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Genta Masada

Quantum ICT Research Institute, Tamagawa University
6-1-1 Tamagawa-gakuen, Machida, Tokyo 194-8610, Japan

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Genta Masada
Quantum ICT Research Institute, Tamagawa University
6-1-1 Tamagawa-Gakuen, Machida, Tokyo, 194-8610, Japan
E-mail: g.masada@lab.tamagawa.ac.jp

Abstract— **Efficient generation of second harmonic waves of 200 mW with 70% of conversion efficiency at 473 nm was achieved by using a periodically poled $KTiOPO_4$ crystal inside an external cavity. Calculations based on the theory of second harmonic generation with an external resonator show good agreement with the experimental results. Such a second harmonic wave power is sufficiently high as a pump light to drive an optical parametric oscillator to generate a squeezed light applicable to our future research of the quantum radar.**

I. Introduction

Squeezed light is a nonclassical state of electro-magnetic field and has noise suppressed below the standard quantum limit in one quadrature component while increased in the other. A theoretical research of squeezed light started in 1960-1970s. Firstly squeezed light was expected to be applied for an optical communication by controlling quantum noises. A mathematical formula of squeezed light was established by Yuen who originally named it two photon coherent states in 1976 [1]. As a method for measuring quantum noise of squeezed light which was below shot noise limit, a balanced homodyne detection was also proposed by Yuen and Chan in 1983 [2]. Around the same time theoretical research revealed the fundamental property of squeezed light. It was indicated that the fragile property in a lossy channel was a limiting factor to realize actual application such as the optical communication [3]. Nowadays one of the important applications of squeezed lights is quantum enhanced sensing such as gravitational wave detector with ultimate resolution [4,5]. Another important application is continuous variables quantum information processing based on quantum teleportation technology which utilizes two mode squeezed lights as an essential resource for quantum entanglement [6]. As a novel application of squeezed lights, we are interested in quantum radar, for example, quantum illumination [7-9]. In these applications the final outcome is limited by squeezing level. So it is important to generate highly squeezed light.

One of the successful methods for generating continuous wave highly squeezed light is utilization of a sub-threshold optical parametric oscillator (OPO) [10-15]. An OPO includes a nonlinear optical crystal for utilizing second order nonlinear optical effect. To generate highly squeezed light, it is necessary to pump the OPO efficiently with a pump beam which has twice the frequency of squeezed light and is usually generated by second harmonic generation (SHG) process. Therefore it is very important to develop a frequency doubler with high conversion efficiency as a pump resource for the OPO. Over the past few decades a considerable number of the experiments have been performed to generate continuous wave second harmonics. A common method to generate second harmonic waves is to utilize an external resonant cavity which has bow tie configuration and includes a nonlinear optical crystal [16-22].

In this article we introduce development of frequency doubler as a pump source for squeezer which will be used for quantum radar research in future work. A continuous wave Nd:YAG laser with wavelength of 946 nm is used for fundamental light source. Efficient generation of second harmonic waves of 200 mW at 473 nm was achieved by using a periodically poled $KTiOPO_4$ (PPKTP) crystal inside an external cavity with fundamental waves of 285 mW. The conversion efficiency corresponds to 70 %.

II. Experimental setup

Fig.1 shows the present optical configuration of frequency doubler which consists of a symmetric bow tie cavity and a nonlinear optical medium, a PPKTP crystal. The cavity of frequency doubler has two flat mirrors M_1 and M_2, and two spherical mirrors M_3 and M_4 whose radius of curvature is 25 mm. One of the flat mirrors M_1 has partial transmittance T of 0.104 at 946 nm and is used as the input coupling mirror for fundamental wave input. Other mirrors have high reflectance at 946 nm. And all mirrors have high transmittance at 473 nm which is the second harmonics wavelength. The mirror M_4 is used as output coupler for the SHG. The PPKTP crystal has the length l_c of 10 mm and 1*1 mm^2 of cross section, and is placed between the two spherical mirrors M_3 and M_4. The l_1, l_2 and l_3 are distance between each mirror and the total cavity length l can be calculated by $l_1+2*l_2+l_3$. The d is the width of the cavity and should be kept as minimum as possible in order to suppress cavity folding angle θ which causes an optical aberration.

