Characterization of Thermal Induced Nonlinear Effects in Silicon Microcylindrical Resonators

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Abstract: We explore the thermal nonlinearity in hydrogenated amorphous silicon microcylindrical resonators that are fabricated from the silicon optical fiber platform. In particular, we use a pump/probe technique to experimentally determine the thermal response time from which we can infer the material absorption coefficient.

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1. Introduction

In recent years ultra high quality factor (*Q*) and small mode volume WGM resonators have been fabricated in various dielectric and semiconductor materials. The unique properties of the resonators, such as low power nonlinearities, have enabled many applications ranging from metrology to all-optical signal processing. In particular, silicon WGM resonators fabricated from the silicon-on-insulator (SOI) technology have been investigated to show all-optical functionalities such as switching, modulation and memory devices [1]. In a recent demonstration we proposed an attractive alternative approach to standard SOI WGM microresonators, by fabricating a high *Q* hydrogenated amorphous silicon (a-Si:H) microcylindrical resonator from the silicon fiber platform [2]. One of the main advantages of this method is that the resonator's surfaces are ultra smooth so that the surface scattering losses are negligible compared to those based on SOI technology. Furthermore, resonators of various sizes and materials can be easily produced, and the process is relatively inexpensive.

In this paper we explore the thermally induced nonlinear effects in a-Si:H fiber based microresonators. It is well known that, at sufficiently high *Q*, silicon WGM resonators can operate in a regime where relatively small input powers can lead to large thermal nonlinearities. Owing to the large thermo-optic effect of a-Si:H, the refractive index increases due to an increase in resonator temperature associated with the absorbed power. The thermal nonlinearity can be exploited as an efficient means to induce modulation. Using a simple modulation experiment we determine the thermal response time, associated with how fast the temperature of the optical mode changes, and show that this can be used to infer the absorption coefficient of the a-Si:H microresonator. This method is non-destructive, localised to the point of measurement and applicable to a wide variety of geometries, including bottle or bubble shaped WGM resonators.

2. Fabrication and Characterization

We have based our investigations on a a-Si:H core fiber with a 5.6 µm diameter, with a linear loss of 2.5 dB/cm at 1.55 µm, as measured by the standard cut-back measurement. The silicon resonator is fabricated using a two-step process. Firstly, the semiconductor is deposited into a silica capillary using the high pressure microfluidic chemical

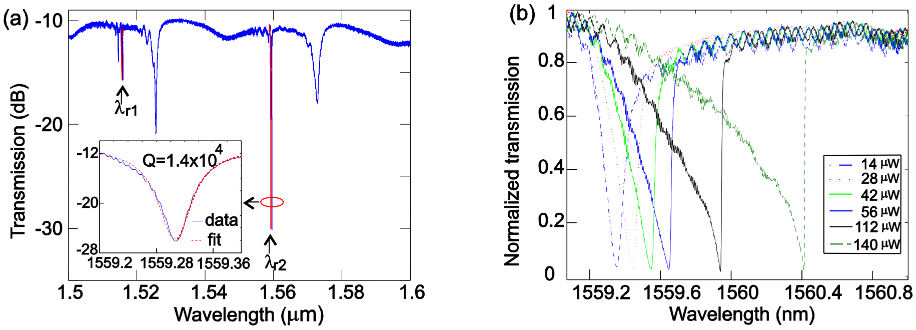

Fig. 1. (a) Transmission spectrum, λ_{r1}~1.515 µm and λ_{r2}~1.56 µm, with measured loaded *Q* factors, $Q_{r1}=1.8\text{x}10^4$ and $Q_{r2}=1.4\text{x}10^4$, respectively. Inset: Lorentzian fit to determine *Q* for 1.56 µm resonance, at ~14 µW of coupled power. (b) Transmission as a function of coupled input power.

deposition technique [3]. The silica template is then completely etched away from the a-Si:H core fiber, using a buffered HF solution, producing the microcylindrical resonator.

