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***Abstract*—We generated second harmonic waves of a continuous wave Nd:YAG laser using an external cavity with a periodically poled $KTiOPO_4$ crystal. With the fundamental wave input of 256mW, we succeeded in generating the second harmonic output of 180mW at the wavelength of 532 nm. Wavelength conversion efficiency under this condition is 70%. We also performed theoretical calculations of second harmonic generation, taking into account the effect of the external cavity. Numerical results assuming absorption loss induced by the second harmonic show very good agreement with experimental results. Furthermore, since the absorption coefficient in this result is lower than in past experiments, it is expected that the stability of the optical cavity will be improved.**

I. Introduction

Second harmonic generation (SHG) is a wavelength conversion method that utilizes nonlinear optical effects, making it possible to reduce the wavelength of incident laser light by half. By applying this method to near-infrared solid-state lasers, it becomes possible to generate stable, high-quality laser light even in short wavelength regions such as visible light and ultraviolet light. In recent years, second harmonic generation has become important in generation process of quantum light such as squeezed light. In order to obtain the second harmonic of a continuous wave laser with high efficiency, a method using an external resonator is often used [1], [2], [3], [4], [5].

In this study, we generated the second harmonic of a continuous wave Nd:YAG laser with a wavelength of 1064 nm using an external cavity with a periodically poled $KTiOPO_4$ (PPKTP) crystal as a nonlinear optical medium. A tilt-lock method was used to control resonance conditions of the cavity [6]. Advantages of a tilt lock method are the simple experimental setup and the ability to generate error signals without the use of expensive electro-optic modulators. As a result, with a fundamental wave input of 256 mW, we succeeded in generating a second harmonic output of 180 mW at the wavelength of 532 nm. Wavelength conversion efficiency under this condition was 70 %. We also performed theoretical calculations for second harmonic generation using an external cavity. Assuming the absorption loss induced by the second harmonic, numerical results showed very good agreement with experimental results. It was also found that the absorption coefficient in this calculation result was lower than in previous experiments in which the second harmonic of 476 nm was generated [7]. Therefore, it is expected that the stability of the optical cavity will be improved.

II. Design of external cavity with a PPKTP crystal

Fig. 1 shows a bow-tie cavity for second harmonic generation using a PPKTP crystal (Raicol) as a nonlinear optical medium. A continuous wave 1064 nm beam from Nd:YAG laser light source (Coherent, Mephisto S Laser System) is introduced into the cavity through input mirror M_1, and the wavelength-converted 532 nm beam is output from mirror M_4. The cavity consists of two plane mirrors M_1 and M_2 and two concave mirrors M_3 and M_4 with a radius of curvature of 25 mm. The plane mirror M_1 has a partial transmittance T of 0.107 at the wavelength of 1064 nm, and is used as a mirror for inputting the fundamental wave. Other mirrors have high reflectivity at the wavelength of 1064 nm. Additionally, all mirrors have high transmittance at the wavelength of 532 nm. Mirror M_4 is used as a second harmonic output mirror. The PPKTP crystal has a length l_c of 10 mm and a cross section of $1{\times}2$ mm^2 and is placed in the center of two concave mirrors M_3 and M_4. l_1, l_2, l_3 are the distancs between each mirror, and the total length l of the resonator is calculated by l_1+2×l_2+l_3. In order to suppress the cavity bending angle θ, which causes optical aberrations, it is necessary to make the cavity width d as narrow as possible.

To achieve high conversion efficiency, it is necessary to optimize the light focusing conditions within the PPKTP crystal and maximize the nonlinear parameter E_{NL}. In this study, we applied Boyd and Kleinman theory to set the optimal light focusing conditions [8]. Focusing parameter ξ is defined using crystal length l_c (=10 mm) and confocal parameter b of the Gaussian beam as followoing equation

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

The confocal parameter b is calculated by the following relationship

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

where w_1 is the beam waist size in the nonlinear optical crystal, and k_ω is the fundamental wave vector, which is expressed by the following formula

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

n_ω is the refractive index (=1.8297) of the nonlinear optical crystal PPKTP at the fundamental wavelength of 1064 nm.

