Solid-State Raman Laser for MMT Sodium Guide Star

W. T. Roberts, Jr. , James T. Murray, W. L. Austin
Lite Cycles, Inc.,Tucson, AZ

Richard C. Powell
Optical Sciences Center, University of Arizona, Tucson, AZ

J. Roger P. Angel
Steward Observatory, University of Arizona, Tucson, AZ

ABSTRACT

Generation of Sodium Guide Stars for adaptive optics requires very precise control of the frequency and bandwidth of the laser to maximize the brightness of the generated guide star. The ruggedness, efficiency and ease of use of a solid state system has great potential for improving the reliability and power of the laser guide star over the dye laser system currently used. The dearth of solid state transistions at the precise wavelength required for exciting resonance scattering in sodium drives us toward Raman shifting to downshift a nearby solid-state transition line tuned to work with the Raman-shifting material. The system being developed for the 6.5 meter Multiple Mirror Telescope (MMT) takes two approaches to creating the sodium guide star: one uses YGAG (Yttrium Gallium Aluminum Garnet) to maximize the Raman-shifted output at the sodium D_2 resonance. The second approach is to thermally tune the output of YAG to reach the appropriate wavelength for Raman shifting to 589 nm. Initial results from YGAG indicate that it will not be a suitable material for creating the sodium guide star laser. Initial results from the YGAG laser is presented, along with a discussion of the potential of the technology.

1 Introduction

The size and altitude of sodium guide stars make them significantly more attractive to Adaptive Optics (AO) system developers than Rayleigh guide stars. However, the lack of good, robust lasers for production of sodium stars has hindered the progress of artificial guide star AO for a number of years. Dye lasers are capable of producing sodium stars.[1] However, the inefficiency and size of the pump lasers, system complexity and limited useful power detract from the utility of these systems. Solid state lasers based on sum-frequency-mixing of two independent Nd:YAG lasers (one operating on the 1.064 μm transition and the other on the 1.318 μm transition) have achieved some success.[2] However, the complexity and relatively high cost have limited the acceptance of these systems as an standard in Adaptive Optical systems.

Aside from these and other guidestar laser concepts, the Solid State Raman Laser is a viable alter-

Part of the SPIE Conference on Adaptive Optical System Technologies • Kona, Hawaii • March 1998
SPIE Vol. 3353 • 0277-786X/98/$10.00

native. It has the advantages of laser-diode-pumped solid state reliability and efficiency. In addition, the natural effect of Raman beam-cleanup[3] results in a beam quality which significantly improves the ability to focus the light to a small, efficient spot on the mesosphere.

Previous attempts to produce light at 589 nm by Raman shifting the output of a doubled Nd:YAG laser have resulted in limited success.[4] Unfortunately, the amount of shift in $CaWO_4$ is slightly more than optimum for hitting the center of the sodium D_2 line. The wide gain bandwidth of the Nd:YAG pump laser allows operation at the D_2 line, but it is significantly below the optimum for producing bright laser output.

In this paper we detail our current efforts in the development of a solid-state Raman laser that centers the Raman gain for optimum efficiency. The laser being developed will be used as a artificial guidestar source for the upgraded MMT telescope.

2 Laser Requirements

The brightness of the sodium guide star is strongly dependent on the characteristics of the laser source. Therefore, it is essential to optimize the operational parameters of the laser source for maximum backscatter return from mesospheric sodium atoms. Sources which are not optimized lead to concerns with safety and background light pollution.

The brightness of the beacon return is related the average power of the laser source, so it is tempting to select stategies that maximize the laser output power. However, these stategies often fail beacuse the effects of saturation are either over-looked, or worst yet, ignored. When the intensity of the laser spot in the mesosphere, which is directly related to the peak power of the laser, is below the saturation intensity of mesospheric sodium ($\tilde{}$ 64 W/m^2), the beacon return is proportional to the average power of the laser. However, when the intensity of the laser spot is increased beyond saturation, the beacon return begins to level-off with respect to the applied average power. So the payout required for a given return is much much more costly for inherently high-peak-power sources since they attain saturation at a much lower average power than do low-peak-power sources. It is therefore essential to choose a strategy the minimizes the peak-to-average power ratio to avoid saturation and optimize beacon return.