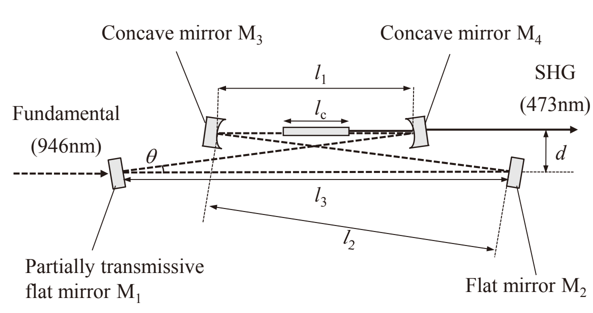

Fig.1 Schematic diagram of frequency doubler with a bow tie cavity.

In order to achieve high conversion efficiency, it is necessary to improve the efficiency of nonlinearity E_{NL} by optimizing a focusing condition in the PPKTP crystal. In conventional Boyd and Kleinman theory [23], the focusing parameter ξ is defined as

$$\xi = l_c/b \tag{1}$$

by using the crystal length l_c and the confocal parameter b of the Gaussian beam.

In Eq.(1) the b is calculated by the following relation

$$b = {w_1}^2 k_\omega \tag{2}$$

where the w_1 is beam waist size in nonlinear optical crystal and the k_ω is fundamental wave vector expressed as

$$k_\omega = \frac{2\pi}{\lambda_\omega} n_\omega \tag{3}$$

by using the refractive index of nonlinear optical crystal n_ω (=1.835 in KTP) at fundamental wavelength λ_ω (=946 nm). In Boyd and Kleinman theory, it is shown that the E_{NL} has maximum value when the focusing parameter ξ is 2.84. The optimum focusing condition was experimentally verified in PPKTP crystal at 860 nm in recent work [24]. Based on these results, the optimum beam waist size w_1 is expected as 17 μm in our optical configuration. Fig.2 shows calculation results of the beam waist sizes based on the ABCD matrix analysis. Assuming that the total cavity length l is kept at 220 mm, the w_1 shows the optimum value of 17μm at 31.5 mm of the l_1. The other beam waist size w_2 between flat mirrors M_1 and M_2 is estimated as 155μm. At this time the l_2 is 55.5 mm and l_3 is 77.6 mm, respectively, and the d is kept as 10.0 mm which yields the cavity folding angle θ of 10.4 degrees.

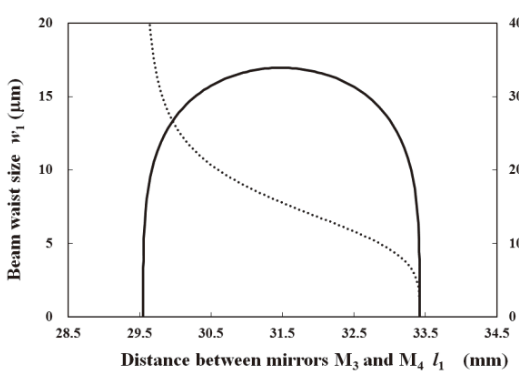

Fig.2 Calculation results of the beam waist size in bow tie cavity based on the ABCD matrix analysis. Solid line indicates beam waist size w_1 at the center of PPKTP crystal. Dotted line represents beam waist size w_2 between flat mirrors M_3 and M_4.

