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Intracavity second-harmonic generation of 1.06 μm in $GdCa_4O(BO_3)_3$ crystals

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Abstract. The characteristics of intracavity second-harmonic generation (SHG) at 1.06 μm in $GdCa_4O(BO_3)_3$ (GdCOB) crystals cut for different type I phase-matching (PM) directions of $(\theta, \phi) = (66.8°, 132.3°)$; $(19.4°, 0°)$; $(90°, 46°)$ have been investigated. It was found that the intracavity SHG was significantly efficient in the PM direction of (66.8°, 132.3°), and that the intrinsic lower effective nonlinear coefficient (d_{eff}) was responsible for the less-efficient SHG in the other two directions. A maximum CW SHG output power of 2.81 W was obtained with an optical conversion efficiency of 18.7%, while the corresponding effective intracavity SHG efficiency was determined to be 41.3%. The intracavity SHG efficiency of GdCOB has been found to reach two-thirds of that obtained with type II phase-matching $KTiOPO_4$ (KTP).

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As nonlinear optical crystals, KTP ($KTiOPO_4$), LBO (LiB_3O_5), and BBO (β-BaB_2O_4) have found wide applications in intracavity second-harmonic generation (SHG) of solid-state lasers to produce visible and UV continuous-wave coherent sources. All of these crystals, however, suffer from a common drawback in their growing process that they are incongruent melting and can only be grown by using the flux-growth method, making it difficult to get large-size crystals with good optical quality. This situation has limited further development of these nonlinear optical crystals.

Recently, $GdCa_4O(BO_3)_3$ (GdCOB), a newly developed nonlinear crystal, has emerged as a promising candidate for frequency conversion [1, 2]. This crystal possesses many desirable features such as large nonlinear coefficient comparable to that of LBO, high damage threshold ($\sim 1\ GW/cm^2$) [1, 3], small walk-off angle, and relatively large angular acceptance [4]. Most importantly, the GdCOB crystal is congruent melting, allowing production of large-size single crystals with high optical quality through the conventional Czochralski technique. SHG efficiency of greater than 50% was achieved with a Q-switched Nd:YAG laser [1]. Our group has found that the type I phase-matching (PM) direction in which the effective nonlinear coefficient reaches its maximum does not lie on the principal plane of the crystal [4].

In this paper, we report the results of our investigation on intracavity SHG at 1.06 μm in GdCOB crystals cut for different type I PM directions, carried out by employing an end-pumped Nd:YVO_4 laser formed with a three-mirror folded resonator. The characteristics of intracavity SHG, the effective intracavity SHG efficiency, together with the results of a comparison made between the SHG efficiency of GdCOB and that of KTP, are presented in the paper.

1 Experimental setup

The arrangement of our intracavity SHG experiment is shown schematically in Fig. 1. M_1 was a concave mirror with radius of curvature of 150 mm, AR coated at 809 nm on the entrance face, HR coated at 1.06 μm, and HT coated at 809 nm on the other face. The folding mirror M_3 was also a concave mirror with radius of curvature of 100 mm, HR coated at 1.06 μm and HT coated at 532 nm on the curved face, and AR coated at 532 nm on the other face, and served as the output coupler for the SHG green light. M_2 was a flat mirror, HR coated at both 1.06 μm and 532 nm. The pump source employed in the experiment was a fiber-coupled