Another primary concern is the relative spectral overlap between the laser source and sodium absorption profile. The sodium D_2 absorption spectrum is composed of two inhomogeneously broadened lines, each ~1 GHz wide, with centers separated by ~1.7 GHz. The full width at half-maximum (FWHM) of the entire complex is ~3 GHz wide. Ideally the output spectrum of the laser would directly match the inhomogeneuosly-broadened D_2 profile. However, for low-peak-power sources which operate below the saturation intensity, it is often more benifical to operate the laser with a narrower spectrum which is center about the primary absorption peak.

3 MMT Laser Design

The layout of the MMT guide star laser is shown in Figure 1. It consists of three distinct sections containing a Nd:YAG laser, frequency-doubling section, and a synchronously-pumped solid-state Raman laser. The Nd:YAG laser consists of a zig-zag slab of Nd:YAG, pumped with 120 W of cw laser diode power at 808 nm. The laser cavity is configured in a standing-wave linear resonator, which is 1.5 m long and mode-locked at 100 MHz. The mode-locked pulses from this laser enter the frequency-doubling section which contains two LBO crystals with a phase-compensation stage. The

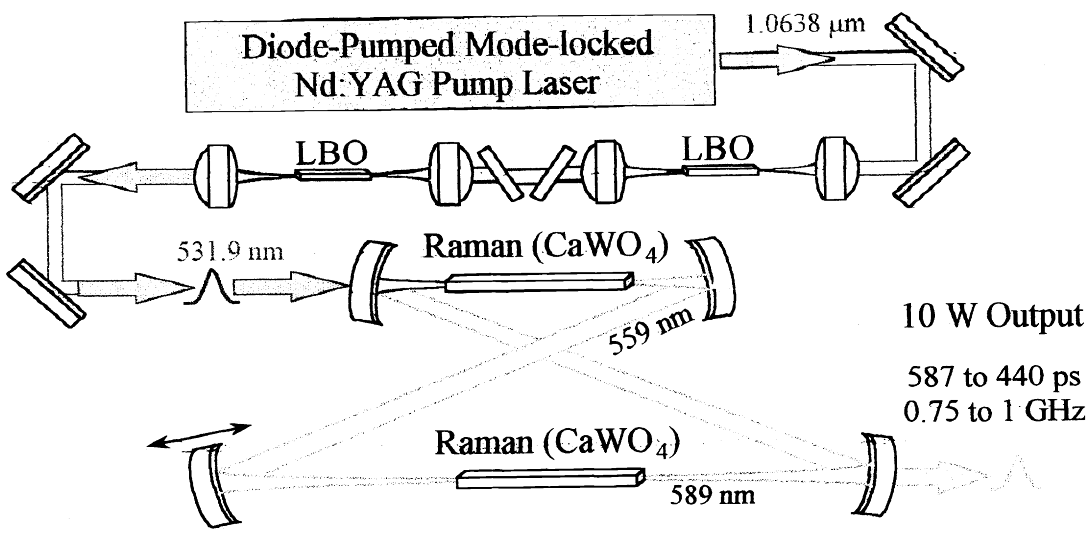

Figure 1: General layout of the MMT guide star laser showing Nd:YAG laser, doubling region, and Raman laser.

frequency-doubled pulses are then focused into a Raman laser cavity through a dichroic mirror which transmits the pump (532 nm) and reflects the first and second Stokes (559 and 589 nm, respectively). The Raman cavity is configured in a common bow-tie architecture, with two $CaWO_4$ crystals centered in the focus points of the cavity.

Previous experiments[4] have shown that the combination of an Nd:YAG pump with $CaWO_4$ Raman crystals results in radiation the does not exactly overlap the D_2 absorbtion line. Rather, a broad gain profile results which is centered between the D_1 and D_2 lines of sodium (see Fig. 2). While there is sufficient gain overlap to achieve lasing precisely on the D_2 line at 589 nm, the peak is significantly below the D_2 line to dramatically reduce the efficiency of the system. We have verified this result with an experimental setup similar to that shown in Figure 1. The result of this experiment is shown in Figure 2. Here the output of a doubled intracavity Raman laser, which utilized Nd:YAG and $CaWO_4$ as the pump and Raman laser media, is compared with the output of a sodium lamp in an echelle spectrograph. In this figure, increasing wavelength is toward the top of the frame. The spot at the top is the sodium lamp D_1 line (589.6 nm) while the spot near the bottom is the D_2 line (589.0 nm). Slightly to the right of these two spots, at about 589.25 nm is the intense output of the Raman-shifted laser. The laser spot is broad due to the combination the Nd:YAG and $CaWO_4$ linewidths.

