VIII-B Development and Research of Advanced Tunable Solid State Lasers

Diode-pumped solid-state lasers can provide excellent spatial mode quality and narrow linewidths. The high spectral power brightness of these lasers has allowed high efficiency frequency extension by nonlinear frequency conversion. Moreover, the availability of new and improved nonlinear optical crystals makes these techniques more practical. Additionally, quasi phase matching (QPM) is a new technique instead of conventional birefringent phase matching for compensating phase velocity dispersion in frequency conversion. These kinds of advanced tunable solid-state light sources, so to speak "Chroma Chip Lasers," will assist the research of molecular science.

In this projects we are developing Chroma Chip Lasers based on diode-pumped-microchip-solid-sate lasers and advanced nonlinear frequency conversion technique.

VIII-B-1 Performance of Widely Tunable Yb:YAG Microchip Lasers

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[*OSA TOPS on ASSL 2000* **34**, 106 (2000)]

The properties of the trivalent ytterbium ion doped YAG, such as a smaller quantum defect, longer upper state lifetime, simple energy structure (no excited state absorption) and so on, would promise to achieve a high power and high stability laser operation in microchip configurations. In addition, the wide emission bandwidth of the material around 1 µm allows tunable and/or mode-locked operation. In this work, we have developed a tunable intracavity frequency-doubled Yb:YAG microchip laser that outputs a maximum green power of 520mW with single frequency around the Ar^{3+} laser wavelength of 515 nm by using a 400-µm thick Yb:YAG. By using LBO crystal a wide tuning range from 515.3 to 537.7 nm ($\Delta\lambda$ = 22.4 nm, $\Delta\nu$ = 24.4 THz) was obtained (Figure 1). Then, we applied this tunable green laser to a wavelength-multiplexing holographic memory. We recorded 3 discrete images at 3 different wavelengths in the same position of a 600 ppm Fe-doped $LiNbO_3$ crystal and each image was reconstructed at each wavelength. The laser was proven to have a narrow linewidth and a wide tunability, in order to satisfy wavelength-multiplexing in the holographic storage system as shown in Figure 2. Next, in order to evaluate the potential of Yb:YAG tunability, the wide-bandwidth reflectivity dielectric mirror was deposited directly onto the Yb:YAG microchip. The output coupling mirror had a radius of curvature of 30 mm, and the cavity length was 25 mm. Experimental result of the tunability of the Yb:YAG microchip laser for different output couplers. With a reflectivity of 99.9% around 1010~1100 nm, the widest tunability of 84.5 nm, from 1024.1 to 1108.6 nm was obtained. The output beam was coupled as partially reflected beam at the birefringent filter. The oscillation range that extends beyond the Yb:YAG gain bandwidth, 9.5 nm, was realized since it has a simple energy- level manifolds. If it possible to keep wide band ($\Delta\nu$ ~ 22.4 THz) laser oscillation under mode-locking operation, transform-limited pulsewidth of approximately 50 fs should be feasible. The tuning bandwidth increased by using the high-reflectivity output coupler and peak wavelength shifted to longer wavelength. The shorter band-edge was limited by increase of reabsorption loss in the Yb:YAG, and longer band-edge by coating bandwidth in our experiment. The bandwidth of 22.4 THz indicates the potential of mode-locked operation of the Yb:YAG laser.

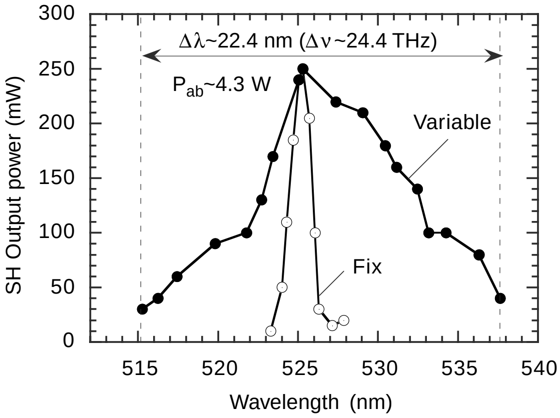

Figure 1. Tuning curve of the intracavity frequency-doubled Yb:YAG microchip laser.

