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Invited Paper

Hollow Whispering Gallery Resonators

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ABSTRACT

In recent years, whispering gallery mode (WGM) devices have extended their functionality across a number of research fields from photonics device development to sensing applications. Here, we will discuss some such recent applications using ultrahigh Q-factor hollow resonators fabricated from pretapered glass capillary. We will discuss device fabrication and different applications that can be pursued such as bandpass filtering, nanoparticle detection, and trapping. Finally, we will introduce our latest results on visible frequency comb generation.

Keywords: whispering gallery resonators, hollow resonators, frequency comb

1. INTRODUCTION

Hollow whispering gallery resonators (WGR) are widely used for a number of applications[1,2]. The very high optical quality factors (Q-factor) that can be achieved and the small optical mode volume of WGRs mean that they are unique tools for studying nonlinear optics. Also, since the modes are very sensitive to even the smallest change in environmental parameters, they make very compact sensors. Such resonators have been used to measure fluctuations in temperature[3,4], pressure[5,6,7], stress[8], refractive index[9], etc. Among the numerous applications proposed for WGRs, probably the most important are in the fields of nano/biosensing[10-13], nonlinear optics[14-17] and telecommunications[18-20]. The ultranarrow linewidth filtering capability of WGRs combined with their small size and possible dense on-chip fabrication could have a huge impact on the telecommunications industry. To date these devices have yet to be realized due to a number of technical challenges; hence, there is still significant research required on WGRs for optical communications. A WGR resonator coupled to an optical waveguide typically yields Lorentzian-shaped dips in the transmission signal through the waveguide, thereby creating a bandstop filter. However, the creation of an efficient bandpass filter using WGRs would also have many applications. Here, we show that such a bandpass spectrum can be generated using a WGR and an ultrathin optical waveguide[19] by taking into account the strong scattering induced at the coupling point between the resonator and waveguide.

Biosensing could also benefit from the unique properties of hollow WGRs, but commercially available systems are currently not available due to, again, technical issues regarding WGM stability and functionalization. Proof-of -principle research has produced some impressive detection capabilities and, to date, the detection sensitivities continue to increase[1, 9-13]. One test bed for biosensing, and with many applications in its own right, is nanoparticle detection with WGRs. For this application, hollow resonators, such as the microcapillary, microbottle, and microbubble devices, have shown to have improved sensitivities due the large evanescent field penetrating into the liquid core of the cavity. Here, we demonstrate, for the first time, single nanoparticle detection using truly quasi-droplet WGRs and show that they can outperform solid WGRs in terms of dispersive and dissipative sensitivity.

When a light source emits equally-spaced spectral lines, the spectrum is termed a *frequency comb*; this phenomenon can be generated using four-wave mixing (FWM) in an optical resonator. Frequency combs are used in several areas of optics, such as frequency metrology, and, recently, their generation in hollow WGRs has been realized[14-17]. In contrast to the more conventional comb design, those based on WGRs are smaller and do not require high-power or ultrafast lasers to generate the comb. Until recently, most frequency combs in WGM systems were at telecommunications wavelengths and there has been an ongoing drive to push them towards visible wavelengths. In this work, we report on a method of engineering dispersion in a microbubble WGR to force it into the anomalous regime by varying the bubble's wall thickness, thereby demonstrating a Kerr effect frequency comb in the 750-820 nm region.

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In this paper, we will present some of the experimental results from our group achieved over the last year. We will report on the observation of bandpass filtering, nanoparticle detection and trapping, and frequency comb generation in the near visible wavelength range.

2. WHISPERING GALLERY RESONATOR FABRICATION

Hollow silica microbubbles were used for the work presented here[2-4,10-13] and the fabrication method is depicted in Fig. 1. A silica capillary with an OD/ID ratio of 0.7 was heated in the focus of counter propagating CO_2 laser beams and tapered down to a diameter of around 20 μm by pulling on one end using a motorized translation stage. Next, a section of the tapered region was reheated with the CO_2 beam while simultaneously flowing nitrogen through the capillary. When the wall of the capillary softens, it expands into a bubble shape due to the internal aerostatic pressure. We have achieved ultrathin walled bubbles using this fabrication technique[5]. Such resonators were used for temperature and pressure sensing[1-7]. The microbubble devices are very versatile and we can exploit the aerostatic pressure tuning for a range of applications.

