A Self-Oscillating Phase Conjugate Resonator as an Optical Frequency Comb

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Abstract: We demonstrate a phase conjugate resonator with a forward-propagating four-wave mixing process that oscillates with the build-up of spontaneous emission. The oscillation exhibits frequency comb properties: equal frequency spacing and phase coherence among different components.

1. Introduction

An optical frequency comb (OFC) [1] is a light source with a series of equidistant frequency components, which is a versatile tool for a variety of applications, ranging from molecular spectroscopy to boosting communication capacity. One appealing direction of work is to extend the OFC resolution into MHz regime, as with electro-optically-produced combs.

A phase conjugate mirror (PCM) [2-4] typically consists of counter-propagating beams with degenerate frequency or nearly-degenerate frequencies, which forms a grating. The grating results in the generation of a conjugate beam by four-wave mixing (FWM) upon the injection of a probe beam. The unique property of PCM is the conjugate beam possesses a phase of $-\boldsymbol{\phi}$, which is exactly the reversal of the incoming beam's phase, $\boldsymbol{\phi}$. This phase conjugation allows for aberration correction in an optical system.

So far, only the counter-propagating PCM has been realized, where the gain is limited [2-4], although sometimes sufficient to lase. A phase conjugate resonator (PCR) is a resonator with PCM serving instead of a normal mirror. Here we realize a PCR with a forward-propagating PCM with large gain, so that it oscillates in a fiber-optical cavity with the build-up of spontaneous emission. A multi-tooth comb is observed and the phase coherence is confirmed by measuring the beating signal.

2. Experimental setup and results: optical frequency comb

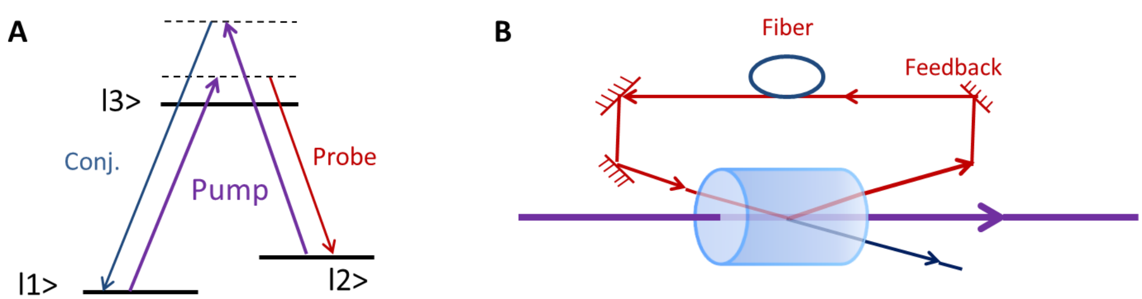

Fig.1. (A) Four-wave mixing process in a double-lambda energy level scheme and (B) a schematic diagram of experimental setup.

The forward-propagating PCM is based on a FWM process in hot rubidium vapor with a double-lambda scheme [5]. The double-lambda energy level scheme is shown in Fig.1A, which allows for conversion of two pump photons into one probe and one conjugate photon via spontaneous emission when injected with vacuum. The experimental setup is shown in Fig.1B, where a strong pump beam is separated with the probe and conjugate beams by a small azimuthal angle of 0.5°-1°.

The spontaneously emitted photons are collected into an optical fiber and sent back to the opposite port of the FWM geometry. Due to this arrangement, the feedback photons are first converted into the conjugate frequency and get converted back to the probe frequency after a second trip in the loop. The resonator mode spacing needs to take into account the two trips: c/2L, where c is the speed of light and L is the effective length. Here the resonator is in a ring shape, so the length of one trip is L, instead of 2L in a linear resonator. This two-trip consideration is consistent with the prediction for resonant modes of optical cavities with PCMs [1].

Each conversion happens with phase conjugation, thus the phase coherence is promised. The forward FWM has also been shown to possess high gain [5], thus the PCR can oscillate just with spontaneous emission. A fiber is used in the feedback loop to tune the resonator length and the consequent resonator mode spacing. When the resonator mode spacing is narrower than the FWM bandwidth of around 20-30 MHz, multiple modes lase and an optical frequency comb is formed. Fig.2 shows the resulting OFC, which consists of two sets of combs, one near the probe frequency and the other near the conjugate frequency. Both combs have shown more than ten teeth with equidistant spacing of less than 3MHz. The resolution can be extended further and the device has potential applications in spectroscopy with exceptional precision.

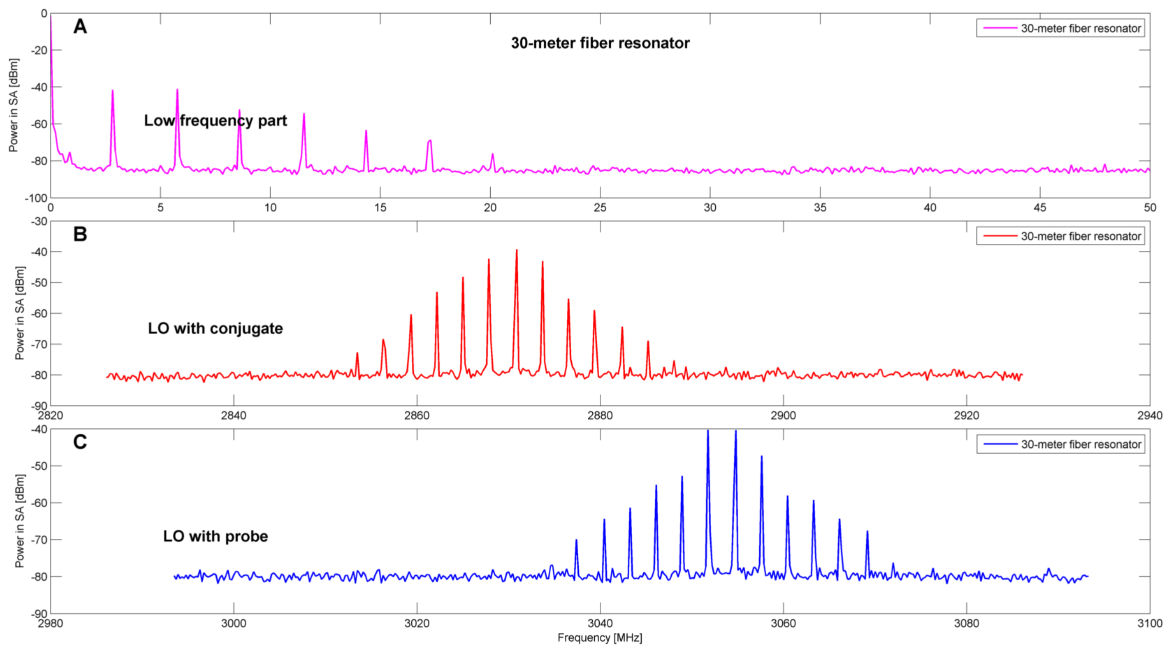

Fig. 2. **(A)** The beating among different comb teeth can be measured by shining the output of the PCR onto a photodiode. The low frequency part shows that the adjacent tooth-spacing is 2.826 MHz and higher orders are the beatings among further-separated teeth. **(B)** and **(C)** The output of PCR consists of both probe and conjugate frequencies and is sent to beat with a local oscillator, with a frequency slightly different from the pump frequency.

3. References

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