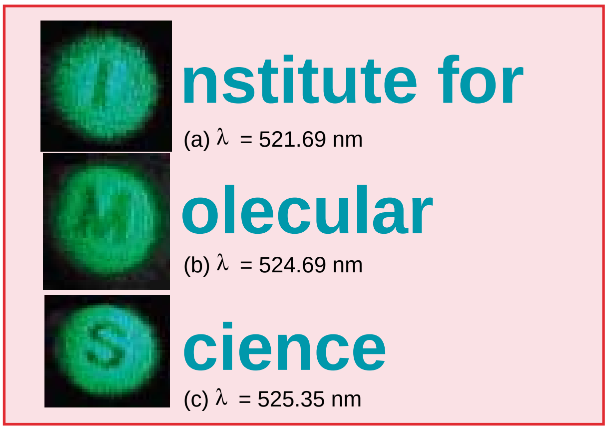

Figure 2. Reconstructed images from wavelength-multiplexed holograms by the tunable intracavity frequency-doubled Yb:YAG laser.

VIII-B-2 High Average Power Diode-Pumped Composite Nd:YAG Laser with Cr^{4+}:YAG Saturable Absorber for Passive Q-Switching

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Passive Q-switching technique is attractive for scientific and industrial applications that do not require accurate repetition rates. This technique can significantly simplify the operation, improve the efficiency, the reliability and the compactness, and reduce the laser costs. In a composite rod both the peak temperature rise and the thermal stress induced by optical pumping are reduced compared to a nonbonded crystal. In this work we show that these improvements, which reduce the thermal lensing effect, made a composite medium a good solution for improving output performances of high average power passively Q-switched lasers.

In experiments we used a composite Nd:YAG rod fabricated by diffusion bonding of a Nd:YAG (5-mm length, 1.1-at.% Nd doping) to an undoped YAG piece (1-mm length). The medium was end-pumped by a 1.55-mm diameter, 0.11-NA OPC fiber-bundles diode. With a plane-plane resonator of 80-mm length and an output mirror of 95% reflectivity at 1064nm, this configuration delivers a cw maximum output power of 7.7 W with an optical efficiency of 36.9%. The slope efficiency is 39.4%, and the laser beam M^2 factor varies among 1.1 and 2.3 on the pump power range. With a Nd:YAG medium (10-mm length, 1.3-at.% Nd doping), the maximum cw power was 8.2-W at 21.8-W absorbed power, the slope efficiency was 41.6%, and the laser beam M^2 factor varies between 1.2 and 3.3 on the pump power range. Cr^{4+}:YAG crystals with varying low-signal transmission T_0 have been used, as well as resonators of various length and output couplings. As an example, Figure 1 shows the average output power for the composite medium and Cr:YAG absorbers of T_0 = 89%, 85%, and 80%. A plane-plane resonator of 80-mm length with an R = 90% output coupler was considered. A maximum average power of 4.21-W in a laser beam of M^2 = 1.3 resulted for the Cr:YAG absorber of T_0 = 89%. The laser generated pulses of 48-ns duration at 24-kHz (~3.65 kW peak power). With the Nd:YAG medium a maximum average power of 3.9-W in a beam of M^2 = 1.9 resulted. When the resonator length was of 40-mm and a Cr:YAG crystal of T_0 = 80% was used, the composite Nd:YAG laser outputs a maximum average power of 2.6-W in a beam of M^2 = 1.45. The pulse width was 17.5-ns, the pulse energy is 0.285-mJ, and the peak power is 16.3-kW. Using the Nd:YAG medium, the maximum average power and beam M^2 factor decreases to 1.8-W and 1.9, respectively. Shorter resonators in spite of reducing the average output power will increases the Q-switched pulse peak power. This way a simple and compact-pumping source for parametric conversion into mid-IR region could be obtained.