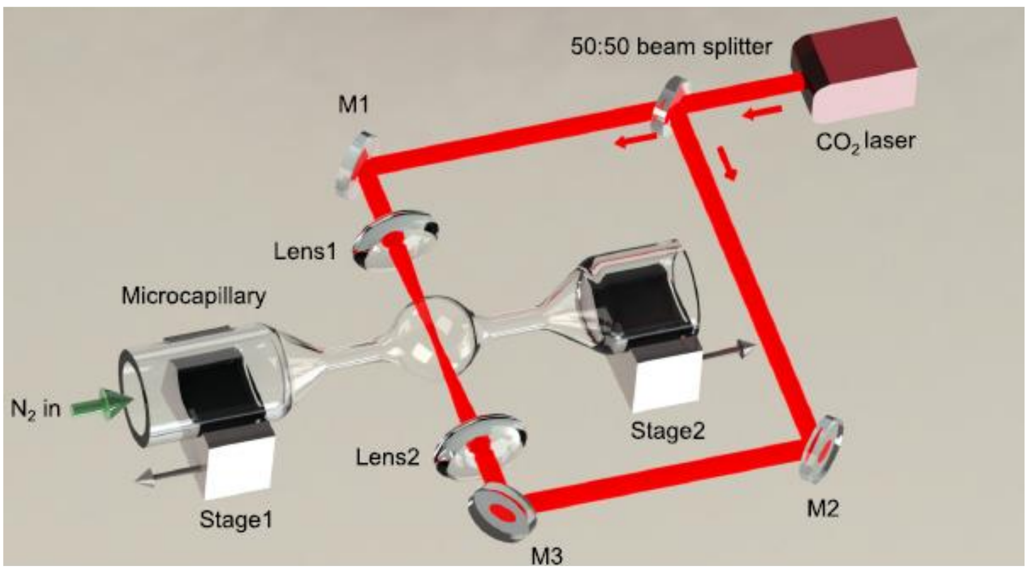

Fig. 1. Microbubble fabrication setup. A CO_2 beam is focused using two lenses (Lens1 and Lens2) onto a tapered silica glass capillary while internally pressurizing it using nitrogen gas. M1, M2, M3: mirrors.

Light is coupled into the microbubble via a tapered optical fiber, generally fabricated using a hydrogen:oxygen flame heat-and-pull rig[21]. Both the resonator and tapered fiber are on translation stages in order to optimise the coupling between the two.

3. BANDPASS SPECTRUM OF A WGR

In this paper, we observe that the transmission spectra of a WGR coupled to a single tapered fiber may exhibit Lorentzian peak behavior when the diameter of the tapered fiber is in the range of 500−700 nm, i.e., smaller than the conventional diameters used (∼1−4μm). Considering that the scattering loss due to the thinner tapered fiber is large when a microcavity is in close proximity to it, we can attribute the bandpass phenomenon to partially resonant light bypassing the strong scattering region mediated by cavity modes, while off-resonant light experiences significant scattering, see Fig. 2, resulting in an appreciable transmission loss[19]. Fig. 2(a) shows the evolution of the transmission spectrum as the tapered fiber-microsphere gap was decreased. From A to H, the gap decreased from 2.4 μm to 0 μm (i.e., in contact). While the gap was decreased gradually (E→A Fig. 2(b)), more and more WGMs were excited. However, some Lorentzian dips disappeared and some Lorentzian peaks emerged as the gap was further reduced. At the same time, the normalized transmittance of the off-resonant light decreased from unity to nearly zero, as shown in Fig. 2(b). This indicates that scattering loss due to the microsphere's close proximity to the nanofiber was no longer negligible in contrast to that seen in previous reports, especially when the gap between the two approaches zero. Since the tapered nanofiber diameter was of subwavelength dimensions, the fiber mode possessed an evanescent component that extended significantly into the free space surrounding the tapered region.

