Kerr Nonlinear Switching in a Core-shell Microspherical Resonator Fabricated From the Silicon Fiber Platform

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Kerr nonlinear switching in a core-shell microspherical resonator fabricated from the silicon fiber platform

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Abstract: We investigate the Kerr nonlinearity in a core-shell microspherical resonator fabricated from a silicon fiber. By exploiting the ultrafast wavelength shifting, sub-picosecond modulation is demonstrated.

OCIS codes: (140.4780) Optical Resonator; (140.3948) Microcavity Devices; (160.6000) Semiconductor Materials.

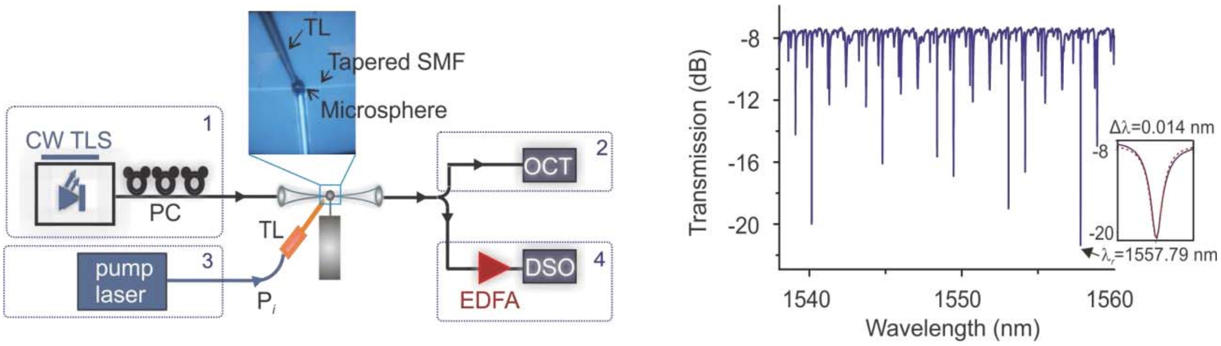
1. Introduction

Efficient light-matter interactions in whispering gallery mode (WGM) microresonators with ultra-high quality factors (Q) and small mode volumes are of interest for the development of compact and low power photonic devices. To date, some of the largest Q factors (10^8) have been obtained in silica fiber resonators owing to the extremely low material loss and ultra-smooth outer surfaces [1]. However, compared to crystalline materials, silica has limited functionality, i.e., lower thermal and Kerr nonlinearities, which restricts the tunability of the resonators.

In this paper we investigate a core-shell microspherical resonator shaped out of an optical fiber with a silicon core surrounded by a silica cladding. The resonator is still silica-based, i.e., the circulating mode is confined by the pristine air/silica interface, but the highly nonlinear silicon core can be modulated to tune the resonances. By pumping the silicon core with femtosecond (fs) pump pulses, we have characterized the Kerr nonlinear resonance shift and demonstrated its use for all-optical modulation on a sub-picosecond timescale. This novel geometry opens a route to obtaining ultra-low loss, high Q silica resonators with enhanced functionality.

2. Fabrication and Characterization

The core-shell microspherical resonator was fabricated from a fiber with a silica cladding diameter of ~82 μm and silicon core of ~50 μm [2]. To shape the resonator, a series of stable CO_2 laser pulses were used to heat the tip of the fiber, forming a concentric sphere with a ~115 μm outer diameter and ~108 μm inner diameter. The setup used to probe the optical properties of the resonator is illustrated in Fig. 1(a), where a CW tunable laser operating over the extended telecoms band (see Box 1) is coupled into WGMs via a tapered single mode fiber with a waist of 2 μm. The transmission spectrum was then measured via an optical component tester (OCT, Yenista CT 400 - Box 2), with the result plotted in Fig. 1(b). The spectrum shows a series of resonance mode families that are excited with a free spectral range of FSR~5 nm, and extinction ratio as high as 14 dB. A loaded quality factor of Q_l ~1.11 x 10^5 was measured for the resonance at λ_r ~1557.79 nm, which is an order of magnitude larger than the pure silicon fiber resonators [3]. We attribute the increased Q to the mode of the core-shell resonator being confined to the low loss silica as well as the spherical shaping which improves the confinement.

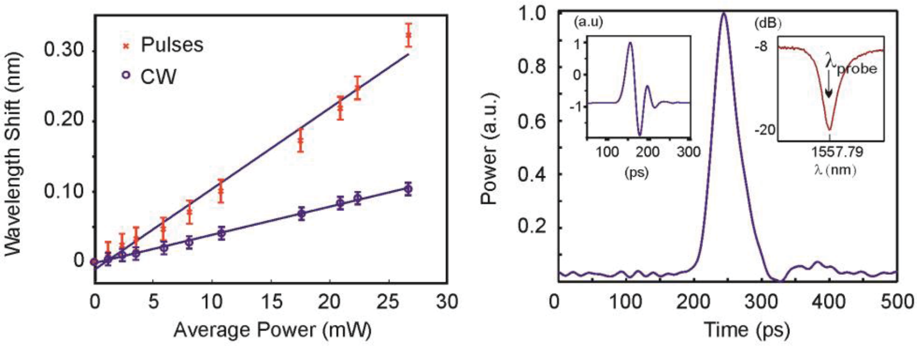


1(a) 1(b)

Fig. 1. (a) Setup for measuring Kerr shift and demonstrating all-optical modulation using different pump lasers P_i, (i=1 for CW and i=2 for pulsed). Polarization controller (PC), fiber amplifier (EDFA), tapered lens (TL), digital sampling oscilloscope (DSO), optical component tester (OCT). Inset: Image of microsphere resonator side pumped via the TL. (b) Transmission spectrum. Inset: Lorentzian fit to determine Q_L.

