Single-Frequency Laser Using a 100-μm Thick Nd:YVO₄ Crystal in a 50-mm Long Cavity

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A new type of single-frequency solid state laser for achieving a highly stable second-harmonic generation in a simple configuration was developed using a quite thin laser medium. A 100-μm thick Nd:YVO₄ crystal with one side coated for high reflection in a 50-mm long cavity which serves as automatic gain discriminator was end-pumped by a laser diode. Single-frequency output powers of 100 mW and 17 mW were obtained for fundamental and second-harmonic waves respectively by 1-W excitation. No chaotic fluctuation was observed with the frequency-doubled output.

Key words: single-frequency, solid state laser, frequency-doubling, diode-pumping, Nd:YVO₄

Single-frequency operation in a diode-pumped solid-state laser is one of the key technologies to get stable frequency-doubled output. One may use etalons, twisted-mode cavities, birefringent filters, and unidirectional-ring cavities to achieve single-frequency operation. However, these techniques are relatively complicated from a practical point of view. If a laser medium itself could serve as gain discriminator, it would provide the means to make up a very simple system.

A clearly simple way, which uses a comparatively short piece of laser material placed close to one of the cavity mirrors, to accomplish single-frequency operation has been suggested by Siegman. However, this idea has not been fully demonstrated maybe because of poor absorption efficiency expected from a short gain medium. This disadvantage has been significantly reduced by emersion of diode pumping technique and of high absorption mediums such as Nd:YVO₄ crystal. Absorption coefficient of this medium is roughly 30 cm⁻¹ for 1% concentration which is nearly 4 times larger than Nd:YAG. Several authors have reported microchip lasers using Nd:YVO₄, 0.2 mm to 2 mm thick Nd:YVO₄ were pumped through their end surfaces coated as a dichroic mirror. However, in these cases, as excitation becomes intense, effective gain length becomes longer. If it occurs, the possibility for the second mode to get energy from the places that are spatially out of phase from the first mode increases at inner part of the laser material. This leads to multi-mode operation which in turn causes amplitude fluctuation during intracavity doubling. To avoid this, one must use an extremely thin laser material so that the second mode does not get gain.

In this letter, we report what is to our knowledge the first demonstration of a single-frequency solid state laser using a quite thin laser material. A π/2 of spatial phase deviation between the first and the second mode throughout the laser material was employed as the measure for deducing the thickness. In other words, the criterion can be written as Δk<π/2, which is reduced to l<c/4πΔν, where k is a wave vector, l the thickness of the laser material, c the speed of light in vacuum, n the refractive index of the material, and Δν the frequency difference between the first and the second mode. For Nd:YVO₄, l<280 μm is required assuming the half gain bandwidth of 125 GHz and n to be 2.16. Thus the thickness of 100 μm was applied, which can be regarded as sufficiently thin for the preliminary experiment.

Figure 1 shows the schematic configuration of the laser system. An a-cut Nd:YVO₄ crystal measures 2×2×0.1 mm³, 1%, 2% and 3% Nd concentration crystals were prepared. Each 100-μm thick Nd:YVO₄ crystal was mounted on an aluminum-alloy heat sink having a 1.2-mm diameter hole for the light path. Silver paste was used for bonding in order to reduce thermal distortion of the crystals by pumping. The 50-mm long standing-wave resonator, which allows extra space for a frequency-doubling crystal, extends from the high-reflectivity coating on one end of the Nd:YVO₄ crystal to the 2.5% transmitting output coupler. The radius of curvature of the output coupler was 100 mm. The long cavity length of 50 mm was chosen to prove the power of automatic gain discrimination by the thin laser material. Since the long cavity holds many longitudinal-modes within the gain bandwidth of Nd:YVO₄, i.e. 80 modes in 50-mm long cavity, if the gain discrimination is not sufficient, the laser would operate at multi-longitudinal-modes under the relatively weak excitation. An AlGaAs laser diode (Sony SLD323XT) with 100×1 μm² emitting aperture was used as a pump source. The center wavelength of the laser diode was temperature-tuned to 809 nm to maximize the absorption. Pump light from the laser diode was collimated and focused by the identical 4.5-mm focal-length objective lenses placed at a confocal condition. The spot size of the focused pump beam was measured to be about 100×5 μm². Polarization of the laser diode was adjusted to the c-axis of the Nd:YVO₄ crystal. All components are mounted on their holders which are connected to the invar rods to prevent any displacement by thermal expansion.

The output of fundamental wave at 1064 nm was observed by a scanning Fabry-Perot spectrum analyzer with a free spectral range of 6 GHz (Newport SuperCavity
Fig. 1. Schematic representation of the laser system. The KTP crystal was located between the 100-μm thick Nd:YVO₄ crystal and the output mirror when frequency doubling was carried out.

Fig. 2. Typical spectrum of fundamental wave at 1064 nm from the laser using 1% Nd-doped 100-μm thick YVO₄ crystal when the laser was operated at 100 mW. The output was observed by a scanning Fabry-Perot spectrum analyzer with a free spectrum range of 6 GHz.

SR-150). Figure 2 shows a typical spectrum from the laser using 100-μm thick Nd:YVO₄ crystal when the laser was operated at 100 mW. The result of 1% Nd doped sample is shown here because 1% crystal has the smallest absorption coefficient. Thus 1% crystal can be expected to have the weakest power of suppressing multi-mode operation at the same thickness. The laser operated at single frequency up to 1-W excitation while the threshold was about 150 mW. This means that the upper limit of excitation to maintain single-frequency operation is at least greater than 6 times above the threshold. On the other hand, in a separate experiment with a similar configuration, using 1-mm thick 1% Nd:YVO₄ and the same 1-W multi-mode laser diode, we observed multi-longitudinal-mode operation at only 1.3 times above the threshold of the first mode. So the upper limit of excitation to maintain single-frequency operation is improved at least by a factor of 4.6. It is a substantial improvement on the single-frequency performance. The laser using 2% and 3% sample also operated at single frequency up to 1-W excitation.

Figure 3 shows the output characteristics of the fundamental wave. 2% crystal was most efficient. For 1% crystal, the absorption efficiency of pumping light was only 20%, and this may be the cause of low efficiency. For 3% crystal, the concentration quenching or poor quality of the crystal may be the cause of the low efficiency. It should be noted that the maximum output powers of the Nd:YVO₄ crystal lasers were limited by the laser diode used as the pump source.

A type-II angularly-phase-matched KTP (KTiOPO₄) crystal for intracavity frequency doubling was located between the 100-μm thick Nd:YVO₄ crystal and the dichroic output mirror (99.9% reflection at 1064 nm and 95% transmission at 532 nm) whose radius of curvature was also 100 mm. The size of the KTP crystal is 3×3×5 mm³.