Boyd and Kleinman theory shows that when the focusing parameter ξ is 2.84, focusing conditions are optimized and then the nonlinear parameter E_{NL} has its maximum value. Therefore, the optimal beam waist size $w_{1.\mathrm{opt}}$ is expressed by the following relationship

$$w_{1.\mathrm{opt}} = \left(\frac{l_c \lambda_\omega}{5.68\pi n_\omega}\right)^{\frac{1}{2}}. \tag{4}$$

Past experimental studies have demonstrated the effectiveness of the light focusing condition of Eq. 4 [9]. Using the parameters of this cavity design, the optimal beam waist size $w_{1.\mathrm{opt}}$ is calculated 0.018 mm.

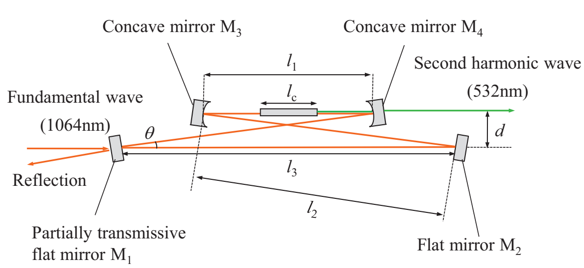

Fig. 1. Design of bow-tie cavity with a periodically poled KTiOPO$_4$ crystal

Fig. 2 shows the beam waist size calculation results based on ray transfer matrix analysis. The total cavity length l is maintained at 218 mm. The beam waist size w_1 is the optimal value 0.018 mm when l_1 is 31.5 mm. At the same time, the other beam waist size w_2 between plane mirrors M$_1$ and M$_2$ is calculated to be 0.16 mm. Here, when the cavity width d is 10.0 mm, l_2 is calculated to be 55.0 mm, l_3 is 76.6 mm, and the cavity bending angle θ is calculated to be 10.4 degrees.

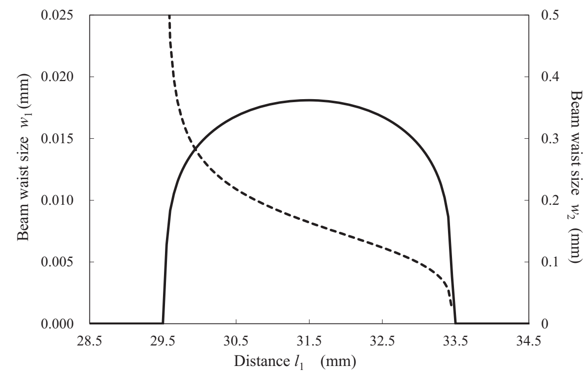

Fig. 2. Calculaiton results of beam waist sizes w_1 (solid line) and w_2 (dotted line) in the cavity.

III. Characterization of SHG cavity parameters

In order to generate second harmonic waves with high efficiency using an external cavity, it is important to accurately know the characteristic parameters of the cavity. As will be described later, in order to evaluate the second harmonic power $P_{2\omega}$ and the wavelength conversion efficiency, it is necessary to accurately know the nonlinear parameter E_{NL}. Experimentally, the nonlinear parameter E_{NL} is defined by the following equation

$$E_{NL} = \frac{P_{2\omega}}{P_\omega^2}. \tag{5}$$

In order to obtain nonlinear parameter E_{NL}, it is necessary to measure the second harmonic output $P_{2\omega}$ when the fundamental wave with power P_ω is input to the nonlinear optical crystal only once without using the cavity effect. When measuring the second harmonic in a single pass, the optical path was blocked between mirrors M$_4$ and M$_1$ so that the fundamental wave did not circulate through the cavity but passed through the crystal only once. Also, since the second harmonic that passed through mirror M$_4$ contained a slight amount of the input fundamental wave, it was separated using a prism.

Fig. 3 shows the experimental results of second harmonic generation using a single-pass configuration. The horizontal axis is the fundamental wave power P_ω measured after the input mirror M$_1$. The vertical axis is the conversion efficiency in a single pass, defined as $P_{2\omega}/P_\omega$. It is clear that the conversion efficiency is proportional to the input fundamental wave power P_ω. From the value of the proportionality coefficient in Fig. 3, the nonlinear parameter E_{NL} was estimated as 0.0098 W^{-1}.