4 Tuning to the D_2 Line

To achieve the spectral requirement for the sodium guide star program, either a method of reducing the shift of the $CaWO_4$, or a method of reducing the wavelength at which the pump laser emits must be found. In this effort, we have concentrated on the latter, and have investigated two techniques of effecting a shift of the Nd:YAG to shorter wavelengths: compositional and thermal tuning.

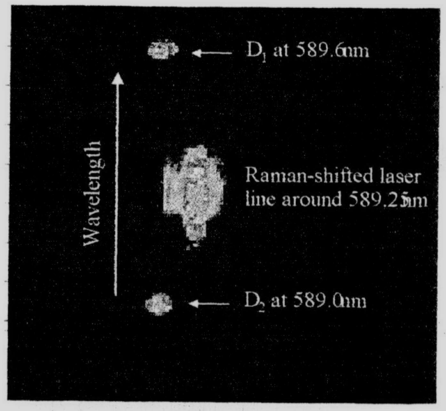

Figure 2: Output of echelle spectrograph showing the D1 and D2 lines of the reference sodium lamp against the output of the Raman-shifted Nd:YAG laser. The laser output is centered at 589.25nm.

4.1 Compositional tuning

It has been reported[6] that the 1.064 μm line of Nd:YAG can be shifted to slightly higher energies by substitution of Ga for Al in the YAG host crystal. From the previous data on the Raman-shifted YAG, we calculated that a shift of 0.41nm was required in the YAG laser to effect the 0.25 nm shift needed in the output of the Raman laser. Thus, a YGAG ($Y_3Ga_{1.1}Al_{3.9}O_{12}$) crystal was grown for the project, from which a rod 3 mm in diameter and 22 mm in length was cut. Once introduced in the original laser cavity, two qualitative effects were observed: first, the absorption of the 808 nm diode pump radiation was significantly diminished below that of pure YAG, and second, the gain in this material was significantly lower than that obtained with Nd:YAG, which are both well-known side-effects of admixing.

The Nd:YGAG was placed in the test laser and the composition-induced shift is shown in Figure 3. Here, the output of the Nd:YGAG laser is shown to have been shifted much nearer to the D_2 line than the original YAG laser. From this result it appears that a slightly higher concentration of Gallium is required for the line to fall exactly on the D_2 peak.

There are two distinct lines that lase in Nd:YGAG: the one mentioned above, and an additional one at slightly shorter wavelengths than the required 589 nm line of sodium. The source of the second line is a result of the admixing coausing a split in degeneracy of the lasing level, which is best observed by reviewing the fluorescence spectra of Nd:YAG and Nd:YGG. In Nd:YAG the transition from the upper level of the $^4F_{3/2}$ state of YAG at 11510cm^{-1} to the third level of the $^4I_{11/2}$ state at 2112 cm^{-1} releases a photon of wavelength 1.06406 μm. The band of radiation about this dominant transition closely overlaps that of a slightly weaker transition from the lower level of the $^4F_{3/2}$ state of YAG at 11425cm^{-1} to the second level of the $^4I_{11/2}$ state at 2031 cm^{-1}, whose radiation is centered at 1.06451μm. These two lines both contribute to the broad lasing bandwidth of normal Nd:YAG. However, when Nd is included in a YGG host, the energy levels of the atom are significantly perturbed such that the two transitions no longer overlap. In pure YGG, the upper level of the $^4F_{3/2}$ state is shifted from 11510cm^{-1} to 11471cm^{-1}, while the third level of the $^4I_{11/2}$ state is shifted from 2112 cm^{-1} to 2058cm^{-1}. This shifts the wavelength of the first transition from 1.06406 to 1.06236 μm, and the wavelength of the second transition from 1.06451 to 1.06056 μm as shown in Figure 4. With our replacement of 22 % of the Al with Ga, assuming a linear interpolation between the lines of the two crystals yielded lines which appropriately matched the ones in Figure 3.

