Generation of twin photon beams from a thermally self-locked semimonolithic optical parametric oscillator and its application

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Abstract

We have developed a thermally self-locked semimonolithic optical parametric oscillator (OPO), which has a triply resonant cavity. The bistable region of the triply resonant oscillation is convenient for the thermal self-locking, since the thermal effect is significant. This OPO has the capability to generate quantum-correlated twin photon beams without any kind of electronic feedback. We have observed the intensity-difference squeezing of 7.5 dB (82%) between the twin photon beams. Sub-shot noise secret telecommunication and sub-shot noise measurement of magnetic field are demonstrated using the twin photon beams.

I. INTRODUCTION

The parametric interaction in optical parametric oscillators (OPO’s) creates a strong quantum correlation between the signal output ($I_s$) and idler output ($I_i$), and results in producing nonclassical twin photon beams which have squeezing on noise of the intensity difference ($I_s - I_i$). The twin photon beams have potential to overcome the standard quantum limit (SQL) in the field of optical communications and precise optical measurements. Generation of the twin photon beams has been demonstrated in cw region by several groups [1] [2] [3] [4]. All of these experiments were demonstrated by using skillful electronic active control for stabilization of the OPO cavities. In the present paper we show a thermally self-locked OPO, which oscillates without any external-feedback locking system, can generate the nonclassical twin photon beams. It is known that a high-finesse doubly resonant OPO can achieve thermal self-frequency locking and operate continuously in a stable oscillation [5]. Since the output mirror of the OPO needs to have enough transmission compared to the intracavity losses so that the produced photon pairs can efficiently escape from the cavity, it is difficult to use such a high-finesse cavity for the generation of the twin photon beams. In the case of a triply resonant OPO in which the optical cavity resonates with the signal, the idler, and the pump simultaneously, the oscillation has a bistable behavior depending on the detuning conditions [6] [7]. We found that the bistable region of our triply resonant OPO, which generates the twin photon beams, is equivalent to the high-finesse condition.
for the thermal self-locking. Our triply resonant OPO has a mechanically very stable semi-
monolithic configuration, and it enables the thermally self-locked oscillation in generating
the twin photon beams. This thermally self-locked system can stably operate for tens of
minutes and we have observed an intensity-difference squeezing of 7.5 dB between the twin
photon beams. Using the twin photon beams generated from the thermally self-locked semi-
monolithic OPO, we demonstrated sub-shot noise secret telecommunication and sub-shot
noise measurement of magnetic field.

II. EXPERIMENTS AND RESULTS

A. Twin photon beams with thermal self-locking

The schematic diagram of our experimental setup is shown in Fig.1. The semimonolithic
OPO consists of a KTP (TYPE II) crystal and a spherical output mirror of 20-mm radius,
and is carefully designed for the mechanical stability to avoid the surrounding vibrations and
acoustic noise. The output mirror is mounted on a piezoelectric transducer (PZT) to adjust
the cavity length. One side of the crystal, which is an input mirror, has a multidielectric
mirror coating of 90 % reflectivity at 532 nm and high reflectivity at 1064 nm, and the other
side has an anti-reflection coating at the dual wavelengths. The spherical output mirror has
high reflectivity at 532 nm and 95 % reflectivity at 1064 nm. It is pumped at a wavelength of
532 nm by a diode-pumped monolithic, cw, frequency-doubled, YAG laser and generates the
signal and idler beams at the wavelength close to 1064 nm. The optical cavity resonates with
the pump, the signal, and the idler simultaneously, what is called a triply resonant OPO. The
signal and idler beams, which have orthogonal polarizations, are separated by a polarizing
beam splitter (PBS), and directed onto InGaAs photodiodes (Fujitsu FID13Y32WS, 300-
µm diameter) through lenses. The photocurrents are amplified by carefully balanced, low-
noise amplifiers. Noise power spectrum of the subtracted photocurrent is monitored by a
spectrum analyzer. The shot-noise level is measured by rotating the half-wave plate (P)
by 22.5 degrees relative to the PBS axis. Since the signal and the idler beams are mixed,
quantum correlation between two arms is destroyed. This shot-noise level is also confirmed
by injecting a laser beam at the wavelength of 1064 nm onto another port of the PBS.