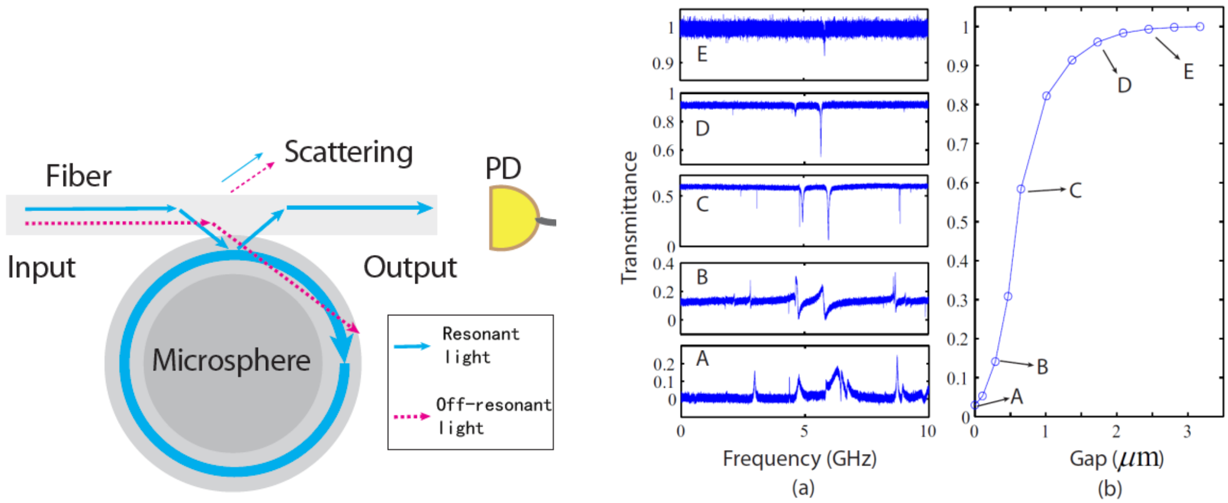

Fig. 2. Left: Schematic of WGR/waveguide coupling with an ultrathin tapered fiber. Right (a): Normalized transmission spectra and (b) the corresponding transmittance of off-resonant light, for varying taper-microsphere gaps. From A to H, the gap decreases from 2.4 μm to 0. For both (a) and (b), the *y* axis corresponds to transmittance, which has been normalized with respect to the maximum value observed in the transmission spectrum A. Adapted from [19].

As shown in Fig. 2 (b), almost all (97%) the off-resonant light was lost when the microsphere was in contact with the ultrathin fiber, while a reduced amount of the resonant light survived (more than 20%). It is worth noting that the linewidth of some peaks was less than 10 MHz (Q factor of ~ 10^7) even while the resonator is in contact with the ultrathin fiber. We also present preliminary results showing a bandpass spectrum with an efficiency of more than 80% from a hollow WGR coupled to an ultrathin optical fiber; it is proposed that this improved efficiency is a combination of the scattering effect described above and modal interference.

4. NANOPARTICLE DETECTION WITH A QUASI-DROPLET WGR

A capillary or a microbubble WGR is essentially a thin glass shell supported on a hollow stem that allows fluids to be passed through the core of the resonator. The wall of the hollow resonator can support WGMs that create an evanescent field along the inner and outer surfaces of the resonator wall[1-3]. These fields allow the modes to interact simultaneously with the environment inside and outside the resonator. These properties make hollow WGRs uniquely suited for sensing applications since minute changes to the environment result in a change of the whispering gallery mode spectrum[10-13]. The core of the hollow resonator can be filled with a fluid in which nanoparticles, for example, are suspended. As the nanoparticles interact with the WGMs of the resonator they cause a shift in the mode resonance position due to either an increased optical path length, a change in refractive index, or due to the particles' excess polarizability.

Here, we show experimentally that the quasi-droplet resonator can outperform a solid microsphere in terms of detection sensitivity and can be used to apply much larger optical forces resulting in highly efficient optical propulsion and optical trapping. We demonstrate detection and control of single nanoparticles in a quasi-droplet micoresonator. We also observe a number of interesting effects, such as regenerative self-modulation driven by the particle motion arising from strong scattering at the waveguide/cavity coupling junction.

