The effect on Kerr comb generation in CW-CCW mode coupled WGM microcavity

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A WGM microcavity including a silica toroid microcavity will generate a counter propagating light as a result of defects or nanoparticles attached to its surface. We call the same direction as the input laser clockwise (CW), and the opposite direction counter-clockwise (CCW). In this work, we discuss how the interaction between the clockwise (CW) and counter-clockwise (CCW) modes affects the generation of a Kerr comb. The experimental results show a strong correlation between the mode coupling strength and the generated Kerr comb. Moreover, we performed a numerical simulation using coupled mode equations to confirm the experimental results and investigate the time domain waveform.

Keywords: Silica toroid microcavity, Four-wave mixing, Kerr comb, CW-CCW mode coupling, Coupled mode equation

1. Background
A silica toroid microcavity is an on-chip device that has an ultra high-$Q$ and a small mode volume. Thanks to its small mode volume, the power density per unit area reaches GW/cm$^2$. In addition, a nonlinear process $\chi^{(3)}$ with silica will result in the generation of a Kerr comb. It is known that the counter-propagating mode is induced by the reflection from impurities such as nanoparticles or material defects in whispering gallery mode (WGM) microcavities. The relationship between a microcavity and mode coupling has already been studied, however research on modal coupling in a Kerr comb system has just begun. In this work, we demonstrate the impact of CW-CCW mode coupling on Kerr comb generation in a WGM microcavity. Because CW/CCW mode coupling is spontaneously induced by a defect, it is generally difficult to control its degree. On the other hand, when applied to a Kerr comb using a microcavity, [modal/mode?] coupling may affect the stability or accuracy of the comb. For this reason, it is very important to clarify the physics for practical Kerr comb based applications. This report summarizes work related to this matter that we undertook in 2015.

2. CW-CCW mode coupling
First, we describe the CW-CCW modal coupling in more detail. CCW light is caused by the Rayleigh scattering of CW light without a wavelength shift and shares the same path. When two modes propagating across each other are coupled, the resonance mode is split in the frequency domain. In this situation, we can define it as mode coupled. We approximate the strength of the CW-CCW mode coupling by measuring the transmittance spectrum with splitting. The splitting width increases as the coupling becomes stronger. We can determine $\kappa$ and $\gamma$ from the splitting and the spectrum width, and thus obtain the visibility of coupling $\Gamma = \kappa/\gamma$. In addition, because it is known that there is a high probability that CW-CCW coupling will be observed with a small diameter microcavity, we deliberately fabricated a silica toroid microcavity with a small diameter.

3. CW-CCW Kerr comb measurement
Figure 1(a) shows our experimental setup. We pumped with CW light and observed the CW and CCW directions simultaneously using an optical circulator. Figure 1(b) and (c) show the measured spectrum of the comb in the CW and CCW directions, respectively. Under adequate excitation conditions, we observed a triangular shape for the CW spectrum envelope, which is the characteristic spectrum in the soliton state. On the other hand, the spectrum in the CCW direction was not smooth. To investigate the reason for the different shape in the CCW direction, we next measured the transmission spectrum of each mode number $\mu$ as shown in Fig. 1(d). The left and right axes in Fig. 1(e) represent the peak power ratio of the CW/CCW comb components and the visibility of coupling $\Gamma$, respectively. The horizontal axis corresponds to each comb mode number $\mu$. As a result, the $\Gamma$ and the CW/CCW ratio show a strong correlation, which indicates that the CCW comb is generated by
the scattering of the CW components. The fact that CCW comb power depends on the mode coupling strength is a likely consequence, but it suggests the following things. First, the result suggests that the four wave mixing occurs in the CW direction, and that nonlinearity is not significant in the CCW direction. Next, when each $\Gamma$ is not constant, the resonant peak of the superposition differs from peak to peak and the FSR is not constant. In this situation, the phase matching condition should be satisfied with this cavity. Moreover, we might achieve a soliton state in the CW direction.

4. RF noise measurement
We measured the RF signal because we considered the possibility that the signals caused by mode splitting occur in the generated comb with the split modes. Previous work indicated that there is a relationship between RF noise and the temporal soliton state, and this might be serious problem in terms of the stability of the Kerr comb. Figure 2(a),(b) show the observed comb spectrum and Fig. 2(c) shows the observed RF noise signal of the CW comb in Fig. 2(a). RF signals are measured by using a photodiode and an electrical spectrum analyzer. Figure 2(d) shows the RF noise of a single comb component with the mode number $\mu=0,3$. Figure 2 (a) Observed CW comb spectrum with 10 dB attenuation. (b) Observed CCW comb. (c) Measured RF signal of CW comb. (d) Solid pink and orange lines represent the RF signals of relative mode numbers $\mu=0$ and 3, respectively.

Although the natural frequency of the cavity is detected, the signal corresponding to mode splitting did not appear. Therefore, we conclude that mode coupling has little effect on the RF region.

5. Simulation
We performed a numerical simulation of Kerr comb generation by using coupled mode equations. Figure 3(a) shows a CW-CCW mode coupling model with two cavities. Since we can set the visibility of coupling $\Gamma$ with respect to each mode, the ideal CW-CCW mode coupling is achieved. In this calculation, modifiable parameters are the visibility $\Gamma$, input power $P_{in}$ and the cavity dispersion. We assumed that the dispersion model is a silica toroid microcavity with a major diameter of $45 \mu m$ and a minor diameter of $4 \mu m$. Dispersion is calculated with the finite element method (FEM). Figure 3(b)-(e) show the result of the numerical simulation. Here we assume that the input power $P_{in}$ is 500 mW and the mode coupling is random ($\Gamma=1.0\sim5.0$). As a result, even in the mode coupled condition, we could obtain a broad spectrum and a soliton waveform in the CW direction. On the other hand, there was no broad spectrum or soliton in the time domain in the CCW direction. This result corresponds to the obtained experimental result. The fact that the soliton waveform was generated is evidence that the CW comb in the experiment can be solitons. In addition, we performed the calculation on condition that the mode coupling value is constant, however, only the CW direction
became a pulse.

6. Conclusion
We demonstrated the impact of CW-CCW coupling on Kerr comb generation in a silica toroid microcavity. Specifically, we confirmed experimentally the dependence of a CCW comb on the degree of mode coupling. In addition, there was no RF noise induced by the mode splitting. Moreover, we calculated the temporal waveform and realized soliton formation only in the CW direction, using coupled mode equations. This result reveals a definite solution for the potential problem regarding the application of a Kerr comb with a WGM microcavity.

References
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