGaAsP microtube).
(EDFA; wavelength range 1520–1600 nm) and an optical
spectrum analyzer (OSA; 0.06 nm resolution) were
used as the source and the detector due to the fast scan speed
of the OSA. Afterwards, to characterize the coupling
more precisely, a tunable laser (wavelength range
1500–1650 nm with a scanning step of 10 pm) and a
power meter were used instead of the EDFA and the
OSA. To study the selective polarization mode excitation
of the microtube, a polarization controller was placed
after the tunable laser. Modes with electric or magnetic
field parallel to the axial direction of the microtube
are defined as transverse electric (TE) or transverse
magnetic (TM).

The normalized transmission spectra under TE and
TM mode excitations are shown in Fig. 3. There are
no obvious resonance modes under TM excitation due
to the scattering loss of mode in the thin wall of the
microtube, demonstrated also in [10]. There are three
major resonance modes at 1525 nm, 1578 nm, and
1634 nm under TE excitation. The typical insertion loss
due to the microtube is around 2 dB. The broadest line-
width of the resonance mode at shortest wavelength
indicates that this mode has the largest loss. The loss
normally consists of absorption and scattering; the scat-
tering loss is nearly wavelength independent in an ideal
microcavity. From the photoluminescence measurement
in Fig. 1, it can be concluded that the absorption of the
InAs quantum dots embedded in the wall of the
microtube declines after 1600 nm. Hence the mode at
the shortest wavelength is most strongly absorbed.

The normalized transmission spectra under various
power TE excitations are shown in Fig. 4. When the exci-
tation level increases by 4 dB, the modes near 1525 nm
and 1578 nm are red shifted by 7 nm and 5 nm, while the
1634 nm resonance remains unchanged. Figure 3 also
demonstrates the modes at shorter wavelengths are
affected by absorption from the InAs quantum dots.
When the mode near 1525 nm or 1578 nm is excited,
the absorption of the resonator increases temperature.
The resonant wavelength is red shifted due to the
diameter increase (up to 20 nm) and change (up to
0.016) in refractive index of the wall of the microtube
with the increasing temperature. Other than the red
shifted spectrum, it is more interesting to notice the
change in the spectral shape. A very sharp rising edge
is observed for the modes at 1525 nm and 1578 nm under
the highest power TE excitation, indicating a dynamical
thermal effect [11]. Such an effect can be explained as
follows when the laser is tuned to longer wavelengths,
which is the case in our experiment. First, we note that
the maximum shift of the resonance mode is proportional
to the power of the mode excitation. When the wave-
length of the laser is slightly tuned over the resonance
mode wavelength, the optical power inside the micro-
tubes starts to drop due to the wavelength mismatch
of the laser and resonance mode. Then, the resonance
mode blue shifts due to the cooling of the microtube,
resulting in a further wavelength mismatch between
the laser and the resonant mode. This process continues
until the microtube reaches thermal equilibrium, and the
time (several milliseconds) of the whole process is much
shorter than the time required for a laser tuning step
(approximately 0.1 second), and a sharp change in the
resonator transmission results. Therefore, a ~3 dB step
rising edge is observed for the modes at 1525 nm and
1578 nm at 10 dBm input optical power. The microtube
can be utilized as an active device (i.e., Q-switch) at
wavelengths near 1525 nm and 1578 nm where the ab-
sorption of the quantum dots is significant, or a passive
device (i.e., filter) at wavelength near 1634 nm, where
the absorption of the quantum dots is ignorable.

This absorption induced thermal effect can be visual-
ized by the generation of pairs of microbottles on an
adiabatically tapered fiber. A thin layer of wax was
coated on the second adiabatic taper before the coupling,
and the transmission spectrum is shown as the solid
curve in Fig. 5, where there is no obvious mode

Fig. 3. (Color online) Normalized transmission spectra under
TE or TM mode excitation.

Fig. 5. (Color online) Transmission spectra of the tapered
fiber only before and after the generation of a pair of
microbottles.
interference due to the single mode propagation in the tapered section. Raman measurements of the glass slide and adiabatic taper fiber are shown in Fig. 6. When a shorter wavelength resonant mode (i.e., 1530 nm) is excited in the microtube, a pair of microbottles is generated, as shown in the left part of Figs. 7(a)–7(e) and 7(f). The new formed microbottles have a diameter of 2–3 μm, a length of 3–4 μm, and a separation distance of 20 μm. The transmission spectrum of the adiabatic taper with the pair of microbottles is shown as dashed curved in Fig. 5. These microbottles introduce an additional insertion loss of 16 dB. Additionally, a faint interference pattern with an extinction ratio of 1 dB and a free-spectral-range of 45 nm can be noted in the spectrum. This pattern is due to the Fabry–Perot effect between these two microbottles. The microbottle composition was confirmed by Raman spectroscopy. The peak around 3100 cm$^{-1}$ (Fig. 6) at the fiber curve indicates C–H bonds from the wax as expected. After the first pair of microbottles is fabricated, there was no obvious damage found on the microtubes. The generation of microbottles is repeatable. When the microtube is placed next to the adiabatic taper fiber on the right side of an already existing pair of microbottles (since the light propagates from right to left), a second pair of microbottles is generated [as shown in the right part of Figs. 7(a)–7(e), 7(g), and media 1]. However, when the light wavelength is tuned at longer wavelength (1640 nm), there is no generation of the microbottles. The formation of the microbottles with short wavelength excitation is consistent with the observed thermal effects in the microtube. When the short wavelength light is coupled into the microtube, the photon absorption turns the microtube into a localized heat source and with a temperature greater than the wax melting point (55–60 °C), resulting in the thermal gradient of over 500 °C/mm. Hence, the wax coating on the adiabatic taper fiber melts and flows away from the microtube, forming a microbottle shape due to the thermal gradient [13]. As a result of the scattering loss at the microbottle sections, the light intensity in the microtube drops dramatically (as is shown in the dashed curve in Fig. 5). Hence, the microtube cools down, and the melted wax ceases to flow and solidifies as microbottles. The generation of a pair of microbottles usually takes 1–2 s, and these microbottles are significantly smaller than those previously reported [14]. These new microbottles and their fabrication method can be of great interest in the microcavity study, and investigation of highly localized thermal gradients.

In summary, we have demonstrated a dynamical thermal effect in InAs/InGaAsP quantum dot microtubes at telecom wavelengths. Such photon absorption induced thermal effect can be visualized by generating pairs of microbottles. This effect can be avoided or exploited by choosing appropriate resonant excitation wavelengths.

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Reference