Broadband microcomb generation in silica spherical microresonators with engineered dispersive waves in normal and anomalous dispersion regime

Authors: Gao, You, Sun, Suwan, Lin, Xukun, Wu, Kailin, Wang, Xiaoying, Yuan, Haiyun, Bai, Jiamin, Wang, Siyu, Guo, Hairun, Guo, Hairun

Date: 2023-08-25T00:00:00+00:00

Abstract

Expanding the bandwidth of frequency combs in microcavities is currently a prominent research area, and one effective approach is to introduce dispersive waves using higher-order dispersion. However, The exploration of high-order dispersion control on quartz microsphere platforms has been limited by the challenge of preserving high Q factors across a broad range of sizes. Here, we fabricated quartz microspheres through arc discharge with diameters ranging from 100-260 µm, achieving Q factors in the range of 108. We achieved a broadband Kerr frequency comb with dispersive wave radiation by manipulating the dispersion of the microsphere through size adjustment. Our experimental results demonstrate that the spectral span of the dispersive wave frequency combs can be extended up to 360 nm. At the same time, we have also demonstrated Raman lasers and Raman-Kerr frequency combs in small microspheres with normal dispersion.This work provides a reference for developing broadband, high-coherence frequency combs on microsphere platforms and offers an efficient implementation scheme for low-noise integrated broadband frequency combs.

Full Text

Preamble

Broadband microcomb generation in silica spherical microresonators with engineered dispersive waves in normal and anomalous dispersion regime

YOU GAO[1], SUWAN SUN[1], XUKUN LIN[1], KAILIN WU[1], XIAOYING WANG[1], HAIYUN YUAN[1], JIAMIN BAI[1], SIYU WANG[1], AND HAIRUN GUO[1],*

[1]Key Laboratory of Specialty Fiber Optics and Optical Access Networks, Joint International Research Laboratory of Specialty Fiber Optics and Advanced Communication, Shanghai University, Shanghai 200444, China

hairun.guo@shu.edu.cn

Compiled August 25, 2023

Expanding the bandwidth of frequency combs in microcavities is currently a prominent research area, and one effective approach is to introduce dispersive waves using higher-order dispersion. However, the exploration of high-order dispersion control on quartz microsphere platforms has been limited by the challenge of preserving high Q factors across a broad range of sizes. Here, we fabricated quartz microspheres through arc discharge with diameters ranging from 100–260 µm, achieving Q factors on the order of 10^8. We generated a broadband Kerr frequency comb with dispersive wave radiation by manipulating the dispersion of the microsphere through size adjustment. Our experimental results demonstrate that the spectral span of the dispersive wave frequency combs can extend up to 360 nm. Simultaneously, we have also demonstrated Raman lasers and Raman-Kerr frequency combs in small microspheres with normal dispersion. This work provides a reference for developing broadband, high-coherence frequency combs on microsphere platforms and offers an efficient implementation scheme for low-noise integrated broadband frequency combs.

http://dx.doi.org/10.1364/ao.XX.XXXXXX

Introduction

The potential of optical frequency combs (OFC) has been demonstrated in various applications, such as massive parallel optical communications [1, 2], optical data centers [3, 4], massive parallel LIDAR [5], low-noise microwave synthesis [6, 7], and photonic neural computing [8, 9].

In recent years, optical frequency comb technology based on high-Q microcavities has received widespread attention from researchers worldwide [10–13]. Currently, fully integrated and highly compact optical frequency comb chips have been realized, providing a multitude of high-performance laser sources for advanced optical metrology [14–18]. WGM microcavities represent a significant platform for investigating microcavity frequency comb technology and served as one of the pioneering platforms in this field. In particular, WGM microcavities such as crystalline fluoride resonators have achieved ultra-high Q factors up to 10^{11} and finesse up to 10^7 [19]. Many classic theories and experimental phenomena of microcavity frequency combs have been verified in WGM microcavities, including the formation of dissipative temporal solitons [2, 10, 20–22], soliton pulse scaling [23], soliton number switching [24, 25], soliton breathers [26], and soliton behaviors due to intermode interactions [27].

Research on broadening frequency combs in WGM microcavities is essential for applications requiring broad spectral coherence, such as spectroscopy, precision frequency metrology, and optical clocks. Introducing dispersive waves (DWs) through higher-order dispersion is an effective way to extend the spectrum. Previous studies have extensively investigated mode-locking, soliton formation, and DW generation processes in optical microcavities based on silicon nitride (Si_3N_4) and aluminum nitride (AlN) platforms [12, 28–31], as well as the role of higher-order dispersion [32–34], which is of significant importance for verifying the dispersion engineering required to generate broadband Kerr frequency combs [35]. It is established that microcavity dispersion can be manipulated via microcavity size control to convert anomalous dispersion to normal dispersion [36]. However, there is relatively little work on dispersion management in quartz microspheres, and the current primary method for generating DW frequency combs in quartz microspheres involves adding coatings to the surface of the microspheres.

