Adiabatic frequency conversion using the Kerr effect in an ultra-high-\(Q\) silica toroid microcavity

Wataru Yoshiki (D3), Yoshihiro Honda (B4), Misako Kobayashi (M2), Tomohiro Tetsumoto (D2)

We report the first demonstration of adiabatic frequency conversion using the Kerr effect in a silica toroid microcavity. Taking advantage of the instantaneous response of the Kerr effect, we achieved adiabatic frequency conversion with a controllable amount of frequency shift and time width. In addition, thanks to the combination of the Kerr effect and the ultra-high \(Q (>10^7)\) of the silica toroid microcavity, we also observed multiple frequency conversion within a photon lifetime.

**Key words**: Silica toroid microcavity; Adiabatic frequency conversion; Ker effect;

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1. Introduction

When the resonant frequency of an optical microcavity in which light is trapped is shifted very quickly, the frequency of the light is also changed following the shift. This phenomenon is known as adiabatic frequency conversion (AFC), and has already been observed with a microring [1] and a photonic crystal nanocavity [2]. In these previous studies the resonant frequency was controlled by exciting free carriers in the cavity via the irradiation of high-power “control” pulses. This results in the AFC of a “signal” light (see Fig. 1). However, the carrier’s finite diffusion time limits AFC controllability. For example, as shown in Fig. 1, the shifted resonance does not return to the original frequency even after the control pulse has been turned off. In addition, free-carrier absorption induces an additional loss, which makes the carrier-induced AFC unsuitable for loss-sensitive applications such as quantum optics.

In this paper, we report the first demonstration of AFC in a silica toroid microcavity using the Kerr effect [3]. A silica toroid microcavity [4] is employed as a platform for the experiments because its ultra-high \(Q\) factor provides a long operation time for AFC, and its large bandgap prevents the generation of free carriers. The Kerr effect responds instantaneously (Fig. 1), thus it allows us to achieve AFC with high controllability of such characteristics as the amount of conversion, the conversion time width, and the number of conversions. Even multiple AFC within a photon lifetime is possible.

2. Experimental setup and procedure

Although the Kerr effect is advantageous as regards a fast response and a low loss, it does not induce a refractive index change as large as that induced by the carrier-plasma effect. This infers that we need to couple a control pulse with the resonant mode in the cavity to obtain a sufficiently large refractive index change. However, if the resonance is utilized, the AFC response time is limited by the photon lifetime. This becomes an issue because AFC occurs only when the resonance is shifted in less than the photon lifetime. Taking this into consideration, we employed ultra-high \((1.9 \times 10^7)\) and moderate \((1.8 \times 10^6)\) modes, respectively, for the signal and control lights. In this condition, the photon lifetime of the control mode becomes much shorter than that of the signal mode, thus making it possible to shift the frequency of the signal mode well within the photon lifetime of the signal mode.

Figure 2(a) depicts a block diagram of the experimental setup. The signal and control lights emitted from the tunable laser sources (TLSs) were both modulated into a rectangular pulse with intensity modulators (IMs). The control pulse was amplified with the erbium-doped fiber amplifier (EDFA) after the IM. The two lights were combined, and then input into a tapered optical fiber, and coupled into a microcavity. The output single light was measured with a photodetector (PD) and an
oscilloscope after the control light was filtered out with a band-pass filter (BPF). Figure 2 shows the experimental procedure. Once the signal light is turned off, the signal output decays exponentially after exhibiting a rapid increase if there is no control input. However, if we input a control light (the red region in the figure), the resonance of the signal mode is shifted, and then the frequency of the light in the cavity also changes via AFC. In this situation, the frequency of light coupled out from the cavity differs from that of light transmitted through the fiber, which creates a beat in the signal output. The beat frequency is equal to the frequency shift induced by AFC ($\Delta f_{\text{AFC}}$). Therefore, observation of the beat proves the realization of AFC and gives us information on $\Delta f_{\text{AFC}}$.

![Fig 2 (a) Experimental setup for the AFC experiments. (b) Schematic illustration of how to observe AFC in the output signal light.](image)

### 3. Experimental results

Figures 3(a)-(d) show experimental results. The output signal lights for different input control powers $P_c$ is shown in Fig. 3(a). As seen from the figure, the output signals have a beat while the control light is being input. The beat disappears immediately once the control light is turned off because the Kerr effect responds instantaneously. Such behavior is rarely observed with carrier-induced AFC [1,2] owing to its relatively slow diffusion time. The figure also indicates that the beat frequency (i.e. $\Delta f_{\text{AFC}}$) becomes higher as $P_c$ increases, and reaches 140 MHz, which is approximately 14 times the linewidth of the signal mode. Such behavior can also be seen in Fig. 3(c) where the relation between the input control power and $\Delta f_{\text{AFC}}$ is plotted. This behavior is intuitively understandable because the Kerr effect must be greater for a higher $P_c$. Figure 3(b) shows the signal output for different control pulse widths. It is clear from the figure that the time width of AFC can also be controlled by changing the time width of the control light thanks to the instantaneous response of the Kerr effect. Therefore, we can say that the time width of the Kerr-induced AFC is also controllable. Note that the red dashed lines in Figs. 3(a)-(c) were calculated by using coupled mode theory, which considers the Kerr effect, and they agree well with the experimental lines.

![Fig 3 The output signal light for (a) a different input control power, (b) a different control pulse width, and (d) two input control pulses. The blue and gray curves represent the signal output with and without the control light, respectively. The control light is being input in the red regions. (c) The frequency shift for different input control powers. The red dashed curves in (a)-(d) are the calculated curves, and the black solid curve in the lower panel of (d) shows the calculated time-dependent frequency shift.](image)
Finally, Fig. 3(d) shows the signal output when two control pulses are input while the signal output is decaying. There are two beats in the figure, and the experimental and calculated curves agree well. In addition, the time-dependent frequency shift obtained with the calculated curve implies that AFC occurs twice as presented in the lower panel of Fig. 3(d). Thus we can conclude that multiple AFC was performed within a photon lifetime.

In summary, Kerr-induced AFC was proven to have controllability as regards the amount of conversion (Fig. 3(a)), the conversion time width (Fig. 3(b)), and the number of conversions (Fig. 3(d)).

4. Conclusion

We described the first demonstration of AFC using the Kerr effect. We performed AFC with high controllability by combining the Kerr effect and the ultra-high $Q$ factor of a silica toroid microcavity.

References