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Article

Rapid and high precision measurement of opto-thermal relaxation with pump-probe method

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ABSTRACT

Opto-thermal relaxation is one of the most important properties of nonlinear optical materials. Rapid and high precision measurement of this parameter is vital in both fundamental research and applications. Current measurement uses either complicated structure with poor precision or high power heating source with low efficiency. Here, we propose a pump-probe method (PPM) to optically measure the thermal relaxation using whispering gallery mode (WGM) microcavities. When the pump laser shines on a microcavity, the materials absorb the input power resonantly and heat up. Then the heat dissipates from the cavities to the surroundings. The opto-thermal effect induces a refractive index change reflected in the signal light transmission spectra. By analyzing the curve character of the transmission spectra of the signal response in the spontaneous relaxation process, the thermal relaxation time can be rapidly measured with high precision. Additionally, we systematically verify the PPM using microtoroids under various pump powers and at various locking points of the signal laser mode. The small rate of refractive index changes ($\sim 10^{-8}$) can be discerned with an input pump power as low as 11.816 μW. Hence, the PPM can be used to detect refractive index perturbation, like gas or liquid sensing, temperature fluctuations with ultra-high sensitivity and be applied to optical materials analysis efficiently.

1. Introduction

Optical nonlinearity is widely studied as a key factor for on-chip optical information processing [1–4]. The nonlinear optical (NLO) materials are deeply exploited due to their tremendous applications in various fields [5–7], like electro-optic modulation, acousto-optic switching, lasing, etc. The requirement of a high optical power or long light-matter interaction length multiply the difficulty in achieving the nonlinearity in a small scale. Whispering gallery mode (WGM) optical resonators [8–10], with circular geometries that can confine light in a small volume with ultra-high quality factors (Q), can significantly enhance light-matter interactions and be integrated as functional optical devices on a chip. Consequently, WGM optical microcavities are widely studied in various fields including sensing [11–17], lasing [18–22], optomechanics [23–27], and nonlinear optics [28–33]. Nonlinear effects like opto-thermal effect [34–36] can be easily observed in an ultra-high Q microcavity and usually regarded as a triangle broadening shape in transmission spectra owing to the resonant wavelength shift when the pump laser wavelength is scanned across the resonance of a microcavity mode. The optical absorption of light that results in refractive index change would also induce phenomena like thermal bistability [37,38], and thermal oscillation [39,40]. These opto-thermal effects have been applied in temperature sensing [41] and infrared light detection [42]. The measurements of the thermal property of NLO materials can give us information about the optical material structure, phonon energy and heat diffusion coefficients [43–46].

In this letter, we propose the PPM to study the thermal relaxation process and measure the thermal relaxation time of silica using the WGM optical microcavities. Thermal relaxation time, as one of the most important coefficient of thermal property, describes how fast the heat transfers from mode volume to the surroundings. Various methods measuring the thermal relaxation time without resonators uses high power pulse laser and fast electric-optic response, which are complicated structure with poor precision or high power heating source with low efficiency. Besides, the previous method in Ref. [45] using microcavities to measure thermal relaxation time relies on repeatedly recording

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thermal broadening spectra distance between two nearby optical modes at various input powers and then fitting curve to get one value. Their method is on the assumption that the spectra distance remains unchanged of these two adjacent modes and iterant measurements are required to get a thermal relaxation time. However, the PPM is much simpler and more efficient, as the thermal relaxation time can be measured individually and timely. Moreover, confirmed in our experiments, our method is independent of many conditions like input pump powers, pump light modes, polarizations, signal light modes, etc. Additionally, our method provides an effective way to monitor refractive index change in real time. In the end, we systematically study the transmission spectra of the signal response at various input power of pump laser and in various locking points of signal light modes.

2. Methods

2.1. Sample fabrication

Silica patterns were firstly prepared using standard photolithography techniques and HF etching on the silica wafer. The silicon substrate was then isotropically etched by xenon difluoride (XeF_2) to form silicon pillars. Finally, microtoroids were obtained by reflowing the disks with a CO_2 laser [9]. The microsphere was fabricated by inserting the fiber stem with the coating stripped off into the optical fiber fusion splicers. The fiber end would be melt under high voltage of the electrodes and shrinked as a sphere smoothly.