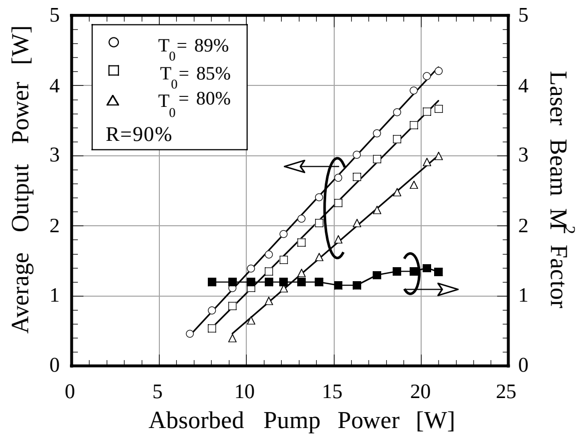

Figure 1. Average output power and beam M^2 factor as a function of absorbed pump power for the composite Nd:YAG, Cr:YAG absorbers.

VIII-B-3 Optical Properties and Laser Characteristics of Highly Nd^{3+}-Doped $Y_3Al_5O_{12}$ Ceramics

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Diode-pumped microchip solid-state lasers have such advantages as compactness, high efficiency, high power, and low numbers of longitudinal and transverse modes. A wide variety of materials have been investigated to develop more efficient and higher power microchip lasers. Although $Nd:YVO_4$ is a suitable material for highly efficient microchip laser owing to its large absorption cross section, high power operation is difficult because its thermo-mechanical properties are poor. On the other hand, while Nd:YAG has good thermal properties, highly efficient microchip laser has never been reported since high doping (> 1 at. %) of neodymium into the YAG crystal is impossible, limiting pump absorption. Recently developed transparent Nd:YAG ceramics are attractive materials because high doping of neodymium is possible without degrading the thermal conductivity. In this work we report measurements of the absorption spectra and the fluorescence lifetime of ceramic Nd:YAG in order to show that it is a promising material as a highly efficient and high power microchip laser. Moreover, we characterized its laser performance. Figure 1 shows the absorption spectra of 2.2 and 4.8 at. % Nd:YAG ceramics and 1.1 at. % single crystal. The 4.8 at. % Nd:YAG ceramic has an absorption coefficient (30.4 cm^{-1}) as large as that of $Nd:YVO_4$.

The input-output power characteristics of 2.4 and 4.8 at. % ceramics and a 0.9 at. % single crystal with microchip structures (the thickness of laser medium < 1mm) are shown in Figure 2. For the 4.8 at. % ceramic, 2.3 times higher output was achieved than that for the single crystal, which indicates the advantage of Nd:YAG ceramics as highly efficient miniature or microchip lasers. We estimated the round-trip cavity losses by obtaining the slope efficiencies with different output-couplers. From this, we found that the loss of the 2.4 at. % ceramic is as low as that of the single crystal. It is concluded that highly Nd^{3+}-doped YAG ceramics are promising as a highly efficient, high-power microchip laser material.

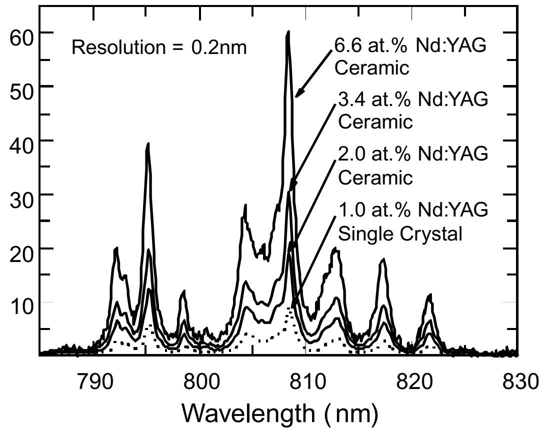

Figure 1. Absorption spectra of Nd:YAG ceramics (solid curves) and Nd:YAG single crystal (dashed curve).

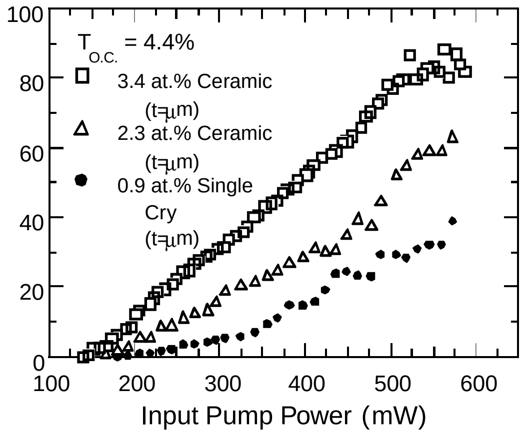

Figure 2. Dependence of the output power on the input pump power for the Nd:YAG ceramics and the single crystal.