A tapered single mode fiber is used to probe the resonator's optical properties over an extended telecoms band. The transmission spectrum in Fig.1(a) shows the sharp resonances associated with the WGM of the resonator. To demonstrate the thermal nonlinearity which manifests as a red shift of the resonant wavelength, a set of power dependent experiments were undertaken by scanning over the resonance at 1.56 µm, as shown in Fig.1(b).

3. Results and Discussion

The experimental setup used to determine the thermal response time relies on a pump/probe method. Two tunable lasers are tuned to WGM resonances λ_{r1} (pump) and λ_{r2} (probe), shown in Fig.1(a), and launched into the tapered fiber. A bandwidth tunable filter was used at the output to isolate the probe, which was monitored on an oscilloscope. The pump was then modulated to produce a thermally induced refractive index change in the resonator which shifted the WGM resonant frequency with respect to the probe wavelength, resulting in its modulation. A fast Fourier transform based post processing of the results confirms that the probe beam acquires a strong Fourier component at the modulation frequency of the pump beam.

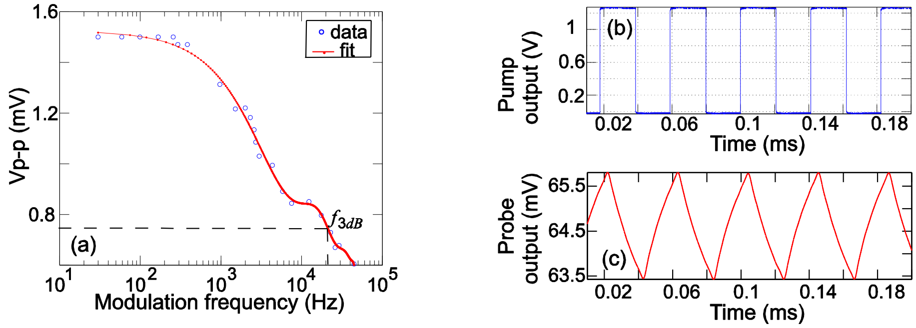

Fig. 2. (a) Measured amplitude response of the probe beam as a function of the modulation frequency of the pump signal. The dashed lines show a 3 dB corner frequency of 21 kHz. (b) Pump input signal at 21 kHz and (c) corresponding probe output signal also at 21 kHz.

Fig.2(a) shows the measurement of the peak-to-peak amplitude (Vp-p) of the probe beam versus the modulation frequency. At lower frequencies a flat response is observed, indicating that the thermal response time is faster than the modulation speed. However, at higher frequencies, when the modulation is faster than the response time, a roll-off in the amplitude is observed. From the system response shown in Fig.2(a), a 3 dB corner frequency of 21 kHz can be measured. Using the usual bandwidth convention the thermal response time can be estimated as $\tau_\theta = 1/(2\pi f_{3dB}) = 7.5\ \mu s$. Fig.2(b) shows the pump signal and Fig.2(c) shows the probe output signal measured by the oscilloscope, at the corner frequency of 21 kHz.

The thermally induced resonant wavelength shifts can then be used to estimate the linear absorption coefficient α. Firstly τ_θ is used to calculate the absorbed power in the cavity then the intra-cavity energy is estimated at various input powers. The value of α can then be obtained from a fit to the absorbed power versus cavity energy using a method based on that in Ref. [4]. As the radiation and surface scattering losses can be assumed to be negligible for our fiber based resonators [2], we obtain α~3 dB/cm which is in good agreement with the material losses estimated from the cut-back measurements.

In conclusion, the thermal nonlinearity in atomically smooth, high quality a-Si:H fiber based microresonators can be exploited to achieve amplitude modulation, which is used to determine the thermal response time. The resonance wavelength shift can then be used to obtain the linear absorption coefficient. This characterization method has the advantage that it is non-destructive and can find application in bottle or bubble shaped WGM resonators, where the cut-back measurement is difficult to perform.

4. References

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