Intra-cavity loss L is also important cavity parameter. We evaluated the intracavity loss L by inputting fundamental waves from the input mirror M$_1$. It has been reported that when a short wavelength second harmonic is

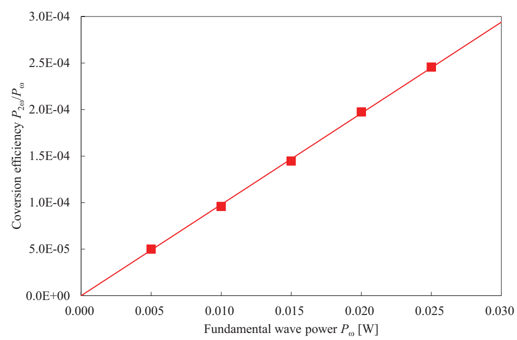

Fig. 3. Wavelength conversion efficiency of single-pass second harmonic generaiton.

generated inside the PPKTP crystal, not only the passive loss L_0 of the fundamental wave but also the additional loss induced by the second harmonic occurs [10]. At this time, the intracavity loss L can be assumed as following equation

$$L = L_0 + aP_{2\omega}. \tag{6}$$

The passive loss L_0 is measured 0.0084 at the current expeimental setup. a is the coefficient of loss induced by the second harmonic, which is difficult to measure directly with the current experimental setup. As will be explained later, the coefficient a is estimated to be 0.012 W^{-1} from the results of second harmonic generation experiments using the cavity.

IV. SHG Experiments and Discussions

Fig. 4 shows the experimental layout for second harmonic generation using the external cavity. To maintain phase-matching conditions, the PPKTP crystal is mounted in a nickel-plated copper oven. And the temperature is controlled at 32 degrees by a Peltier element and a thermistor. In this experiment, a piezoelectric transducer PZT attached to mirror M_2 was feedback-controlled using a tilt-lock method to maintain the cavity length under resonance conditions [6]. Firstly, the input fundamental wave is introduced through mirror M_1. The reflection is input to photodetector PD having a split photodiode divided into two left and right regions and monitored by the oscilloscope. The input optical axis was slightly tilted and misaligned in order to generate not only resonant TEM_{00} but also nonresonant TEM_{10} spatial modes.

Fig. 5 shows the signal from the photodetector PD when the piezoelectric transducer PZT is driven by a triangular wave voltage with a frequency of approximately 30 Hz. The red line is the sum signal (SS) from the two divided photodiodes. On the other hand, the blue line shows the difference signal (DS) from the two divided photodiodes amplified by the servo amplifier (Servo amp). This corresponds to the error signal used for feedback control of the cavity. The signal indicated by the solid and dotted arrows correspond to resonance for the TEM_{00} and TEM_{10} mode, respectively. The error signal in the blue line corresponds to the interference between the optical electric field in TEM_{00} and TEM_{10} modes. When generating second harmonic waves, the cavity was locked to the TEM_{00} mode resonance indicated by the solid arrow.

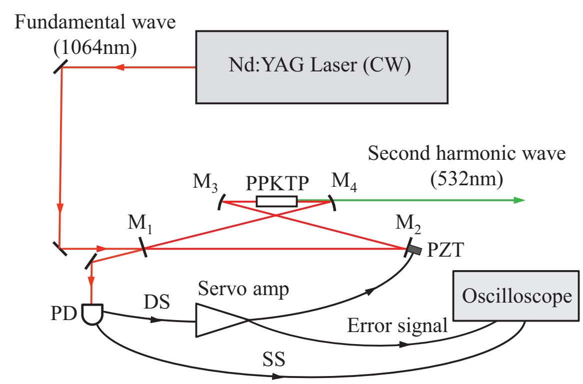

Fig. 4. Experiment layout of second harmonic generation of continuous wave Nd:YAG laser with external cavity.

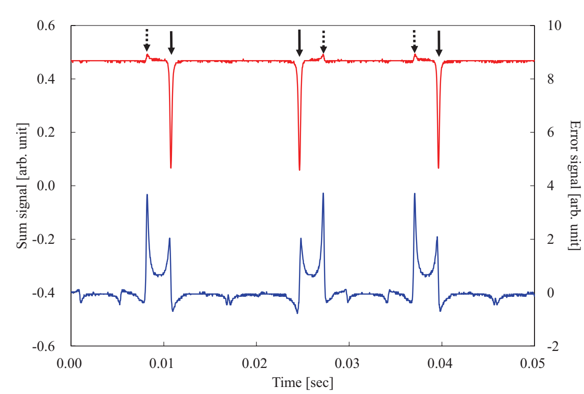

Fig. 5. Signals from split photo diode. The red line represents the sum signal and the blue line represents the error signal obtained from the difference signal from the photodetector PD with a split photodiode. The solid and dotted arrows represent the resonance points of TEM_{00} and TEM_{10} mode, respectively.