In this paper, we have studied the dispersion characteristics of microsphere resonators with different sizes and have successfully generated broadband DW frequency combs [37]. Meanwhile, we have also demonstrated Raman lasers and Raman-Kerr frequency combs in a 130 μm diameter microsphere with normal dispersion. This work provides a valuable reference for the development of broadband, high-coherence frequency combs on microsphere platforms.

Fabrication and Characterization of Microsphere Resonators

First, we used the arc discharge method, in which high-voltage discharges were generated at the fiber end face using a fusion splicer, and a short-pulsed arc rapidly melted it. Under the effect of surface tension, a quartz microsphere resonator was formed at the fiber end face. We prepared microsphere resonators with diameters ranging from 100–260 μm, as shown in Fig. 1(b). We then utilized the experimental system (Fig. 1(a)) to measure the transmission of a 200 μm diameter microsphere resonance by scanning the cw diode laser over it. Using Lorentzian fitting, the results showed that the Q value of the microcavity was approximately 2$×10^{8}$, and the FSR was determined to be 330.52 GHz, as shown in Fig. 1(c). In addition, the coupling ideality with respect to the selected resonant mode of the resonator was characterized, as shown in Fig. 1(d), which is at a high level, indicating almost no loss at the coupling junction.

Meanwhile, we used the same experimental method to test microsphere resonators, and the linewidth and intrinsic Q values are shown in Table 1 .

Another important parameter of microsphere resonators is dispersion, which affects the coherence of the comb spectrum and the generation of spectral bandwidth. The formation of DWs caused by higher-order dispersion terms may cause the comb spectrum to enter the normal dispersion state. The total dispersion of the optical microcavity is determined by both material dispersion and geometric dispersion, and the dispersion profile can be controlled by adjusting the material and structure to achieve an ideal dispersion distribution for the microcavity. The geometric dispersion of microspheres can be directly controlled by their size.

Dispersion Engineering and Simulation

Here, the DWs of microsphere resonators with diameters of 100 µm, 140 µm, 180 µm, 220 µm, and 260 µm are simulated, as shown in Fig. 1(e) [Figure 1: see original paper]. As indicated by the simulation results, a 140 µm diameter microsphere resonator exhibits normal dispersion near the 1550 nm pump, with a zero-dispersion point located close to the pump position, offering the opportunity to cross into the anomalous dispersion region and generate Kerr frequency combs. In contrast, a 100 µm diameter microsphere remains in the normal dispersion regime even at a distance from the 1550 nm pump, making it difficult to generate Kerr frequency combs. The position of the zero-dispersion point (d_2=0) shifts toward shorter wavelengths as the diameter of the microsphere resonator increases. Before 1580 nm, the value of d_2 increases as the diameter of the microsphere increases, resulting in a less flat d and an expanding anomalous dispersion region. Conversely, when the diameter of the microsphere decreases, the dispersion gradually enters the normal dispersion region.

By examining the dispersion curves, it can be seen that changing the diameter of the microsphere from 100 µm to 260 µm gradually shifts the position of the dispersive waves to shorter wavelengths. This demonstrates that size variation of the microsphere enables effective dispersion control.

Broadband Dispersive Wave Frequency Combs

We utilized the experimental setup to realize DW frequency combs, Raman lasers, Kerr frequency combs, and Raman-Kerr frequency combs in microspheres with diameters of 160 µm, 180 µm, and 200 µm, as shown in Fig. 1(b). We simulated the integrated dispersion curves (d) for the three different-sized microspheres, while also predicting the positions of the DWs (the intersection points with d =0), as shown in Fig. 2(a) [Figure 2: see original paper]. As the diameter of the microspheres increased, significant changes were observed in the microsphere dispersion, with the dispersion curves continually increasing in height and the positions of the DWs gradually moving toward shorter wavelengths.

We next carried out experiments for DW frequency comb generation in 200 µm diameter microsphere resonators. When the input power was approximately 280 mW and the laser was tuned from the blue-detuned side, we observed the evolution of the spectrum through primary combs, modulation instability (MI) combs, and DW frequency combs via tuning, as shown in Figs. 2(b), 2(c), and 2(d). Although the spectral envelope appeared smooth, there were still gaps, which may have been caused by a lack of optimal matching with the modal dispersion or the influence of other modes.

In addition, we used the same experimental method to generate broadband DW frequency combs in 160 μm and 180 μm diameter microsphere resonators. Furthermore, by comparing the simulation and experimental results of three different sizes of microsphere resonators, we found that the dispersive wave position in the experiment is in good agreement with the simulation. Meanwhile, the spectral spans exceeded 280 nm for all microspheres, with a maximum spectral span of 360 nm.

