Selective polarization mode excitation in InGaAs/GaAs microtubes

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Received May 31, 2011; revised August 4, 2011; accepted August 4, 2011; posted August 5, 2011 (Doc. ID 148185); published September 1, 2011

We report on selective polarization mode excitation in InGaAs/GaAs rolled-up microtubes. The microtubes are fabricated by selectively releasing a coherently strained InGaAs/GaAs quantum dot layer from its host GaAs substrate. An optical fiber abrupt taper is used to pick up the microtube, while an adiabatically tapered optical fiber is used to couple light into the resonant optical modes of the microtube. By varying the polarization of the light in the adiabatically tapered fiber both transverse electric and transverse magnetic modes are observed in the microtube. We also show that the microtube can be used as a red (660 nm) to infrared light (1.5 μm) optical-optical modulator taking advantage of the thermal-optical effect. © 2011 Optical Society of America

OCIS codes: 3506 OPTICS LETTERS / Vol. 36, No. 17 / September 1, 2011

InGaAs/GaAs rolled-up microtubes are of great interest due to their excellent optical properties, their combination of top-down and bottom-up assembly, and their potential for integration with photonics technology. Most of the current research so far has focused on the study of microtubes with a typical emission range shorter than 1.3 μm. The studied phenomena include photoluminescence [1–3], Raman scattering [4], microlasers [5], and strain effects [6] around these wavelengths. Despite this surge in activity, there have not been studies of this microtube at wavelengths near 1.55 μm. The absorption loss of InGaAs/GaAs at this wavelength is small, thus making these microtubes ideal as microresonators for integrated optical circuits. We have recently reported an approach to safely and precisely transfer InGaAs/GaAs microtubes from their host substrate to any other target using an abruptly tapered optical fiber [7]. With this approach, we were able to integrate microtubes onto grating-coupled silicon-on-insulator waveguides and perform transmission experiments [8]. In this case, as a result of the polarization selectivity of the grating coupler, only transverse electric (TE) modes could be excited in the microtube. This makes the study of transverse magnetic (TM) modes of InGaAs/GaAs microtubes at 1.55 μm difficult. Therefore, we have to find another technique for studying the polarization properties of the microtube, with applications such as polarization filtering [9] in mind.

In this Letter, we report on selective polarization mode excitation in InGaAs/GaAs microtubes using an adiabatically tapered fiber. By controlling the light polarization in the adiabatically tapered fiber, both TE and TM modes can be excited individually. Detailed studies also confirm that the microtube can function as a red to infrared optical-optical modulator utilizing the thermal-optical effect.

Free-standing InGaAs/GaAs microtubes with embedded InAs quantum dots were fabricated on a GaAs substrate, with a 50 nm AlAs sacrificial layer, as described in [5,10]. The diameter can be precisely tuned by varying the layer structure [11], while the wall thickness and length are defined by the photolithography mask. There are surface corrugations patterned (right inset of Fig. 1) in the microtube free-standing region to provide mode confinement along its axial direction [7,8,10,12]. Figure 1 illustrates a microtube with a diameter of ~7 μm and length of larger than 100 μm. In previous studies [1–7], microtubes with thicknesses of less than 150 nm are fabricated. For such thin-walled tube structures, only TE modes are guided, due to much less mode confinement for TM modes [13], wherein TE and TM modes are defined with the electrical field parallel and perpendicular to the tube surface (left insets of Fig. 1), respectively [1]. Therefore, we choose microtubes with larger wall thickness (~250 nm, five rotations) supporting both TE and TM modes for the following experiments.

When a standard telecommunications optical fiber is tapered down to less than 1 μm, it supports only the fundamental mode LP01. Depending on the taper angle and micro distortion, the tapered fiber can be classified as being adiabatic or nonadiabatic. Figure 2 shows the spectra of an adiabatically and a nonadiabatically tapered fiber. Although the waists of both the tapered fibers are similar (as shown in the inset of Fig. 2), slight distortions during the tapering process lead to the excitation of higher order modes in the nonadiabatically tapered fiber. As a result of phase delay between these higher order modes, the polarization state of the light changes. These distortions are not present in an adiabatically tapered fiber. As a result, only TE modes propagate in the adiabatically tapered fiber.

Fig. 1. (Color online) Optical microscope image of an InGaAs/GaAs microtube. (Left insets show schematic of TE and TM modes in the microtube, and right inset shows the free-standing part with surface corrugations).
modes and the fundamental mode LP\textsubscript{01}, a spectrum with more than 30 dB extinction ratio and several nm free spectral ranges (FSRs) are observed, as illustrated by the solid curve in Fig. 2. By controlling the taper profile to satisfy the adiabatic condition, the taper can have a wavelength independent transmission spectrum while maintaining a waist of 1 \( \mu \text{m} \), as shown in the dashed curve in Fig. 2. In the following experiment, an adiabatically tapered fiber is used to couple light into the microtubes. An abrupt taper is used to extract a microtube from its host substrate and hold it for the following experiment. Details of the transfer process can be found in [7].

Figure 3 shows a schematic of the experimental setup for the microtube/adiabatically tapered fiber coupling. A single-mode fiber SMF-28 was used to propagate the light from a 1.5 \( \mu \text{m} \) light source to a detector. The middle of the SMF-28 fiber was adiabatically tapered down to 1 \( \mu \text{m} \) to support only the LP\textsubscript{01} mode. A 1.5 \( \mu \text{m} \) linear polarizer before a CCD camera analyzes the polarization of the scattered light from the InGaAs/GaAs microtube.