5. FREQUENCY COMB GENERATION

FWM parametric oscillation at the telecommunications wavelength around 1550 nm was first reported in a microbubble WGR in 2013[14] and, later, frequency comb generation was also realized[15-17]. In an air-filled silica hollow resonator, the mode is distributed in the wall and on both the inner and outer surfaces due to the strong evanescent field penetration. By varying the wall thickness, the proportion of the mode intensity in the air can be modified, thus changing the effective index and the frequency distribution of cavity modes. It has been theoretically shown[22] that, by reducing the wall thickness, the zero dispersion wavelength shifts towards shorter wavelengths. Therefore, it should be possible to generate a frequency comb in the visible range by optimizing the wall thickness of the microbubble. In this paper, details of how to experimentally achieve a Kerr frequency comb which extends from 750-820 nm using a microbubble is described. An ultrahigh Q-factor microbubble was fabricated using two counter-propagating CO_2 beams on a tapered silica capillary. The bubble's wall thickness was around 1.4 μm, as measured using a scanning electron microscope. A tapered optical fiber was used to couple light, from a tunable laser at 775 nm, into the resonator. The maximum pump power available was 200 mW. Transmission through the tapered fiber was monitored and a TM mode with a Q-factor ~ 2×10^7 was selected. We were able to observe a four-wave mixing signal, indicating that the microbubble was in the anomalous dispersion regime. Next, the input power was increased until parametric oscillation was observed and, subsequently, a frequency comb was achieved[17], see Fig. 3. To improve the comb, more precise dispersion engineering of the microbubble's shape and the thickness of the wall is needed.

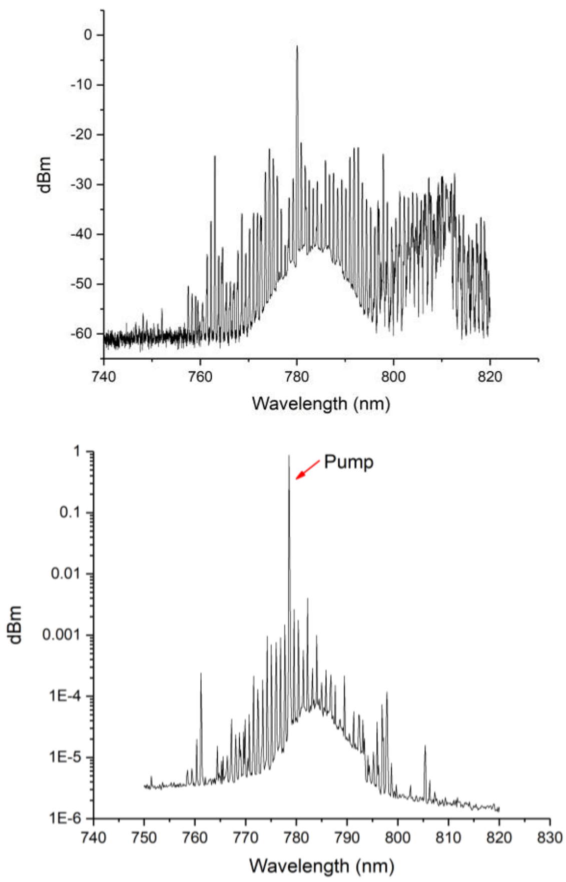

Fig. 3. Top and bottom: Examples of frequency combs generated in different hollow WGRs.

6. CONCLUSION

We have presented three important applications of hollow WGRs optical filtering, nanoparticle sensing, and frequency comb generation. All three experiments rely on the ultrathin wall of the hollow WGR to achieve the required outcome i.e., quasi-droplet modes for opto-fluidic sensing, modal interference and tuning for the bandpass filter, and dispersion control for the FWM process. These results and other works in the literature show that hollow WGR can add another tuning knob for controlling the behavior of WGR devices. Each of the experiments presented here are part of ongoing works and, in the future, we hope to extend our frequency comb deeper into the visible wavelength region and develop the tools to properly evaluate the characteristics of the comb for applications. The bandpass filter also needs to be studied in more detail to determine the effect of the wall thickness and to find the optimal conditions for achieving a more efficient filter. The nanoparticle detection using quasidroplet modes has shown to be very sensitive but is only one aspect of this system. For larger pump powers, the optical forces and thermal effects dominate and the optical carousel effect becomes very strong. This leads to an optomechanical feedback that influences the cavity and particle behavior. Currently we are working to characterize the dynamics of this feedback.

As stated in the introduction, hollow WGRs along with other WGR geometries, materials, and coupling methods each have their own distinct advantages and disadvantages that can be exploited depending on the application. In the future, it is the hoped that WGR devices can move beyond the research laboratory into real world applications; in the meantime methods and techniques must be found to overcome the many technical challenges that inhibit WGRs true potential.

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