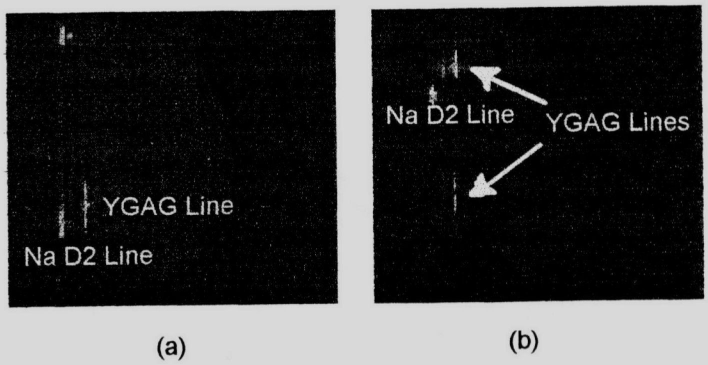

Figure 3: Result of compositionally tuned Nd:YGAG laser. Note in (a) that the inclusion of Ga shifted the line much closer to D_2. However, on resetting the spectrograph(b), the second line of the laser at approximately 588.7nm is evident.

The broadening and splitting of the lasing transition, along with the reduction of the gain cross-section make the approach undesirable for this application. Broadening the pump laser gain spectrum will result in smaller overlap of the laser output with the D_2 line, which reduced the return efficiency. The line-splitting reduces the overall efficiency by promoting gain completition between the nieghboring lines. The output efficiency is further reduced by the reduction in the gain cross-section. Therefore, the elegance and simplicity of this approach is being rejected in favor of temperature-tuning.

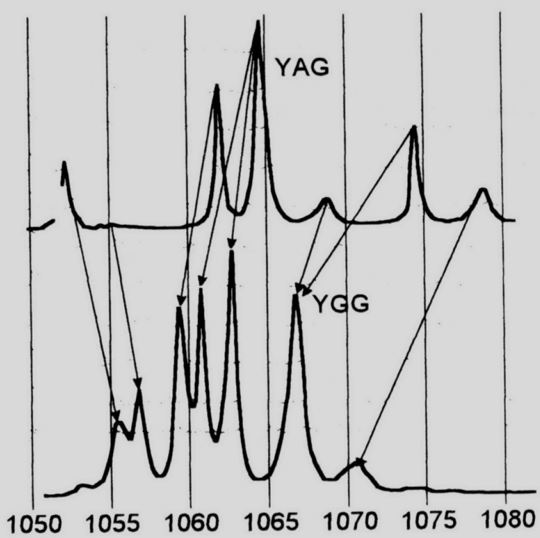

Figure 4: Host crystal shifting of Nd transitions. At top is Nd:YAG, while at the bottom is Nd:YGG. Note the splitting of the prominent peak at 1064nm into two peaks at 1061nm and 1063nm in YGG.

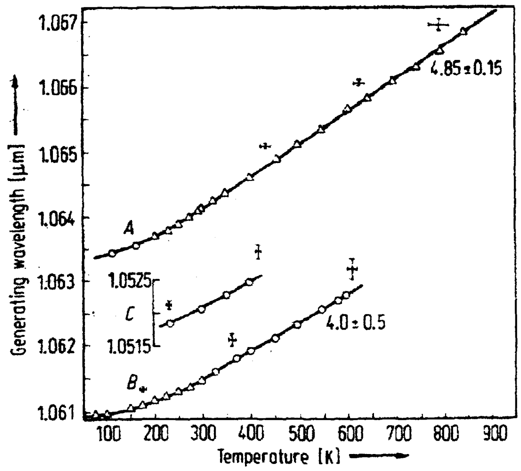

Figure 5: To reduce the lasing wavelength of Nd:YAG by 0.41nm, the crystal should be operated at approximately 220K.

4.2 Thermal Tuning

The required shift of 0.41 nm can be accomplished by cooling the crystal to approximately 220 K,[7] as shown in Figure 5. This approach introduces a number of additional engineering obstacles. Conduction cooling becomes more difficult with significant thermal variation from room temperature. Of particular importance is the design of the crystal housing which mitigates against thermally induced aberrations, and envionmentally seals the cold components.