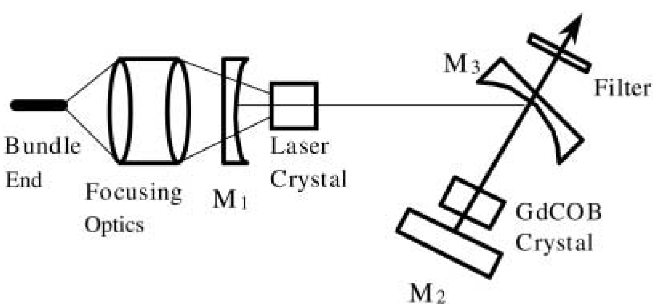

Fig. 1. Schematic diagram of the experimental setup

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diode-laser array (OPC-D030-FCHS, Opto-Power Corp.) capable of emitting a maximum radiation of 30 W with center wavelength around 807 nm at 25 °C. Its output was focused into the laser crystal with a spot of 0.26-mm radius and N.A. of 0.33 by using a focusing optics (ORU-03, Opto-Power Corp.). The laser crystal, 0.6 at. %, a-cut $4 \times 4 \times 7\,\mathrm{mm}^3$ Nd:YVO_4, AR coated at 809 nm and at 1.06 μm on the pumped face, and AR coated at 1.06 μm on the opposite face, was wrapped with indium foil and held in a copper block which was cooled by using thermoelectric coolers, in order to remove efficiently from the crystal the heat generated under high pump-power levels. The GdCOB crystal used in the experiment was grown by our group using the Czochralski technique. It was cut for type I phase matching at 1.06 μm with different PM directions of $(\theta, \varphi) = (66.8°, 132.3°)$, (19.4°, 0°), and (90°, 46°), respectively. The phase-matching angles, θ and φ, were computed by using the Sellmeier equation given by Aka et al. [1]. For comparison, a KTP crystal, cut for type II phase matching at 1.06 μm, was also utilized in the experiment. All the crystals were of dimensions $3 \times 3 \times 12\,\mathrm{mm}^3$, and were AR coated for both 1.06 μm and 532 nm on their end faces. They were actively cooled in a manner similar to the case of the Nd:YVO_4 crystal during the experiment. To take advantage of the intense fundamental wave power density, the nonlinear optical crystal was placed near the end mirror M_2 where a beam waist existed.

2 Results and discussion

For efficient intracavity SHG interaction, it is necessary to provide a tightly focused beam in the nonlinear optical (NLO) crystal. Therefore, the resonator employed in a frequency-doubled laser should be carefully optimized. The resonator configuration shown in Fig. 1 has been utilized successfully to get efficient intracavity SHG operation [5, 6]. It was found through numerical computation that the mode radius in both the laser crystal and the doubling crystal depends strongly on the length of the M_2M_3 arm. So the end mirror M_2 was mounted on a translation stage, allowing easy optimization of the intracavity SHG operation. In our experiment, the length of the M_2M_3 arm was experimentally determined to be 81 mm, while the total cavity length was about 315 mm, yielding a mode radius within the GdCOB crystal ranging from 0.07 to 0.05 mm, depending on the thermal lensing generated in the laser crystal that varies with the absorbed pump power.

GdCOB belongs to the low-symmetry point group m. Its nonlinear coefficient matrix has six independent nonvanishing components that have not been completely determined experimentally so far. As a result, the optimal phase-matching direction in which the effective nonlinear coefficient is maximized still remains uncertain. During the experiment, we carefully investigated, under exactly identical conditions, the intracavity SHG of three GdCOB crystals with different phase-matching directions of $(\theta, \varphi) = (66.8°, 132.3°)$, (19.4°, 0°), and (90°, 46°), respectively. The results, represented in the form of SHG output power versus incident pump power, are shown in Fig. 2. It is clear from this figure that the intracavity SHG efficiency obtained with the phase-matching direction of (66.8°, 132.3°) is considerably higher

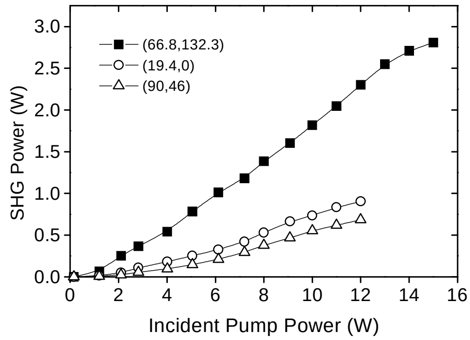

Fig. 2. Intracavity SHG power as a function of incident pump power for three GdCOB crystals with different phase-matching directions

