Brillouin lasing in coupled silica toroid microcavities

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We achieved the 11 GHz mode splitting of supermodes that matched the Brillouin frequency shift in silica and realized the first observation of stimulated Brillouin scattering in coupled silica toroid microcavities.

Key words: Stimulated Brillouin scattering; Coupled microcavity; Toroid cavity;

1. Introduction

Stimulated Brillouin scattering (SBS) is a well-known nonlinear process in which two optical waves interact via an acoustic wave. The acoustic wave is generated via the electrostriction process. SBS in optical fiber, chip-based waveguides and microcavities has received a lot of attention because it can be employed for low-noise lasers, microwave synthesizers, slowing light and light storage. Whispering-gallery mode (WGM) microcavities with high Q factors and small mode volumes enable us to generate SBS with a low threshold power. In this research, it is necessary to match the free spectral range (FSR) to the Brillouin frequency shift (tens of GHz) by using mm-scale cavities or to prepare high-order transverse WGMs that separate the Brillouin frequency shift to generate SBS [1-3]. With these approaches, it is very difficult to fabricate microcavities for SBS because we need to control the size of the microcavities precisely or to fabricate microcavities that have two optical modes that separate the Brillouin frequency shift.

Here we explore coupled microcavities to enhance the SBS effect. When two cavities are placed close together their optical modes are turned into supermodes such as symmetric and anti-symmetric modes. The coupled cavities enable mode separation to be freely tuned, and this allows us to avoid the need for precise control of the cavity size. In our study, we formed coupled microcavities by using a silica toroid microcavity, which has an ultra-high Q factor and a small mode volume and can be fabricated on a chip. Although several studies have reported the development of coupled microcavities based on silica toroid microcavities, supermode splitting is limited to a few GHz [4]. If we can expand the splitting, we can employ coupled microcavities for various applications including stimulated Brillouin scattering (SBS).

In this paper, we report mode splitting of over 10 GHz using silica toroid microcavities. The optimization of the cavity geometry enables us to achieve supermode splitting exceeding 10 GHz. In addition, we show the results of SBS experiments as an application of the large mode splitting. First, we simulate the splitting of the supermodes in coupled silica toroid microcavities and investigate the effect of cavity geometry on supermode formation. Second, we fabricate and characterize PMs based on silica toroid microcavities. Third, we perform SBS experiments. And we finish with a summary.

2. Calculation of coupling coefficient

Supermode splitting is quantified by using the coupling coefficient between the two microcavities that form a supermode. The calculation of the coupling coefficient between a tapered optical fiber and a microsphere has been reported [5]. We extend this method to coupled microcavities. The coupling coefficient between cavity1 (C1) and cavity2 (C2) is determined by the overlap between the profiles of the optical modes in the microcavities, and the phase matching condition. Taking these conditions into consideration, the coupling coefficient $\kappa_{C1C2}$ can be written as

$$\kappa_{C1C2} = \frac{\omega \epsilon_0}{4} \left( n^2 - n_0^2 \right)$$

$$\times \int \int \int_{Vc} \left( E_{C1}(x,y,z) \right)$$

$$\cdot E_{C2}(x,y,z) e^{i\Delta \beta x} dx dy dz$$

where $n$ and $n_0$ are the refractive index of a silica toroid microcavity and air, $Vc$ is the cavity volume, $E_{C1}$ and $E_{C2}$ are the electrical fields of the two cavities, and $\Delta \beta$ is the propagation constant difference. Note that $N_{C1}$ and $N_{C2}$ are normalizing coefficients. The profile of the optical mode in each cavity is calculated by the finite element method (COMSOL Multiphysics [6]). Here we assume the fundamental modes. The splitting of the supermodes $\Omega$ can be written as

$$\Omega \approx \frac{c}{2 \pi n R} |\kappa_{C1C2}|^2.$$  

In this simulation, we assumed microcavity diameters $R$ of 45, 55 and 65 μm. According to Fig. 1, the splitting of the supermodes is larger if we assume a microcavity with a smaller diameter. Moreover, this graph suggests that it is possible to obtain supermodes with a split of more than 10 GHz when 55-μm-diameter microcavities are used.
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Fig. 1. Simulation results showing supermode splitting as a function of the gap between silica toroids.

3. Fabrication

We fabricated the silica toroid microcavities using photolithography, XeF$_2$ dry etching and CO$_2$ laser reflow. We fabricated the microcavities with a diameter of about 55 μm to achieve a split exceeding 10 GHz. As shown in Fig. 2(a), the coupled cavity system consists of two directly coupled silica toroids (C1 and C2), and a tapered optical fiber. PMs need two optical modes with the same frequency. Before coupling the two silica toroids, we selected two modes that were close to each other in frequency in each toroid. The temperature of C2 was controlled, and the resonance frequency of C2 matched the resonance frequency of C1. Under this condition, we moved C2 closer to C1 100 nm at a time. Figure 2(a) shows the transmission spectra for the different gaps between the two silica toroid microcavities. The coupling becomes stronger as the gap decreases because the overlap between the modes in the two cavities becomes larger. As predicted, the mode split is larger for a smaller gap. As shown in Fig. 2(b), we were able to obtain a mode split of about 11 GHz when the two toroids were placed closest together. At that time, the $Q$ factors of the supermodes were about $2 \times 10^6$. The experimental results were in good agreement with the simulation results. However, unlike in the simulation, we do not necessarily use the fundamental modes in the experiments. So in future research we will investigate the way in which the mode splitting changes depending on the optical modes used.

Fig. 2. (a) Mode split for different gaps between two cavities. Inset: microscope image of coupled silica toroid microcavities. (b) Measured transmission spectra of PM. ($M_s$: symmetric mode, $M_a$: anti-symmetric mode)

4. SBS experiment

We performed experiments on the SBS in the coupled cavities. Figure 3(a) shows the experimental setup. We used an optical circulator to detect the backward SBS light. In this experiment, the pump frequency matched the frequency of [??] (Note: Something is missing here) (see Fig. 2(b)). The optical spectrum in the backward scattering light is shown in Fig. 3(b). There are two peaks in the optical spectrum. The right peak represents the Rayleigh scattering, and the left peak represents the SBS. In our experiment, we achieved a threshold power of about 50 mW (Fig. 3(c)). This threshold power should be further reduced by optimizing the coupling condition and the cavity geometry.

Fig. 3. (a) Experimental setup for Brillouin lasing. (b) Optical spectrum of the backscattering light. The pump signal is on the right and the SBS light is on the left. (c) SBS output power for different pump input powers.

5. Conclusion

We reported supermode splitting of over 10 GHz using silica toroid microcavities. Our simulation suggested that larger mode splitting is possible if we use silica toroid microcavities with a smaller diameter. We fabricated silica toroid microcavities with a diameter of about 55 μm and achieved the 11 GHz mode splitting of supermodes, which matches the Brillouin frequency shift in the silica in coupled silica toroid microcavities. The large mode splitting enabled us to perform the SBS experiment.

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