# $As_2S_3$ Microspheres With Near Absorption-Limited Quality Factor

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***Abstract*—We present $As_2S_3$ microsphere optical resonators made out of high purity fiber. The quality factor is the highest reported to date for a nonlinear glass, nearly corresponding to the absorption attenuation value in the fiber.**

***Keywords*—Microsphere, Optical resonators, Chalcogenide glass.**

## I. INTRODUCTION

Whispering gallery mode (WGM) optical microcavities offer multiples advantages for the study of nonlinear processes. Their main advantages are the high achievable quality factor and the small effective mode volume. Many nonlinear processes have been demonstrated in WGM cavities such as all-optical switching in Si rings [1] and cascaded four-wave mixing frequency comb generation in $SiO_2$ toroids [2] or in $Si_3N_4$ rings [3]. Nevertheless, low refractive index glasses and $Si_3N_4$ suffer from a small nonlinear refractive index $n_2$ which limits applications to high quality factor, limiting bandwidth, or to high power regime. Despite having high $n_2$, Si has a high two-photon absorption (TPA) coefficient [4]. This TPA generates free carriers which affect the dispersive properties and the absorption via the free carrier absorption (FCA) [5].

Chalcogenide glasses such as $As_2S_3$ possess high linear and nonlinear refractive indices and a low TPA coefficient [6]. They have already been demonstrated for many applications including high-data rate signal processing and laser oscillation [6][7]. To date, few experiments have been reported with WGM in microcavities such as spheres [8], racetracks waveguides [9] and more recently photoinduced WGM [10]. Broaddus *et al.* [11] demontrated $As_2Se_3$ microspheres with a reported quality factor of $2 \times 10^6$.

In this paper, we report the fabrication and characterization of $As_2S_3$ microspheres with quality factors reaching $3.65 \times 10^7$. To our knowledge, it is the highest value reported in a chalcogenide microcavity and in a nonlinear glass material [12]. Preliminary nonlinear Kerr shifts measurements are also presented.

## II. SPHERE FABRICATION AND CHARACTERIZATION

Chalcogenide glass microspheres are fabricated following a method similar to the one used with silica fibers. The fibers are provided by CorActive High-Tech and have a low attenuation $\sim 0.5$ dB/m. The protective polymer cladding of an $As_2S_3$ fiber is removed with acetone. The fiber is then melted and stretched using a $CO_2$ laser ($\lambda = 10.6$ $\mu$m) until the tip becomes 10-20 $\mu$m wide. Compared to silica glass, the attenuation coefficient of $As_2S_3$ glass at 10.6 $\mu$m is smaller but sufficient to reach the melting temperature. The tapered tip is then oriented vertically to preserve the axial symmetry during exposure to laser light. The surface tension forces the softened glass to form a sphere at the tapered fiber tip. The inset of Fig. 1 shows a typical $As_2S_3$ microsphere made using this technique. Spheres with diameters of 40 $\mu$m and above have been obtained with this process.

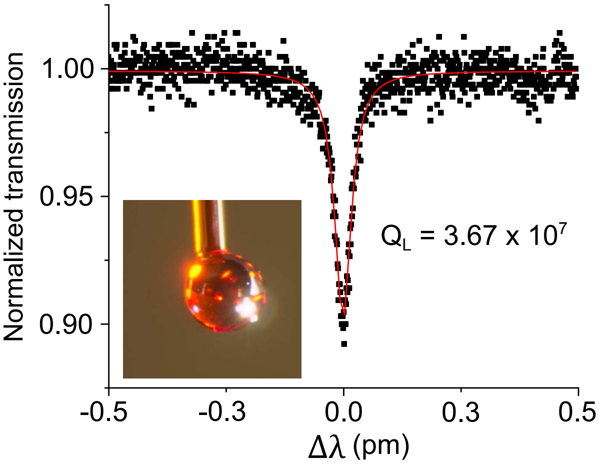

Fig. 1. Transmission spectrum of a resonance with a $Q_L$ of $(3.67 \pm 0.09) \times 10^7$. Inset: Typical image of an $As_2S_3$ microsphere.

The light was injected into the $As_2S_3$ sphere using evanescent coupling from a silica tapered fiber with a diameter of 2 $\mu$m. The transmission spectrum was recorded using a tunable laser (Agilent 81600B) near a wavelength of 1550 nm and a photodiode (Thorlabs DET01CFC). Using a piezoelectric stage that controls the gap between the tapered fiber and the sphere, the coupling level is ajusted to a slightly coupled regime where the measured loaded quality factor $Q_L$ is similar to the intrinsic quality factor $Q_0$. Considering that the quality factor is bounded by the attenuation losses of the $As_2S_3$ fiber ($\alpha \approx 0.115$ m$^{-1}$ at $\lambda = 1550$ nm), the maximal quality factor is estimated as $Q_0^{max} = \frac{2\pi n}{\lambda\alpha} \approx 8.6 \times 10^7$. Figure 1 presents a normalized transmission spectrum of a resonance in this regime. The sphere has a diameter of 324 $\mu$m. The applied Lorentzian fit reveals a full width at half maximum of $(4.2 \pm 0.1) \times 10^{-2}$ pm which corresponds to a $Q_L$ of

$(3.67 \pm 0.09) \times 10^7$. Considering the transmission of $T = 0.90$ in the undercoupled regime, this provides the intrinsic quality factor $Q_0 = 2Q_L/(1+\sqrt{T})$ of $3.77 \times 10^7$ which corresponds almost to $Q_0^{max}$.