than those corresponding to directions of (19.4°, 0°) and (90°, 46°), in agreement with our previous investigation on extracavity SHG of Nd-doped GdCOB [4]. Additionally, for the phase-matching direction of (66.8°, 132.3°), the SHG efficiency increases more rapidly with the incident pump power than in the cases of the other two directions. At the incident pump power of 13 W, a CW SHG output power of 2.55 W was obtained, leading to an optical conversion efficiency of 19.6%. Above this pump level, the conversion efficiency started to reduce. Before the saturation behavior set in, however, a maximum SHG output of 2.81 W was achieved with 15 W of pump power incident upon the Nd:YVO_4 crystal, giving a slightly lower conversion efficiency of 18.7%. The arising of the saturation behavior, as in the situation of other intracavity frequency-doubled lasers, is attributed to the strengthening of the thermal lensing in the laser crystal [5, 6].

Effective intracavity SHG efficiency, defined as the ratio of the SHG power to the fundamental wave power extracted from the identical resonator configuration at the same pump power when operated in the fashion of fundamental wave oscillation, can give some useful information on frequency-conversion ability of a nonlinear optical crystal [7]. During our experiment, to account for the internal losses added by the NLO crystal, we changed the polarization direction of the fundamental wave with respect to the NLO crystal, keeping the type I phase-matching interaction from taking place, and carefully investigated the output characteristics of the fundamental wave operation with the end mirror M_2 replaced by different couplers of 5%, 10%, 15%, 25%, and 30%, respectively. Figure 3 shows the results obtained with the GdCOB crystal of (66.8°, 132.3°) remaining in the cavity. Since the output characteristics with three couplers of 10%, 15%, and 25% were too close to distinguish from one another, only the results corresponding to the 5%, 15%, and 30% couplers are presented in Fig. 3. Below the incident pump power of 4 W, the highest optical conversion efficiency was achieved with the coupler of 5%. When the incident pump power was over 5 W, however, the 15% coupler became the optimal one. At the incident pump power of 15 W, 6.8 W of fundamental wave power was obtained, resulting in an optical conversion efficiency of 45.3%. Combining this result with that obtained in the situation of intracavity SHG operation shown in Fig. 2, we determined the effective intracavity SHG efficiency at this pump level to be 41.3%.

It was found during the experiment that the output characteristics of the laser were nearly identical when operated

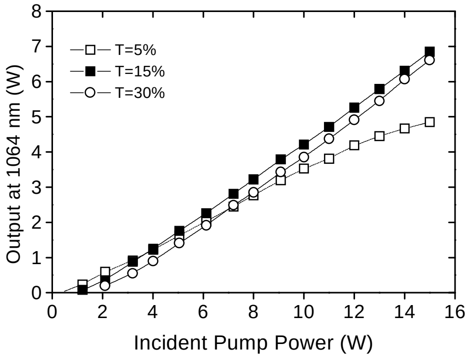

Fig. 3. Output power at 1.06 μm versus incident pump power for different couplers and with the GdCOB crystal remaining the cavity

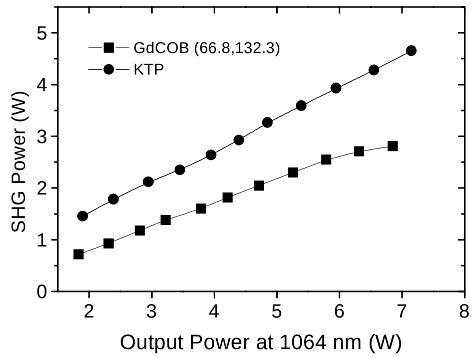

Fig. 5. Intracavity SHG power as a function of fundamental wave output power for GdCOB and KTP crystals