Fig. 6 shows the results of second harmonic generation using an external resonator. The fundamental wave power P_ω shown on the horizontal axis was measured in front of mirror M_1. Blue circles are the power of the second harmonic $P_{2\omega}$ and red squares are the conversion efficiency $P_{2\omega}/P_\omega$. When the input power P_ω is small, the second harmonic power $P_{2\omega}$ increases quadratically, and the conversion efficiency increases linearly. As the second harmonic output P_ω increases, the conversion efficiency tends to gradually become saturated, as in past studies. This is because most of the input fundamental wave P_ω is converted and depleted. Finally, when the fundamental wave power P_ω was 256 mW, the second harmonic power $P_{2\omega}$ was 180 mW. At this time, the wavelength conversion efficiency is 70 %.

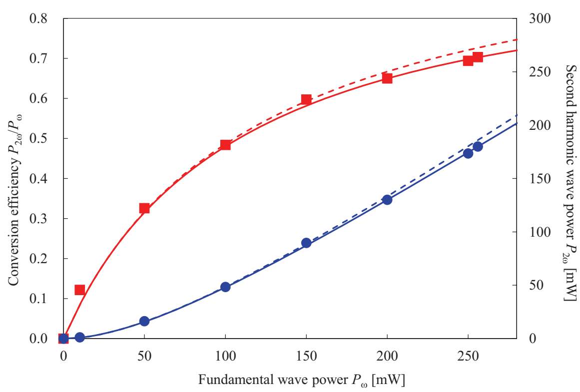

Fig. 6. Results of second harmonic waves at 532 nm with the external cavity. Blue circles are the second harmonic output $P_{2\omega}$ and red squares are the conversion efficiency $P_{2\omega}/P_\omega$. All lines represent calculation results.

The second harmonic generation process using an external cavity can be analyzed using the following theoretical formula [2]

$$\sqrt{P_{2\omega}} = \frac{TP_\omega\sqrt{E_{NL}}}{\left(1-\sqrt{1-T}\sqrt{1-L}\sqrt{1-\sqrt{E_{NL}P_{2\omega}}}\right)^{\frac{1}{2}}}. \tag{7}$$

Using this formula, we can calculate the relationship between the powers of the second harmonic wave and the fundamental wave. It is also possible to calculate the conversion efficiency $P_{2\omega}/P_\omega$. In Fig. 6, the broken lines are the calculation results when the coefficient a of the loss induced by the second harmonic is assumed to be 0, and show slight differences from the experimental results. The solid lines are the results assuming that the coefficient a is 0.012 W^{-1}, and show good agreement with the experiments. In the past experiment in which a PPKTP crystal was used to generate second harmonic waves at 473 nm, the coefficient a was reported to be 0.04 W^{-1} [7]. Compared to this experiment, it is thought that generating the second harmonic with a longer wavelength of 532 nm would have a smaller effect on loss. From this, it is thought that the thermal effects due to light absorption are small, and stability of the cavity is expected.

V. Summary

Second harmonic generation is a wavelength conversion method that utilizes nonlinear optical effects, and can reduce the wavelength of incident laser light by half. In order to obtain the high wave length conversion efficiency, an external resonator with nonlinear optical crystal is often used. In this work second harmonic waves of a continuous wave Nd:YAG laser was generated by the external cavity using a periodically poled $KTiOPO_4$ crystal. We achieved second harmonic output power $P_{2\omega}$ of 180 mW at the wavelength of 532 nm when the fundamental wave input power P_ω was 256 mW. The wavelength conversion efficiency was 70% at this time. Calculations based on SHG theory were also performed using actual cavity parameters. The calculated results were shown to be in good agreement with the experimental results by assuming that the loss coefficient a induced by second harmonics was 0.012 W^{-1}. This value is smaller than previous experiments that generated the second harmonic at 473 nm. The newly constructed cavity for second harmonic generation at 532 nm is less susceptible to thermal effects due to light absorption and is therefore expected to have high stability.

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