5 Raman Laser

There are two distinct approaches to building a Raman laser for guide star application: to double the 1064 nm output of the Nd:YAG laser followed by two Raman shifts (i.e., second-Stokes), or to perform a single Raman shift first, and then double the shifted output. In the case of low-gain, the second approach is superior. This has to do with the maximization of the limited Raman gain available in the $CaWO_4$ crystals. The small-signal Raman gain is given by

$$G = exp[G_R],$$

where G_R is the Raman gain-parameter, which is given by

$$G_R = g\, I_p\, L,$$

where g is the running gain parameter (which is fixed by the material), I_P is the pump intensity, and L is the length of the crystal. For a Gaussian beam, the Rayleigh range limits the distance over which Raman shifting can be induced. Hence, the effective length of the Raman crystal is given by

$$L_{eff} = \frac{2\pi\omega_0^2}{\lambda},$$

while the peak intensity is given by

$$I_p = \frac{2P_p}{\pi\omega_0^2}.$$

Therefore, the quantity G_R is dependent on only the peak-power of the pump laser and the laser wavelength. The running gain of the Raman crystal, g, is inversely proportional to the pump wavelength. Therefore, for a single crystal, the Raman gain parameter is inversely proportional to the pump laser wavelength; i.e..

$$G_R \propto \frac{P_p}{\lambda^2}.$$

Thus, by postponing the Raman conversion until after doubling, the Raman gain paramerter is increased by a factor of four. This is the primary reason for the improved performance of this configuration.

In addition, the Raman cavity is designed to trap the first-Stokes radiation to resonantly enhance its intensity to a value which is much larger than the pumping radiation intensity. The trapped first Stokes radiation (559 nm) is used to pump the second-Stokes mode at the desired 589 nm wavelength, through cascaded conversion. This technique combines the efficiency of synchronous-pumping and resonace-enhancement in a single device.

The Raman resonator is configured in a bow-tie cavity with a pair of $CaWO_4$ crystals located at the cavity focus points. The input mirror is highly transmissive at 532 nm to allow the pump power into the cavity. The second and third cavity mirrors are high reflectors at 532 nm to allow the second crystal to be pumped as well as the first. The 911.3 cm^{-1} shift of $CaWO_4$ causes a mode to arise at the first Stokes wavelength of 559 nm, which then cascade-converts to the second Stokes wavelength of 589 nm. Because of the fairly low running Raman gain of $CaWO_4$, little loss can be tolerated in the cavity at the first Stokes wavelength. Thus, the principle requirement is that all mirrors in the cavity be very good high reflectors at 559 nm, and all transmissive surfaces (i.e., the surfaces of the $CaWO_4$ crystals) be AR coated at 559 nm. In addition, the four cavity mirrors must also be reflective at 589 nm (first three HR's and last a partial reflector) to resonate the second Stokes field. Finally, in order to avoid cascading to the third Stokes wavelength, the losses at that wavelength (622 nm) must be made as high as possible to suppress the build-up of the third Stokes field.

A computer model was developed to predict the performance of the laser under various conditions. The model calculates the steady-state of the system by mapping intensities of the pump, first, second and third Stokes pulses over several roundtrips using a roundtrip-iterator (RTI). The RTI combines the net effect of Raman conversion and passive losses suffered at the mirrors and crystals to achieve a roundtrip intensity transformation function.[3] This intensity transformation function operates on an input intensity state of the system to generate an output state, which is then feedback as the new input state. This procedure is repeated until a final state is achieved; i.e., the output state is equivalent to the input state. When an output state is achieved the efficiency is determined, and this result is indexed with the fixed parameters of the system (e.g., pumping level, second Stokes output coupling percentage, roundtrip loss, etc.). Optimization is accomplished by finding the peak efficiency as a function of the input parameters.

We estimate that the maximum passive transmission losses at all four wavelengths to be around 4 % power loss (i.e., 96 % roundtrip transmission not including mirrors). The optimum second Stokes output coupler reflectivity (R_{OC}) is therefore determined by utilizing the RTI procedure where the Raman gain parameter (G) is parametrically varied between 0.1 and 1 in 0.1 step increments. The compilation of these data points are shown as the parametric curves in Fig. 6. Photon efficiencies in excess of 40 % are achieved when $G_R \geq 0.4$ and the reflectivity of the second Stokes output coupler is in the nieghborhood of 20 %.