in the manner of fundamental wave oscillation, no matter which GdCOB crystal was placed in the resonator. Figure 4 shows the results of the fundamental output power at different incident pump powers for several cases of various GdCOB crystals and a KTP crystal, along with a special case in which the NLO crystal was removed from the cavity. The output coupling for all the cases was 10%. In the situation where the NLO crystal was removed from the resonator, the physical length of the M_2M_3 arm was adjusted to keep the resonator as identical as possible to the other cases. In Fig. 4, the numbers marked on the horizontal axis are used to indicate the different cases mentioned above. '1' corresponds to the GdCOB crystal of (66.8°, 132.3°) remaining in the resonator; '2' to GdCOB of (19.4°, 0°); '3' to GdCOB of (90°, 46°); '4' to KTP; and '0' represents the situation where no NLO crystal existed in the cavity. It is clear from the figure that the attainable fundamental power, with different GdCOB crystals remaining in the cavity, was almost identical. This result enables us to deduce that the circulating fundamental power within the resonator, when the laser was operated under SHG conditions with different GdCOB crystals used as doubler, was of almost the same magnitude. So the distinction between the SHG efficiencies, as shown in Fig. 2, originates entirely from the difference between the effective nonlinear optical coefficients (d_{eff}) of the three phase-matching directions used.

From Fig. 4, one can notice that the fundamental output power, extracted when the NLO crystal was removed from the resonator, was merely slightly higher than those achieved in other cases with the NLO crystal remaining in its place. This suggests that the internal losses introduced by these NLO crystals were not significant. It is also noticed from Fig. 4 that the fundamental output power, attainable from the laser when KTP was placed in the cavity, exhibits a negligible difference from those obtained with GdCOB placed in the cavity. Consequently, the distinction existing in their intracavity SHG efficiencies reveals the difference of their effective nonlinearity in certain phase-matching directions. Figure 5 gives the results of intracavity SHG power as a function of attainable fundamental power for KTP and GdCOB of (66.8°, 132.3°). It can be seen that the effective intracavity SHG efficiency of GdCOB reaches its maximum at the fundamental power of 5.7 W, and was determined to be 44.7%. At the same fundamental power level, the SHG output power achieved with KTP was 3.8 W, resulting in an effective intracavity efficiency of 66.7%. The results presented here indicate that the SHG conversion efficiency of GdCOB has reached two-thirds of that of KTP. With the improvement in optical quality of GdCOB, one can expect that the SHG conversion efficiency will be further increased.

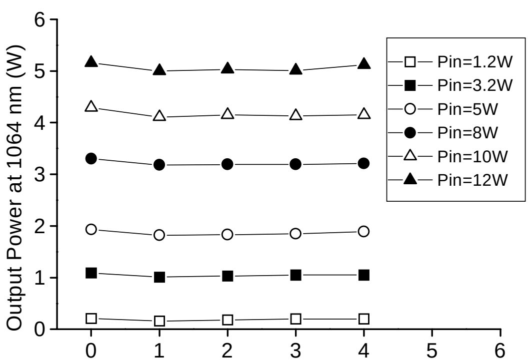

Fig. 4. Fundamental wave output power at several incident pump levels with and without the NLO crystal in the cavity. The meanings of the numbers on the horizontal axis are as following: 1 corresponds to GdCOB of (66.8°, 132.3°); 2 to (19.4°, 0°); 3 to (90°, 46°); 4 to KTP; and 0 represents the situation where no NLO crystal existed in the cavity

3 Conclusions

In summary, we have investigated, by employing an end-pumped $Nd:YVO_4$ laser formed with a three-mirror folded resonator, the characteristics of intracavity SHG in GdCOB crystals cut for different type I phase-matching directions of $(\theta, \varphi) = (66.8°, 132.3°)$; (19.4°, 0°); and (90°, 46°). It was found that the highest intracavity SHG conversion efficiency was attained in the phase-matching direction of (66.8°, 132.3°), and that the less-efficient SHG in the other two directions is fully attributed to their intrinsic lower effective nonlinear coefficient (d_{eff}). A maximum CW SHG power of 2.81 W was achieved with an incident pump power of 15 W, giving an optical conversion efficiency of 18.7%, while the effective intracavity SHG efficiency was determined to be 41.3%. It is shown through comparative investigation that the SHG conversion efficiency attained with GdCOB can reach two-thirds of that of KTP.

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