Raman-Kerr Frequency Combs in Normal Dispersion

Finally, we generated broadband frequency combs with normal dispersion in a 130 μm diameter microsphere resonator. Figure 3 illustrates the process of Raman laser, Raman-Kerr frequency combs, and DW frequency combs generated during the long-wavelength tuning of the pump light in a 130 μm diameter microsphere. We calculated the integrated dispersion d of the 130 μm microsphere, and we can see that the microsphere at this size is in the normal dispersion region, as shown in Fig. 3(a). When the pump was tuned to 1542.7 nm, a Raman laser was generated, and a clearly visible first-order Stokes laser with a frequency shift of approximately 3.755 THz, close to the center peak of the Raman gain, was observed at 1672 nm. Furthermore, a second-order Stokes laser could be observed at 1826 nm, and a weaker anti-Stokes laser could be observed at 1431.6 nm on the short-wavelength side of the pump light, as shown in Fig. 3(b).

This phenomenon is due to the overlap of the resonant peak of the microsphere with the broad Raman gain, resulting in a Raman laser dominated by Raman oscillation. From Fig. 3(c), it can be observed that when the pump is tuned to 1543.9 nm, numerous sidebands are generated around both the Raman laser and the pump laser. This is due to the large energy accumulation in the microsphere resonator, which transfers energy to adjacent resonant modes that happen to be located within the MI gain band, thus exciting Kerr frequency combs. At this point, local Raman-Kerr frequency combs appear in the spectrum, and the dominance of the Raman effect can be inferred from the intensity of the Raman laser.

When the pump is tuned to 1546.9 nm, Fig. 3(d) shows an overall increase in spectral intensity with a smoother spectral envelope, and the maximum spectral span is approximately 400 nm. Equally spaced comb teeth indicate that the frequency combs generated near the Raman laser are within the same mode family as the pump mode. However, the intensities at the first-order Stokes and anti-Stokes laser frequencies did not increase, possibly because the MI gain band is much smaller than the Raman gain band, and the pump detuning is relatively small, making it easy for the resonant peak to approach the peak of the MI gain band. The Raman gain band is relatively wide, and the resonant peak within the gain band is not significantly affected by Raman gain reduction.

Fig. 3(e) indicates that by fine-tuning the coupling position between the tapered fiber and the microsphere based on this experiment, a broadband Kerr frequency comb with an almost disappeared Raman effect can be observed in the spectrum, and a small wave packet exists at 1702 nm. As it appears at the midpoint between the first-order Stokes laser and the second-order Stokes laser, it can be inferred that this may be a long-wavelength DW dominated by the Kerr effect. Moreover, it can be inferred from the d curve (Fig. 3(a)) and Raman-Kerr frequency comb simulation (Fig. 3(f)) that the wavelength corresponding to d =0 is very close to the experimental DW wavelength of 1702 nm, thereby confirming it as a long-wavelength DW frequency comb.

Therefore, a successful transition from Raman laser to Raman-Kerr frequency combs dominated by the Kerr effect was achieved in a microsphere with a diameter of 130 μm. The final result was the conversion to a long-wavelength DW frequency comb, which verified the competition process between the Raman effect and the Kerr effect.

Conclusion

In conclusion, we have demonstrated the generation of both DW frequency combs and Raman-Kerr frequency combs in high-Q microsphere resonators. Microsphere resonators of varying sizes were fabricated using arc discharge, achieving Q values of up to 10^8. Furthermore, dispersion management was achieved by controlling the size of the microsphere, and frequency combs with broad bandwidth near the pump wavelength were demonstrated in microspheres of three different sizes. The relationship between the position of the DWs and microsphere cavity diameter was verified. Additionally, the effect of size on the Raman-Kerr competition was observed, with smaller microsphere cavities exhibiting stronger Raman effects and a greater tendency to produce Raman lasers, cascaded Raman effects, and Raman-Kerr frequency combs in the normal dispersion region. As the diameter increased, the Raman effect weakened, making it easier to produce broadband Kerr frequency combs. Furthermore, dispersion can be fine-tuned by adjusting the coupling position between the tapered fiber and microsphere, allowing for switching between Raman lasers and Kerr frequency combs.

This work provides valuable insights for the development of broadband, highly coherent frequency combs in microspheres, laying a foundation for the integration of Kerr frequency combs in these cavities.

Funding

National Key Research and Development Program of China (2020YFA0309400); National Natural Science Foundation of China (11974234); Shanghai Science and Technology Development Foundation (20QA1403500).

Acknowledgments

We acknowledge funding from National Key Research and Development Project of China, National Natural Science Foundation of China, and Shanghai Science and Technology Development Funds. This work is also supported by 111 Project (D20031) by MoE of China. Preforms of the crystalline resonators are fabricated in the Engineering Technology Training Center at Shanghai University.

Disclosures

The authors declare no conflicts of interest.

Data Availability Statement

Data and simulation codes related to this work are available from the corresponding author upon reasonable request.

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