3. Results and Discussion

To investigate nonlinear tuning of the resonance wavelength, we used a tapered lens (TL) fiber to side pump the resonator with two different sources: (1) a CW laser at 1550 nm and (2) a femtosecond fiber laser at 1540 nm (720 fs FWHM duration, 40 MHz repetition rate), illustrated via Box 3 in Fig. 1(a). The resonance shift was then monitored on the OCT (Box 2). A linear red shift proportional to the average pump power was observed for both CW and pulsed excitations, as shown in Fig. 2(a). For the femtosecond pump, a maximum shift of 0.32 nm was obtained at average power of ~27 mW, while at the same power a 0.10 nm shift was obtained for CW pump. We attribute the modest CW shift to the thermal nonlinearity and the larger shift for the pulsed pump to the ultrafast Kerr nonlinearity. Significantly, our previous measurements conducted using an unshaped coaxial resonator were only able to induce a thermal shift [4]. Thus we attribute the Kerr shifting observed here to the spherical shaping which helps to focus the pump within the highly nonlinear silicon core. We note that because the side coupled light is not launched into a circulating mode, the pump thresholds required to observe the nonlinear shifts are larger than what has previously been reported in Refs. [1,5]. However, this scheme does have the advantage of removing many of the restrictions associated with resonance pumping, such as the necessity for a precise pump wavelength as well as bandwidth limited coupling.



2(a) 2(b)

Fig. 2. (a) Wavelength shifting as a function of average power for Kerr (crosses) and thermal (circles) shifts. (b) All-optical switching of CW probe when pumped with a high power, short pulse. Insets: left image is the temporal impulse response measured on the DSO; right image shows the CW probe position with respect to cold cavity resonance dip.

In order to confirm that the larger shift of the pulsed pump is due to the ultrafast Kerr effect, we set up a simple all-optical modulation scheme. Here, the high power femtosecond pulses delivered by tapered lens were used to modulate a weak CW probe positioned at the cold cavity resonance wavelength, which was monitored on a 30 GHz digital oscilloscope as illustrated in Box 4 of Fig. 1(a). An instantaneous on/off switching was observed when the intense fs pump interacts with the silicon core, inducing a Kerr index change, as shown by the impulse response in the inset of Fig. 2(b). Although it is not possible to resolve the full temporal dynamics on our bandwidth limited measurement system, by applying a filter to remove the high frequency components we can obtain the averaged modulated bright signal pulse plotted in Fig. 2(b). This pulse was recorded for an average pump power of 10 mW, resulting in a modulation depth of 5.9 dB. As for the side pumping scheme the switching speed is determined simply by the 720 fs pump pulse duration, we expect the on/off switching time to be sub-picosecond, an order of magnitude faster than previously reported in our silicon fiber resonators [5].

In conclusion, we have experimentally characterized the Kerr nonlinear wavelength shift in a silicon core, silica clad microspherical resonator. By exploiting the ultrafast nature of the shifting we have demonstrated all-optical modulation with a sub-picosecond switching speed, of great interest for applications in optical processing networks.

4. References

[1] M. Pöllinger and A. Rauschenbeutel, "All-optical signal processing at ultra-low powers in bottle microresonators using the Kerr effect," Opt. Express **18** , 17764 (2010).

[2] E. F. Nordstrand, A. N. Dibbs, A. J. Eraker, and U. J. Gibson, "Alkaline oxide interface modifiers for silicon fiber production," Opt. Mater. Express **3**, 651, (2013).

[3] N. Vukovic, N. Healy, P. Horak, J. R. Sparks, P. J. A. Sazio , J. V. Badding, and A. C. Peacock., "Ultra-smooth microcylindrical resonators fabricated from the silicon optical fiber platform," Appl. Phys. Lett. **99**, 031117, (2011).

[4] F. H. Suhailin, N. Healy, M. Sumetsky, L. Xiao, J. Ballato, A. Dibbs, U. Gibson, and A. C. Peacock , "Tunable coaxial resonators based on silicon optical fibers," in Advanced Photonics, Barcelona, p. SoM2B.3, (2014).

[5] N. Vukovic, N. Healy, F. H. Suhailin, P. Mehta, T. D. Day, J. V. Badding, and A. C. Peacock., "Ultrafast optical control using the Kerr nonlinearity in hydrogenated amorphous silicon microcylindrical resonators," Scientific Reports **3**, 2885, (2013).