## III. NONLINEAR WAVELENGTH SHIFT MEASUREMENTS

To determine the nonlinear Kerr coefficient, a method similar to [13] is used. The setup is presented in Fig. 2. The emission from a narrow linewidth tunable laser (TLS) near 1540 nm passes through a first polarization controller (PC1). A function generator (FG) provides 80 ns square pulses to a 10 GHz intensity modulator (IM) with a period of 100 ms. The coupling conditions are optimized using the second polarization controller (PC2). The light pulse is coupled to a cavity with a diameter of 31 $\mu$m via a tapered silica fiber. The transmitted pulse is detected by a photodiode (PD) and recorded on a oscilloscope (OSC). At low power, when the laser emission is tuned inside the cavity resonance, the pulse transmission corresponds to the resonance transmission at the laser emission position as depicted in the inset (a) of Fig. 3. As the laser power is increased, the resonance is red-shifted due to the Kerr effect as the intensity inside the cavity increases (inset (b) of Fig. 3). Since the pulse is longer than the cavity build-up time $\sim$ 2 ns, its shape is not affected. Also, the pulse length is small enough to minimize fast thermo-optic effects with a characteristic time of the order of 8 $\mu$s in our case [14]. In this regime, the quasi instantaneous Kerr nonlinearity dominates. The experimental transmission values are obtained with the ratio of the transmitted amplitude inside and outside the resonance. The power was continuously switched from low to high power. Measurements at high power were discarded if the low power transmission values before and after did not match. This procedure minimized errors due to random fluctuation. To compute the transmission value as the resonance shifts, coupled-mode equations are solved for the cavity energy $|a_c|^2$ and temperature with the Runge-Kutta method.

Experimental values for two resonances are shown in Fig. 3. Resonances 1 (black circles) and 2 (blue dots) have a $Q_L^{(1)} = 2.86 \times 10^6$ and $Q_L^{(2)} = 2.48 \times 10^6$ and a $Q_0^{(1)} = 4.1 \times 10^6$ and $Q_0^{(2)} = 3.9 \times 10^6$ respectively. Simulations suggest a $n_2$ between $3 \times 10^{-14}$ cm$^2$/W (green curve) and $8 \times 10^{-14}$ cm$^2$/W (red curve). These values agrees with literature [15]. The fact that the second resonance has a higher transmission despite its lower loaded quality factor could possibly be attributed to a higher absorption, which would explain its lower $Q_0$. A higher absorption increases the contribution of the thermo-optic effects and increases the red-shift of the resonance. This discrepancy is under investigation.

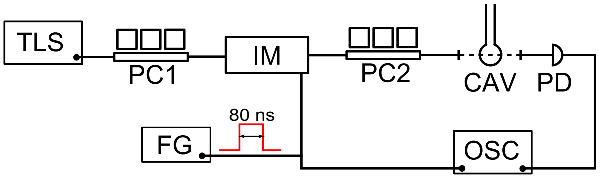

Fig. 2. Experimental setup for Kerr wavelength shift measurements.

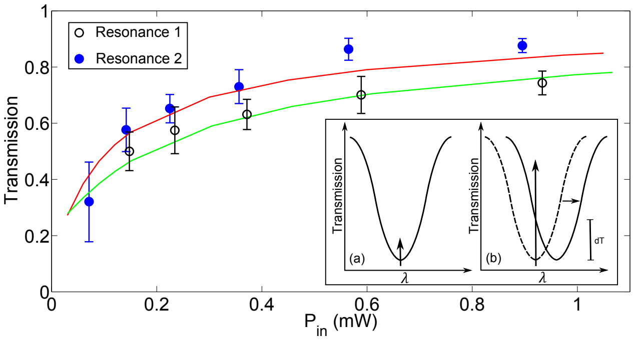

Fig. 3. Measured transmission (black circles and blue dots) and simulations (green and red curves) after a nonlinear shift. Inset: Nonlinear Kerr shift of the resonance during the pulsed signal for (a) low power (b) high power.

## IV. CONCLUSION

We reported high quality factor $As_2S_3$ microsphere optical resonators made out of a tapered fiber tip. The measured loaded quality factor is the highest reported value to date for a nonlinear glass and it corresponds to the near-absorption attenuation value of the fiber. Measurements showing a nonlinear Kerr shift are also presented.

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