A schematic of experimental setup for frequency doubler is shown in Fig.3. A continuous-wave 946 nm beam from Nd:YAG laser source is introduced to frequency doubler from the input coupling mirror M_1. The PPKTP crystal is mounted in a nickel-plated copper oven and surrounded from four side surfaces in order that the homogeneity of temperature distribution is improved. The crystal assembly is attached with Peltier device and thermistor by thermally-conductive epoxy and controlled at 60 degrees which is phase matching temperature of a PPKTP crystal at 473 nm. The 946 nm beam is phase-modulated at 18 MHz by an electro-optic modulator (EOM) with a function generator (FG). The reflection of fundamental wave from input coupler mirror M_1 is monitored by photo detector (PD). The electrical signal from the PD at radio frequency is mixed with the FG signal and sent to the low pass filter (LPF) to generate error signal. Then the error signal is sent to servo-amplifier to drive piezo transducer (PZT) which is mounted with the mirror M_4 in order to lock the cavity at the resonant condition by

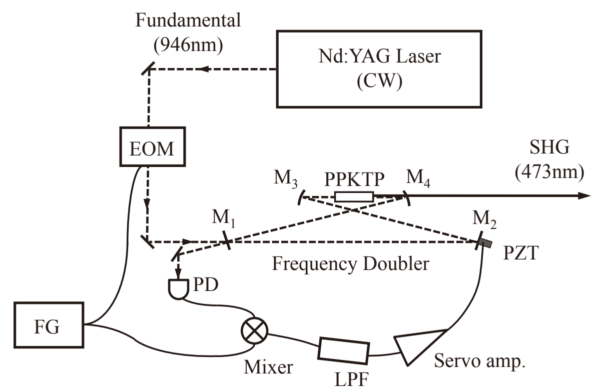

Fig.3 Optical experimental setup for second harmonic generation by using an external bow-tie cavity including a PPKTP crystal.

conventional Pound-Drever-Hall method [25].

III. CHARACTERIZATION OF PPKTP CRYSTAL

Firstly it is important to precisely measure characteristic parameters of the frequency doubler. The efficiency of nonlinearity E_{NL} and the intracavity loss L of the fundamental waves are required for evaluating the second harmonic wave power and the conversion efficiency which will be discussed later. Experimentally the E_{NL} W^{-1} is defined as

$$E_{NL} = \frac{P_{2\omega}}{{P_\omega}^2} \tag{4}$$

where P_ω and $P_{2\omega}$ are the power of fundamental and second harmonic wave respectively with single pass frequency doubling. In other words E_{NL} is conversion efficiency per 1 W of P_ω. For measuring the single pass frequency doubling, an optical path is blocked between the mirrors M_4 and M_1 in order that the fundamental beam does not circulate the cavity and goes through the crystal only one time. Fig.4 shows an experimental result of second harmonic generation with single pass configuration. The horizontal axis is fundamental wave power P_ω which is measured after the input coupler mirror M_1. The vertical axis is single pass conversion efficiency defined by $P_{2\omega}/P_\omega$. The conversion efficiency is proportional to the input power. Then the E_{NL} is derived from the proportionality coefficient and evaluated as 0.0151 W^{-1} by a linear fitting.

Next the intracavity loss L of the fundamental wave is evaluated by injecting a weak beam from the input coupler mirror M_1. It is reported that the intracavity loss increases by the pump induced loss in optical crystal at rather shorter wavelength [10,14,15]. In that case the intracavity loss L can be expressed as

$$L = L_0 + aP_{2\omega} \tag{5}$$

where L_0 is a passive loss without a pump beam and a is a coefficient of pump induced losses respectively. The present measurement shows the passive loss L_0 of 0.0157. In this work it is difficult to directly measure the coefficient a for the reason of experimental setup. So the value of a is assumed as

0 or 0.04 W^{-1} when the characteristic of the frequency doubler is theoretically analyzed in the next chapter.

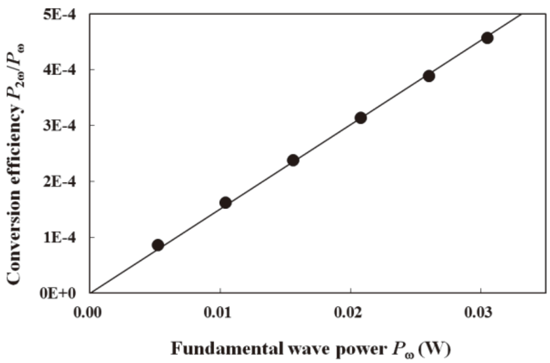

Fig.4 Evaluation result of the efficiency of nonlinearity in PPKTP crystal.

