CW Self-Frequency-Doubling Laser Operating on Nd : MgO : $LiNbO_3$ High-Gain Polarization

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The CW second-harmonic wave of high-gain polarization at λ=1.085 μm was demonstrated with Nd : MgO : $LiNbO_3$ self-frequency-doubling laser cavity inserted with a quarter wave-plate of the fundamental wavelength. The pump power threshold for the second-harmonic generation as low as 9.9 mW was achieved. The maximum second-harmonic output was 11.4 mW, the conversion efficiency for the total second-harmonic output was 11.3% per Watt.

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Self-frequency-doubling offers the potential for simple design, efficient doubling and good conversion efficiency. Several research groups reported self-frequency-doubling laser in a pulsed mode.[1-3] Cordova-Plaza *et al.* and Lallier *et al.* have demonstrated CW fundamental wave oscillation with Nd : MgO : $LiNbO_3$ but without self-frequency-doubling.[4,5] In Nd : MgO : $LiNbO_3$ crystal, to achieve 90° phase matching for secondary harmonic generation (SHG), the fundamental wave oscillation must be in the σ polarization ($E \perp c$), while the second-harmonic wave has π polarization ($E \parallel c$), therefore, a Brewster angle window had to be inserted in the cavity to force the fundamental wave to oscillate in σ polarization at λ=1.093 μm (low-gain polarization) and suppress π polarization at λ=1.085 μm (high-gain polarization). Fan *et al.* achieved the first CW operation of a self-frequency-doubling laser at λ=1.093 μm with Nd : MgO : $LiNbO_3$ pumped by a dye laser, the pump threshold for the self-frequency-doubling was about 48 mW and the maximum second-harmonic output was just 1.1 mW.[6] Due to the small effective stimulated-emission cross section of low-gain polarization, the pump power threshold for SHG was quite high. In addition to the high phase-matching temperature (about 152 °C), the threshold was further raised.[6] Because of the high threshold the self-frequency-doubling with Nd : MgO : $LiNbO_3$ pumped by a diode laser has not been demonstrated up to now.[4] Therefore, it is important to decrease the threshold pump power for the self-frequency-doubling of Nd : MgO : $LiNbO_3$ crystal.

We designed a new Nd : MgO : $LiNbO_3$ self-frequency-doubling laser in which a quarter wave-plate at λ=1.085 μm fundamental wavelength was inserted at 45° orientation relative to the axes of the crystal and used to force the π polarization laser at λ=1.085 μm to change to σ polarization to achieve the phase-matching of frequency-doubling process. For the first time to our knowledge, our experiment demonstrated the self-frequency-doubling of high-gain porlarization at λ=1.085μm of Nd : MgO : $LiNbO_3$ crystal.

The experimental arrangement is illustrated in Fig. 1. The pump laser was a CW Rhodamine 6 G dye laser tuned to the 598 nm absorption line of Nd : MgO : $LiNbO_3$. The optical isolator I was inserted between the pump laser and lens L to reduce measurement errors owing to feed back. The lens L with focal distance f=120 mm was used to focus the pump beam to the centre of Nd : MgO : $LiNbO_3$ crystal. The *y*-cut crystal with the dimensions 3×3×10 mm was placed on the centre of the nearly concentric cavity consisting of M_1 and M_2. The faces of crystal were coated to minimize the reflection of the fundamental wave. The parameters of the cavity are listed in the caption of Fig. 1.

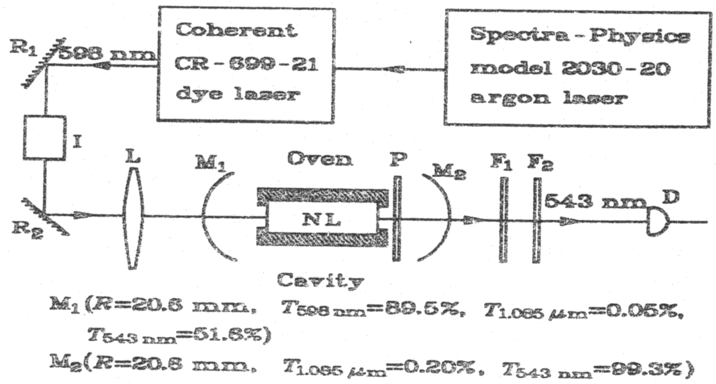

Fig. 1: Schematic of the Nd : MgO : $LiNbO_3$ self-frequency-doubling laser experimental arrangement and parameters of the laser cavity.

