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***Abstract*—Efficient generation of second harmonic waves of 400 mW from fundamental waves of 570 mW with 70% of conversion efficiency at 430 nm was achieved by using a periodically poled $MgO:LiNbO_3$ crystal inside an external cavity. Calculation results based on the theory of SHG with an external resonator show good agreement with experimental results. Theoretical speculation is also showing a possibility of 87% efficiency by using the improved effective nonlinearity and intracavity losses, and optimizing the transmittance of input coupler in future work.**

I. Introduction

Squeezed states of light is an important resource for quantum optics. Yuen established a mathematical formula of squeezed states for the purpose of applying to communication by controlling a quantum noise [1]. However it is indicated that its fragile property in a lossy channel is a limiting factor to realize actual communication [2]. In recent years, an important application of squeezed light is gravitational wave interferometer [3] and quantum information processing with continuous variables [4]. For the latter example, quadrature squeezed vacuum states are applied to realize quantum teleportation which is a fundamental protocol in quantum information processing [5]. The fidelity of such protocols is limited directly by the squeezing level. So it is important to generate highly squeezed light to achieve a better performance.

A typical method to generate highly squeezed light is utilization of a subthreshold optical parametric oscillator (OPO) which includes a nonlinear optical medium. In a recent work Masada, *et al.* have reported the efficient generation of highly squeezed light by utilizing an OPO with a periodically poled MgO-5mol%-doped $LiNbO_3$ (PPMgLN) bulk crystal [6], [7]. To generate highly squeezed light, it is necessary to pump the OPO efficiently with a high pump power which is usually applied from second harmonic generation (SHG). So it is very important to develop a frequency doubler with high conversion efficiency as a pump resource for the OPO. Masada, *et al.* have also reported the efficient generation of second harmonic waves with a PPMgLN crystal inside an external cavity and generated 400 mW at 430 nm from 570 mW of fundamental waves with 70% of conversion efficiency. The purpose of this work is to give a theoretical review for previous SHG experiments with a precise measurement of nonlinearity and intracavity loss of the frequency doubler.

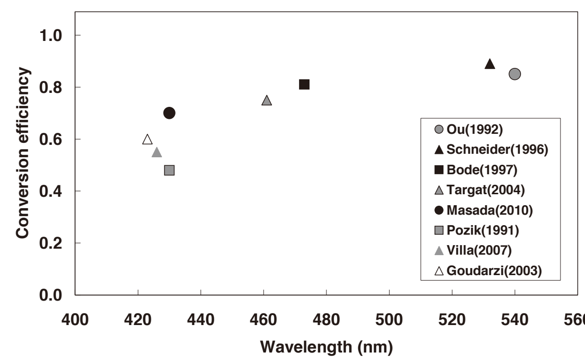

Fig. 1. Summary of previously reported conversion efficiency of SHG experiments at a visible light region.

Over the past few decades a considerable number of the experiments have been performed to generate continuous wave second harmonics at a wavelength region of visible light as shown in Table. I. A common method to generate second harmonic waves is to utilize an external resonant cavity which includes a nonlinear optical medium. At 540 nm Ou, *et al*. utilized a $KTiPO_4$ (KTP) crystal as a nonlinear medium for a frequency doubler with a bow-tie configuration and generated 560 mW of second harmonic wave power with conversion efficiency of 85% [8]. Schneider, *et al*. achieved 1.1 W of second harmonic wave power with conversion efficiency of 89% at 530 nm by utilizing a $MgO:LiNbO_3$ (MgLN) crystal with a semimonolithic cavity [9]. At blue light wavelength Bode, *et al*. achieved 81% of efficiency at 473 nm by utilizing a $KNbO_3$ (KN) crystal with a semimonolithic cavity [10]. And Targat, *et al*. achieved 75% efficiency at 460 nm by using a periodically poled KTP (PPKTP) crystal with a bow-tie cavity [11]. There is a trend that conversion efficiency reduces at shorter wavelength region as shown in Fig. 1. A major factor of degradation of the efficiency is probably due to nonlinear optical absorption of blue light, blue light induced infrared absorption (BLIIRA) and/or photo-refractive effect. At around 430 nm the highest conversion efficiency is 70% which is achieved by Masada, *et al* [6].