2.2. Laser wavelength locking method

The resonant modes of the optical microcavities are analyzed using a continuous-wave tunable laser (NewFocus TLB-6700) linearly scanning its wavelength, which is controlled by a triangle wave generated by the function generator. First, a resonant wavelength value would be roughly found by a fast wavelength scanning process from short wavelength to longer wavelength. Then we stop scanning and set the laser in such wavelength. Next, setting the function generator to a square wave with duty cycle of 99% at 1 mHz, and by manually changing the offset, we precisely tune the wavelength to its resonant point with a step of 1 mV. The transmission of signal laser is monitored simultaneously during this process. When the lowest transmission value is observed, the laser is locked to its resonant mode successfully.

2.3. Experimental setup

The experimental setup is shown in Fig. 1. A continuous-wave tunable laser of about 1440 nm wavelength as the pump laser is coupled into the microcavity through optical fiber. The wavelength is linearly scanned, which is controlled by a triangle wave generated by function generator. Another continuous-wave tunable laser of about 1540 nm wavelength as a signal laser is not scanned but fixed at certain wavelength near resonance of a cavity mode and then it is controlled by function generator to slightly tune the wavelength so that it is locked on-resonance (details in Section 2.2). The 50/50 fiber coupler is used to combine pump laser and signal laser so that they are coupled into one microcavity through the fiber taper-optical microcavity evanescent side-coupling scheme. Two individual fiber-based polarization controllers are used to adjust polarizations to get the optimized coupling strength. The output light is first decoupled by a 10/90 coupler. The 10% of light is connected to the optical spectra analyzer (OSA) to get wavelength spectra and the 90% of light is subsequently divided by 1440/1540 wavelength division multiplexing (WDM) and detected by two photodetectors, which are connected to an oscilloscope to monitor each transmission spectra.

3. Results

The mechanism of our method is illustrated in Fig. 2a. The continuous-wave tunable pump laser is scanned across the modes of microcavity. As the pump laser is gradually up-scanned from shorter to longer wavelength, lots of power is resonantly absorbed by the silica microcavity, which heats the microcavity and results in the effective refractive index shift owing to opto-thermal effect. In our case, the silica has a positive opto-thermal coefficient, the resonant wavelength redshifts during the pump laser up-scanning process (the dash line (red online) in the region I). Since the signal laser is locked in a fixed wavelength near on resonance (solid dot (green online) named “locking point”), the transmission of the signal laser will therefore change from the initial fixed lower

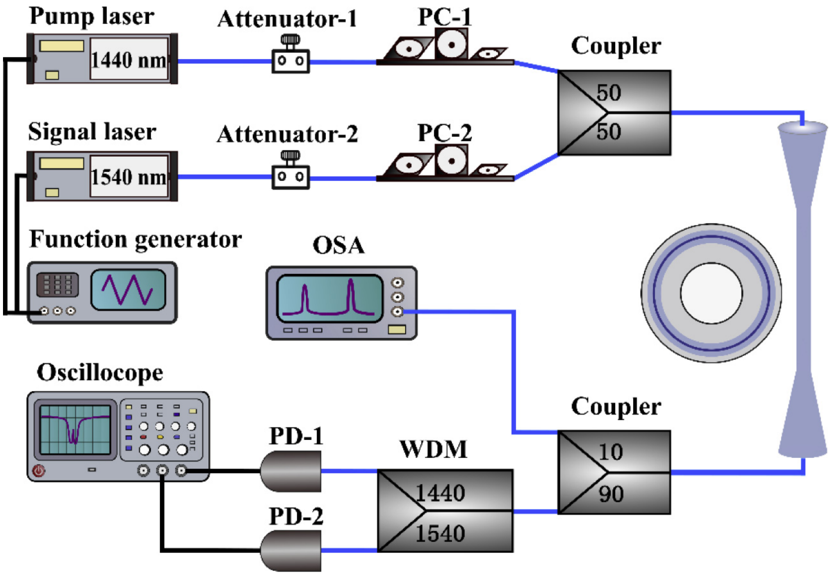

Fig. 1. (Color online) Illustration of experimental setup: PC, polarization controller; PD, photo detector; OSA, optical spectra analyzer; WDM, wavelength division multiplexing.