The quarter wave-plate P at λ=1.085 μm with anti-reflection films was placed between the crystal NL and M_2 and used to change the polarization direction of the fundamental wave from $E \parallel c$ to $E \perp c$ during a round trip, vice versa. We chose to use 90° phase-matching to avoid Poynting vector walk-off and obtain a higher conversion efficiency. The crystal was placed in an oven. The temperature of the oven was controlled and stabilized by a home-made electronic feedback system. The precision of temperature control was ±0.01°C. Phase-matching was achieved by temperature tuning the crystal birefringence. The second-harmonic outputs from M_2 were received and measured by detector D through the filters F_1 and F_2.

In this system a half of the intracavity intensities of the fundamental wave (only σ polarization of $E \perp c$) was available for the self-frequency-doubling owing to the requirement of the phase-matching. The total effective stimulated-emission cross section at λ=1.085 μm including both π and σ polarization were about 4 times of that at λ=1.093 μm as shown in Fig. 2 of Ref. 6. Therefore, the threshold pump power for SHG with high-gain polarization at λ=1.085 μm should be lower than that of low-gain polarization systems.

The harmonic output from M_2 versus the absorbed pump power and the pump power incident on cavity curve for high-gain polarization system is shown in Fig. 2(a). For comparing, we also measured the second-harmonic output of low-gain polarization at

λ=1.093 μm with the same crystal and laser system except replacing the quarter waveplate with a Brewster angle window and the result is shown in Fig. 2(b). The output wavelengths were actually measured with a monochromator of 0.1 nm-precision. The threshold pump powers of self-frequency-doubling for high-gain polarization at λ=1.085 μm and low-gain polarization at λ=1.093 μm are respectively 9.9 and 32.1 mW. The curve a and b cross at the pump power of about 80 mW. When the pump powers are lower than 80 mW, the second-harmonic outputs of high-gain polarization are higher than that of low-gain polarization. Above the crossing point, the coversion efficiency for low-gain polarization system is higher since all of the power is in the correct polarization for phase-matching and the intracavity circulating powers in low-gain and high-gain polarization systems are essentially identical in the case of far above threshold, because as soon as the photon density becomes appreciable, the gain of the system gradually reduces and eventually becomes independent of the emission cross section.[7] The maximum second-harmonic output powers from M_2 and the conversion efficiencies, defined as the ratio of total second-harmonic output to pump power absorbed above threshold,[6] are 11.4 mW, 11.3% per Watt and 12.2 mW, 23.5% per Watt respectively for high-gain and low-gain polarization systems. According to the calculation method of Ref. 6, the second-harmonic powers leaking out from M_1 (the transmissivities at λ=543 nm was 51.6%) were included and the curves of the second-harmonic output versus the absorbed pump power were extrapolated to 1 Watt when the conversion efficiencies were calculated.

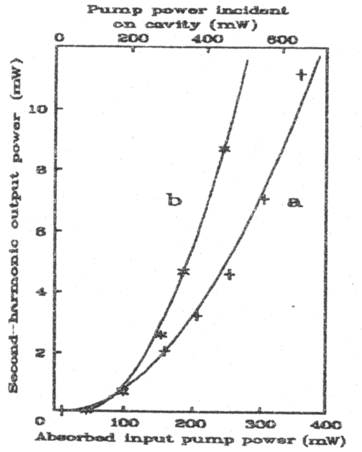

Fig. 2: Second-harmonic output power from M_2 vs the absorbed input pump power and the pump power incident on cavity curve. Curve a for 1.085–0.543 μm; Curve b for 1.093–0.547 μm.

Because the pump irradiance absorbed by the crystal inevitably results in the temperature rise, the control temperature on the crystal must correspondingly be decreased to maintain the optimum phase-matching. The control temperatures were linearly decreased as the pump powers were increased. The control temperatures for high-gain polarization at λ=1.085 μm were from 144.70 °C to 132.01 °C which were lower than that for low-gain polarization at λ=1.093 μm (159.62 °C to 149.06 °C).

In conclusion, we have given the first demonstration of self-frequency-doubling with high-gain polarization at $\lambda=1.085\,\mu m$ of Nd : MgO : $LiNbO_3$. Lower pump power threshold is the significant advantages of the system designed by us. The maximum output power of CW self-frequency-doubling laser was raised about 1 order of magnitute than the published result (1.1 mW) with the same kind of crystal.[6] It could be used in the system with low pump power, for example, the diode laser pump and as a new wavelength (543 nm) it would be interesting.

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