TABLE I
SUMMARY OF CONTINUOUS WAVE SHG EXPERIMENTS WITH HIGH CONVERSION EFFICIENCY AT VISIBLE LIGHT.

Authors	Nonlinear optical medium	Wavelength (nm)	Efficiency (%)	SHG power (mW)
Ou (1992) [8]	KTP	540	85	560
Schneider (1996) [9]	MgLN	532	89	1100
Bode (1997) [10]	$KNbO_3$	473	81	500
Targat (2005) [11]	PPKTP	461	75	234
Masada (2010) [6]	PPMgLN	430	70	400
Polzik (1991) [12]	$KNbO_3$	430	48	650
Villa (2007) [13]	PPKTP	426	55	330
Goudarzi (2003) [14]	PPKTP	423	60	225

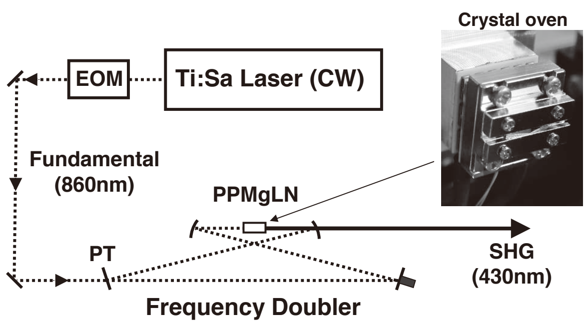

Fig. 2. Schematic diagram of experimental setup for frequency doubler.

II. EXPERIMENTAL SETUP

A schematic of experimental setup is shown in Fig. 2. A continuous-wave Ti:Sapphire laser at 860 nm is used as the fundamental source. The optical system mainly consists of a cavity with bow-tie configurations as an optical frequency doubler which utilizes the PPMgLN crystal as a nonlinear optical midium. The 860 nm beam is phase-modulated at 9.1 MHz by an electro-optic modulator (EOM) in order to lock the cavity at the resonance by conventional FM sideband locking technique [15]. The cavity of frequency doubler has two spherical mirrors whose radius of curvature is 50 mm and two flat mirrors. One of the flat mirrors has partial transmittance (PT) at 860 nm and is used as a coupling mirror. Other mirrors have high reflectance (HT) at 860 nm. The PPMgLN crystal with 8 mm long and 1*1 mm2 cross section is placed between the two spherical mirrors of the frequency doubler. The round trip length of the cavity is about 500 mm which yields the beam waist size of 21 μm in radius at the crystal center. The PPMgLN 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 as shown in the inset picture of Fig. 2. The crystal assembly is attached with Peltier device and thermister by thermally-conductive epoxy and controlled at $50°$C which is phase matching temperature of a PPMgLN crystal at 430 nm.

III. CHARACTERIZATION OF PPMGLN CRYSTAL

Firstly it is important to precisely measure the characteristic parameters of the PPMgLN crystal which is utilized for the frequency doubler. The effective nonlinearity E_{NL} of the PPMgLN crystal and the Loss L of the intra cavity at fundamental waves are necessary for evaluating the second harmonic wave power and the conversion efficiency which will be discussed later.