First, an erbium-doped fiber amplifier (EDFA) and an optical spectrum analyzer (OSA) were used as the light source and detector for initial alignment because of the fast scan speed of the OSA. Then a tunable laser and power meter were used as light source and detector for more precise measurement. By moving the free-standing part of the microtube along the three linear directions (\( x, y, \) and \( z \) axis) and rotating along its axial direction, we can optimize the coupling to the microtube. A polarization controller after the tunable laser optimizes the polarization of light at the contact point of taper and microtube and ensures a near linear polarization there. The resulting transmitted spectra for both TE and TM polarizations are shown in Fig. 4. There are multiple TE modes, with the major modes at around 1524 nm and 1553 nm. By changing the input light polarization, a new set of TM modes around 1505 nm, 1533 nm, and 1564 nm appear and the previous modes disappear. The resonance wavelengths \( \lambda \) of TE/TM modes can be determined by

\[
\lambda = \frac{\pi D n_{\text{eff}}}{m},
\]

where \( D \) is the diameter of the microtube (\( \sim 7 \mu \text{m} \)), \( n_{\text{eff}} \) is the effective refractive index of the resonance mode, and \( m \) is an integer. The separation between the major azimuthal TE/TM modes (which we consider as FSR, neglecting smaller higher order modes) are 28–31 nm, close to calculated value of 32 nm, which we can find assuming a ring-like geometry and using the equation

\[
\text{FSR} = \frac{\lambda^2}{n \pi D},
\]

where \( \lambda \) is the resonant light wavelength (1.55 \( \mu \text{m} \)), and \( n \) is the refractive index of GaAs (3.4). The agreement between the experimental and calculated FSRs demonstrates that the microtube has whispering-gallery-like resonant modes. The mismatch of the resonance wavelengths between TE and TM modes is due to the slight difference of mode propagation constants between these two polarizations. The smaller linewidth of TM modes compared to TE modes can be due to the perturbation of the tapered fiber (i.e., TM modes are closer to the critical coupling point than TE modes). To our knowledge, this is the first experimental demonstration of TM mode excitation in a semiconductor tube cavity at transparent wavelengths. Therefore, the microtubes could be used as polarization filters, provided that the wall thickness is large to support both TE and TM modes.
A 1550 nm mode locked laser (with 500 femtosecond pulses) was used as a light source for optical mode imaging since other sources were not strong enough to be recorded by the CCD camera. Figure 5(a) shows the optical image of the microtube and the adiabatic taper under visible light illumination. When the illumination light is off and the polarization of the input light from the mode locked laser is optimized to excite TE mode, a very clear mode image is observed around the microtube, as shown in Fig. 5(b). When the transmission axis of the polarizer aligns with the y or z axis, the optical mode image appears or vanishes. Therefore, the mode image observed in Fig. 5(b) is confirmed to be TE polarized. Changing the polarization of light from the mode locked laser, the mode image dims considerably and very weak scattered light is observed, as shown in Fig. 5(c). The failure to observe TM mode image is due to the central wavelength of the tunable laser being far away from the TM mode resonance wavelengths, as shown in inset of Fig. 4, resulting in less TM mode excitations.

To study the modulation response of the microtube, a 1 mW 635 nm laser was used as the pump laser through the abrupt taper, and the 1.5 μm tunable laser was used as the probe laser through the adiabatic taper. By pumping the microtube through the abrupt taper, both TE and TM mode spectra are observed to shift to longer wavelengths. The thermo-optic effect is given by

$$\frac{\delta n}{\delta T} = -\frac{n}{4E_g} \times \left( \frac{\delta E_g}{\delta T} \right),$$

where $T$ is the temperature, $E_g$ is the bandgap of GaAs (1.42 eV), and $\delta E_g/\delta T = -0.45$ meV/K for GaAs [14], leading to an increase in the refractive index of the semiconductor material with temperature. The shift of the resonant modes due to this thermo-optic effect will cause changes in the transmission of light initially tuned to a mode and this can be used in a modulation scheme.

To test this scheme, the pump laser was directly modulated at 500 Hz and the probe laser was set to the TM mode resonance wavelength of 1533.62 nm (we chose the TM modes because of their narrower linewidth), as shown of point A in Fig. 6(c). A 125 MHz photoreceiver was used to detect the modulated probe laser, as shown in Fig. 6(a), where the 500 Hz modulation is successfully transferred from the red light (0.6 μm) to infrared light (1.5 μm). When the probe laser wavelength is reset to 1533.82 nm, as shown of point B in Fig. 6(c), the modulation is shown as Fig. 6(b), with 1 kHz repetition. The mechanism for generating double repetition frequency is as follows. When the pump laser is switched on, the TM resonance wavelength is shifted from 1533.62 nm to 1534.10 nm. As a result, the 1533.82 nm probe laser is attenuated for the first time during this shift, and it is attenuated for the second time when the pump laser is off.

In conclusion, we utilized an abrupt taper fiber to pick up the InGaAs/GaAs microtube, and used an adiabatically tapered fiber to couple light at 1.55 μm in and out of the microtube. Both TE and TM modes were experimentally observed, depending on the light polarization in the adiabatically tapered fiber. The microtubes could function as polarization filters, provided that they support both TE and TM modes. Pumping the microtube by a 635 nm laser caused the spectrum shift to a longer wavelength. The microtube can work as a red light (0.6 μm) to IR light (1.55 μm) optical-optical modulator utilizing the thermal-optic effect.

This work is supported by the Natural Science and Engineering Research Council of Canada, and the Nanofabrication Facility at McGill University. The authors thank the effort from Mr. Jonathan Buset.

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