IV. SHG Experiment and Discussions

Fig. 5 shows typical results of the frequency doubler. The horizontal axis shows the fundamental wave power P_{ω} measured before the input coupler mirror M_1. The right and left axes represent second harmonic wave power $P_{2\omega}$ and conversion efficiency $P_{2\omega}/P_{\omega}$, respectively. The highest second harmonic wave power $P_{2\omega}$ of 200 mW was achieved at the fundamental wave power P_{ω} of 285 mW. This result corresponds to the conversion efficiency of 70 %. To analyze the performance of the frequency doubler with an external resonator, the following theoretical formula

$$\sqrt{P_{2\omega}} = \frac{T P_{\omega}\sqrt{E_{\mathrm{NL}}}}{\left(1-\sqrt{1-T}\sqrt{1-L}\sqrt{1-\sqrt{E_{\mathrm{NL}}P_{2\omega}}}\right)^2} \tag{6}$$

is introduced [16]. By using this formula the relation between the second and fundamental wave power can be calculated. The conversion efficiency is also calculated by using relation $P_{2\omega}/P_{\omega}$. In Fig.5 the dashed lines are calculation results by assuming that a=0 and deviated from experimental results. The solid lines are result with assuming

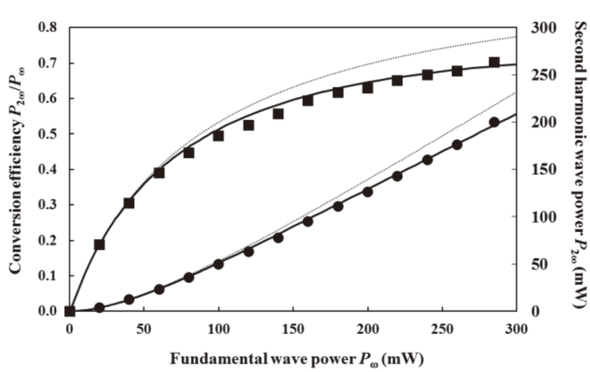

Fig.5 Experimental results of the frequency doubler. Circles and squares represent second harmonic wave power $P_{2\omega}$ and conversion efficiency $P_{2\omega}/P_{\omega}$, respectively. Dotted and solid lines are calculation results assuming a=0 W^{-1} (with pump induced loss) and 0.04 W^{-1} (without pump induced loss), respectively.

the coefficient of pump induced loss a of 0.04 W^{-1} and show good agreement with the experiments.

Usually the optical parametric oscillator (OPO) can be realized by the same optical configuration with frequency doubler. If we construct the OPO with the same bow tie cavity, the oscillation threshold of pump power is expected as 237 mW by assuming the current optical parameter values, T=0.104, L=0.0157, and E_{NL}=0.0151 W^{-1} in the following relation

$$P_{th} = \frac{(T+L)^2}{4E_{NL}}. \tag{7}$$

The maximum second harmonic wave power of our frequency doubler 200 mW corresponds to 0.92 of normalized pump parameter x which can be calculated as

$$x = \sqrt{P_{2\omega}/P_{th}}\,. \tag{8}$$

Such a second harmonic wave power is sufficiently high as a pump light to drive an optical parametric oscillator to generate a squeezed light applicable to our future research of the quantum radar.

V. Conclusion

In conclusion the efficient generation of second harmonic waves of 200 mW at 473 nm was achieved by using a periodically poled $KTiOPO_4$ crystal inside an external cavity. This result corresponds to 70% of conversion efficiency. Calculations based on the theory of SHG with an external resonator with present experimental parameter were also performed. The calculation results show good agreement with the experimental results by assuming the coefficient of pump induced loss a of 0.04 W^{-1}.

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