The E_{NL} (W^{-1}) is defined as

$$E_{NL} = \frac{P_{2\omega}}{P_{\omega}^{2}} \tag{1}$$

where P_ω and $P_{2\omega}$ are the power of fundamental wave and second harmonic respectively with single pass frequency doubling. In other words E_{NL} is a conversion efficiency per 1 (W) of P_ω. Fig. 3 shows an experimental configuration of single pass frequency doubling. A fundamental beam pass is blocked after the crystal in order that the beam does not circulates 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 after the input coupler which has a transmittance of T. The vertical axis is single pass conversion efficiency which is the second harmonic wave power $P_{2\omega}$ divided by P_ω. The conversion efficiency is proportional to input power which agrees well with a consequence from classical nonlinear optics. The E_{NL} corresponds to the slope efficiency of the characteristic line in Fig. 4 and is obtained as 0.011 (W^{-1}) which is rather smaller than the previously reported value of OPO crystal which is 0.043 (W^{-1}). A difference might be caused by an imperfection of the periodically poled structure, since a fabrication process is still under developing. So the characteristic parameter sensitively differs from samples to samples and summarized in Table. II.

Next the Loss L of the intra cavity at fundamental waves was evaluated by injecting a weak coherent beam from the input coupler. It is reported that the intracavity loss increases by the blue light probably due to BLIIRA and/or photo-refractive effect [6]. The experimental results can be expressed as a following equation

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

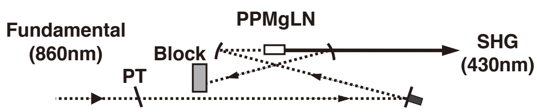

Fig. 3. Experimental setup for single pass second harmonic generation.

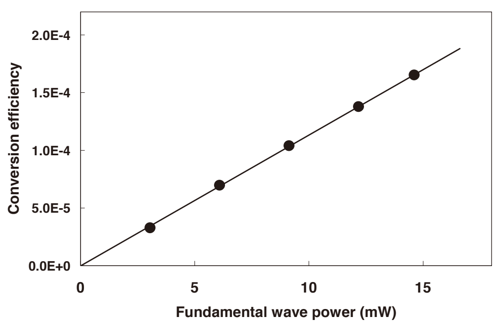

Fig. 4. Experimental result of the conversion efficiency with single pass frequency doubling.

where L_0 is a passive loss without a pump beam and a is a coefficient of pump induced losses respectively. The analysis shows the loss without a pump beam L_0 is 0.0187, which is larger than the previously reported value of 0.0124 with the OPO [6] and might be caused by imperfection of the periodically poled structure and highly reflective coating of mirrors. In this work it is difficult to measure the coefficient a for a reason of the present experimental set up. So the previously obtained value 0.0246 (W^{-1}) at the OPO crystal [6] will be used for the analysis of frequency doubler later.

IV. SHG EXPERIMENT AND DISCUSSIONS

Fig. 5 shows typical results of the SHG with fundamental wave power up to 570 mW. The second harmonic power of 400 mW is generated from fundamental wave power of 570 mW which corresponds to the conversion efficiency of 70%. To analyze the second harmonic waves, the theoretical formula by Polzik, *et al.* is introduced as following equations [12]. The second harmonic wave power $P_{2\omega}$ generated with an external resonator is described as

$$\sqrt{P_{2\omega}} = \frac{TP_\omega\sqrt{E_{NL}}}{(1-\sqrt{1-T}\sqrt{1-L}\sqrt{1-\sqrt{E_{NL}P_{2\omega}}})^2} \quad (3)$$

where P_ω is fundamental wave power, T is transmittance of input coupler, respectively. When the pump induced loss exists, the intracavity loss L described as Eq. (2) is used for the L in Eq. (3). The conversion efficiency η is described as a ratio of $P_{2\omega}$ and P_ω