The oscillation threshold of our OPO was about 6 mW at exact triple resonance. This
low value is obtained by the high efficiency of triply resonant parametric coupling. Total
output power is 30 mW when the pump power is 40 mW, that is, the conversion efficiency is
65 %. Optical bistability is observed in this OPO, as shown in Fig.2, when the cavity length
(the cavity detuning) is scanned. We notes that the OPO output resonance curve has an
asymmetric curve. A vertical steep part on the left side of the resonance is observed, which
is evidence of a bistable behavior in the triply resonant OPO. This bistable region is very
sensitive to variation of the optical cavity length and equivalent to a high-finesse cavity,
and the thermal self-locking gain is very high in this region. When the cavity detuning
approaches the bistable region while scanning slowly the cavity length, the stable thermal
self-locking oscillation of the OPO has started and locked automatically close to the top of
the resonance. This stable oscillation continued over 30 minutes without active stabilization,
and the twin photon beams were generated under the thermal self-locking condition.
Figure 3 shows noise power spectrum observed on the spectrum analyzer. Curve (a) shows the shot-noise level of total intensity of the twin photon beams, and curve (b) shows noise power spectrum of the intensity difference between the twin photon beams. Significant squeezing is observed in spite of the thermally self-locked condition, without any external-feedback locking system. The maximum noise reduction is 7.5 dB (82 %) below the shot-noise level, at a noise frequency of 3 MHz. We observed noise reduction below the shot-noise level up to about 50 MHz.

B. Sub-shot noise secret telecommunication

Sub-shot noise secret telecommunication is demonstrated by using the twin photon beams generated from our thermally self-locked semimonolithic OPO. When one of the twin photon beams is modulated by the information signal below the shot-noise level, the transmitted information signal is hidden by the shot noise (quantum noise). This simple technique is useful for secret telecommunication. The experimental setup for the sub-shot noise secret telecommunication is shown schematically in Fig.4. We placed a home-made amplitude modulator, consisting of a LiNbO$_3$ crystal and a polarizer, in the signal beam behind the output port of the PBS. The modulated sinusoidal signal is very small below the shot-noise level at the frequency of 10 MHz. When we receive the photon-beam partner, we can detect the secret modulated signal by canceling the shot noise with the subtraction circuit. The detected signal below the shot-noise level is down-converted to 50-kHz signal, and is monitored on an oscilloscope. Figure 5(a), observed on the oscilloscope, shows that the transmitted signal is hidden by the shot noise when the two outputs of the PBS has no quantum correlation. Figure 5(b) shows the detected down-converted signal, recovered by the subtraction circuit using quantum correlation between the twin photon beams.

C. Sub-shot noise measurement of magnetic field

We demonstrated sub-shot noise measurement of AC magnetic field by using the twin photon beams, and the schematic diagram of the experimental setup is shown in Fig.6. A Faraday glass (HOYA FR-5, 29 mm) and a polarizing beam splitter (PBSM) are placed in the signal beam behind the output port of the PBS. AC magnetic field (4 MHz) is applied to the Faraday glass, and this field rotates the polarization of the signal beam. The rotation of the polarization is transformed to variation of the intensity through the PBSM. Using quantum correlation between the signal and the idler beams, we could detect the AC magnetic field of 0.8 Oe (peak) below the shot-noise level. Figure 7 shows the detected signal of the magnetic field on the power spectrum, appearing as a small peak at 4 MHz.

III. CONCLUSION

The twin photon beams, which have the intensity-difference squeezing of 7.5 dB (82 %), have been generated from the thermally self-locked semimonolithic OPO. Considering the total detection efficiency of $\sim$0.86, the intensity-difference squeezing inferred at the output
of the OPO is estimated to be $\sim 95 \%$. Two applications of the twin photon beams have been experimentally demonstrated. One is sub-shot noise secret telecommunication that the transmitted signal is hidden by quantum noise. Information of digital on-off signals can be secretly transmitted by using the same system, and such an experiment is now in progress. This technique turns out be an interesting “Quantum Steganography”, which hides the presence of the information signal behind quantum noise. The other application is sub-shot noise measurement of magnetic field, and we observed the magnetic field below the shot-noise level. This kind of application with other sensing materials will be useful for precise measurements of other physical parameters as well.

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FIG. 2. Experimental variation of the OPO output power when the OPO cavity length is scanned (20µsec/div).
FIG. 3. Noise power spectrum of (a) the shot-noise level and (b) the intensity difference between twin photon beams.

FIG. 5. Experimental results of the detected secret signal below the shot-noise level (Time: 10µsec/div). (a): The transmitted signal is hidden by the shot noise. (b): The secret transmitted signal is detected by using twin photon beams.

FIG. 7. Experimental results of the detected magnetic field below the shot-noise level: (a) shot-noise level; (b) intensity-difference noise spectrum.
REFERENCES