VIII-B-4 Development of Multifunction Nonlinear Optical Wavelength Converter

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Wavelength conversion based on nonlinear optics yields high efficiency without any sacrifice in coherency. Recently developed *Quasi-Phase Matching (QPM)* technique has produced designability of phase matching wavelength and efficiency, together with artificial characteristics of converters in space, frequency, and time domains by using digital patterns defined by photolithography. QPM giving new degree of freedom thus brought about stronger impact than growth of new crystals in the nonlinear optics. We here proposed efficient wide-band infrared generation with cascaded QPM crystals for optical parametric oscillation (OPO) and difference frequency generation (DFG) around 6 µm region, where double bond structures of molecules have characteristic absorption lines. Figure 1 illustrates the geometry, measured emission wavelengths in OPO and required QPM period in DFG in efficient nonlinear crystal, lithium niobate (LN). Since LN has moderate absorption at 6 µm, direct access to 6 µm induces thermal fluctuation enhanced in OPO cavity. Our approach is to use OPO in the transparent region of LN and access to 6 µm by single-pass DFG, which is less sensitive to thermal disturbance. We devised first OPO stage and obtained IR emission plotted in Figure 1(b) with closed circles. The 0.5mm-thick QPM device with a period of 30.9 µm was fabricated by electric field poling in liquid electrodes as shown in Figure 1(d).

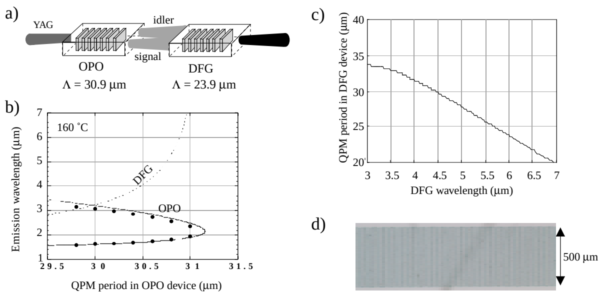

Figure 1. QPM OPO-DFG light source for widely tunable IR light: a) geometry, b) wavelength tunability depending on QPM period, c) calculated DFG period, d) periodical domains in a QPM LN device.

VIII-B-5 Periodical Twinning in Crystal Quartz for Ultraviolet Nonlinear Optics

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[*Oyobuturi* **69**, 548 (2000)]

Crystal quartz is attractive for operation in ultraviolet nonlinear optics, which has low absorption from 150 nm, high chemical stability, and low thermooptic coefficients compared with conventional ultraviolet nonlinear crystals. Growth techniques are well established because of widespread in surface-acoustic-wave and timing applications, but unfortunately, it doesn't meet the birefringent phase matching condition due to small birefringence, and electric field poling condition due to lack of ferroelectricity. We devised a new poling technique in crystal quartz using mechanical twinning and demonstrated periodical polarity reversal by using thermal stress. Figure 1 shows an observed twin structure with a period of 80 µm, obtained by thermally induced stress between patterned Cr films and a quartz. The Cr patterned substrate was heated to just below Curie temperature in order to attain reasonable film stress and reduce coercive stress. Twins tend to generate from the edge of Cr pattern and the required duty ratio of Cr to the period was more than 0.5. The depth of twins, however, were several microns, indicating not suitable for bulk nonlinear optics. New technique is under development to improve the depth profile of the twins for a practical UV generator.

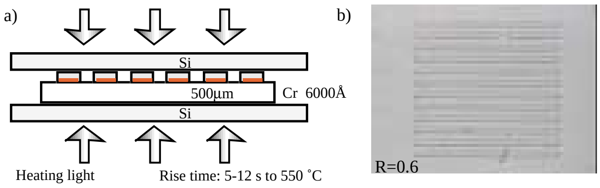

Figure 1. Twin patterning in crystal quartz: a) patterning method by the thermally induced in-plane stress, b) observed periodical twins with a period of 80 µm period, *R*: duty ratio of the Cr film to the period.