$$\eta = \frac{P_{2\omega}}{P_\omega}. \quad (4)$$

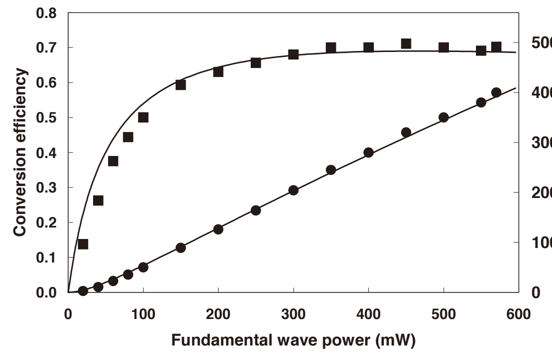

Fig. 5. A property of frequency doubler with the PPMgLN crystal. Circles and squares indicate the power of second harmonic wave at 430 nm and the conversion efficiency respectively. Solid lines are calculation results with Eq. (3)and (4)

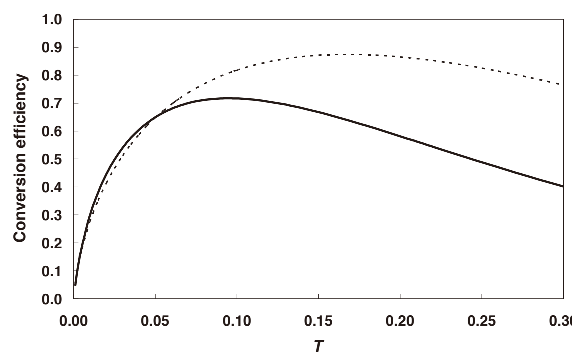

Fig. 6. Calculation results of conversion efficiency η as a function of T with Eqs. (3) and (4). Solid line is calculation result by using current experimental parameters. Dashed line is calculation result by using improved parameters.

The optimum T is given by following equation

$$T_{opt} = L/2 + \sqrt{L^2/4 + E_{NL}P_\omega} \quad (5)$$

which maximizes the $P_{2\omega}$ and η under the experimental parameters of E_{NL}, L, and P_ω. So it is important to improve the E_{NL} and L which are mostly material constants and sensitively depend on the fabrication process of periodically poling, and to optimize the T in order to achieve a high conversion efficiency.

Solid lines in Fig. 5 are calculation results by using Eq. (3) and (4) with experimental parameters E_{NL}=0.0113 (W^{-1}), L_0=0.0187, a=0.0246 (W^{-1}), and T=0.063. The analysis shows good agreements with experimental results. It is noticeable that the 70% of efficiency is the highest value at around 430 nm, although the both characteristic parameters E_{NL} and L_0 are degraded compared to the OPO experiments. Fig. 6 shows calculation results of η as a function of T under the condition of P_ω=570 mW which is the maximum fundamental wave power in previous experiments. By using current experimental parameters for frequency doubler

TABLE II
COMPARISON OF CHARACTERISTIC PARAMETERS IN CRYSTAL SAMPLES

Use application	Effective nonlinearity E_{NL} (W^{-1})	Intracavity loss L_0	Coefficient a (W^{-1})
Frequency doubler	0.011	0.0187	-
OPO [6]	0.043	0.0124	0.0246

summarized in Table. II, the T of 0.063 is almost the optimized transmittance as shown by solid line in Fig. 6. There is a possibility to improve the efficiency slightly more by using T of 0.1. If the PPMgLN crystal which is used for the OPO experiments and has high-performance characteristic parameters, a significant improvement of conversion efficiency will be expected. In Fig. 6 dashed line shows calculation results by using the OPO crystal parameters described in Table. II. The results are showing 87% of efficiency will be expected with the optimized of input coupler T at around 0.17 in future work.

V. CONCLUSION

In conclusion, the efficient generation of second harmonic waves of 400 mW at 430 nm with 70% of conversion efficiency was achieved by using a periodically poled MgO:LiNbO$_3$ crystal inside an external cavity. The calculation results based on the theory of SHG with an external resonator with characteristic parameters show good agreement with the experimental results. To achieve higher conversion efficiency, it is necessary to improve the nonlinearity and intracavity losses by improving a periodically poled structure, and to optimize the transmission of input coupler in future work.

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