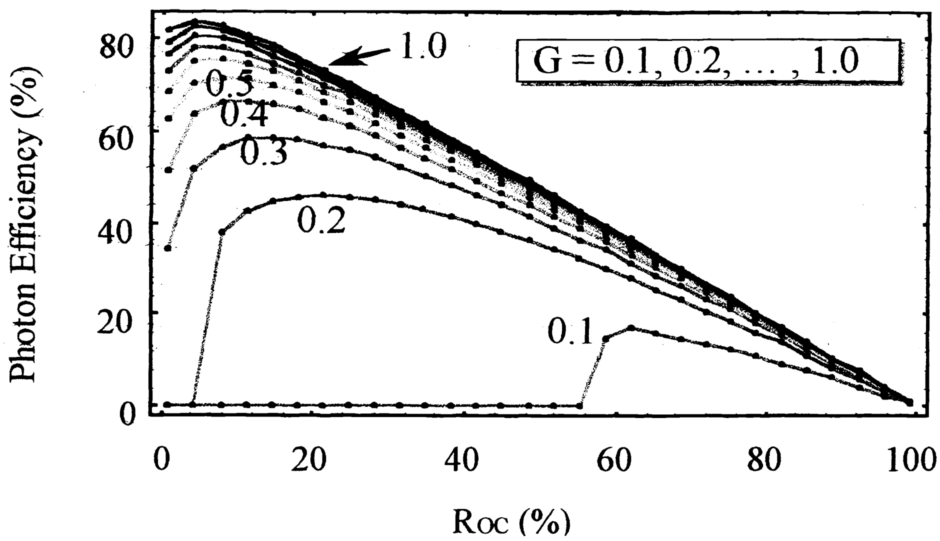

Figure 6: The output photon efficiency at steady state as a function of output coupler reflectivity R_{oc} and total cavity gain G. Note that all but the lowest gain curve is relatively flat and close to maximum for a reflectivity of 10-20%.

6 Summary

There are very restrictive requirements on the development of guide star lasers for creating sodium beacons from astronomical adaptive optics. The physics of excitation of the sodium layer drives the requirements for the exciting laser to be one that (1) exactly matches the wavelength, and preferably the spectral bandwidth of the mesospheric sodium, (2) operates in the highest duty-cycle possible, and (3) achieves high average output powers ($\geq$ 10 W is useful for most astronomical observatories). In addition, (4) the laser should be rugged enough to withstand the telescope environment, (5) reliable enough to be maintained on-line for several hours at a time, and (6) fit within the budgetary constraints (both in terms of purchase price and operational cost) of major astronomical observatories.

One major step in satisfying these goals is the laser in development for the next generation MMT. The laser uses a doubled diode-pumped Nd:YAG laser to sychronously pump a Raman laser operating at second Stokes resonance. Tuning of the pump laser was originally intended to be done through variation in the host crystal composition, but the result of this was to broaden and lower the gain to the point that the power requirement in the laser could not be attained. Current efforts are directed toward tuning the output by lowering the temperature of the Nd:YAG crystal in the pump laser to shift the output.

Analytical and numerical simulation of the design of the laser have led to a solution that should be near optimum for meeting the power, wavelength, duty cycle and spectral bandwidth requirements of this class of guide star laser. Results from this laser are anticipated soon, leading to a final design and delivery before the MMT is brought on line.

7 REFERENCES

[1] Bruce Jacobsen, Ty Martinez, Roger Angel, Michael Lloyd-Hart, Steve Benda, Dave Middleton, Herb Friedman, and Gaylen Erbert, "Field evaluation of two new continuous-wave dye laser systems optimized for sodium beacon excitation," Proceedings of SPIE, Vol. 2201, pp. 342-351 (1994).

[2] T. H. Jeys, "Development of a Mesospheric Sodium Laser Beacon for Atmospheric Adaptive Optics," Lincoln Laboratory Journal 4 (2), 133 (1991).

[3] J. T. Murray, "Frequency Conversion in New Nonlinear Optical Materials", Master's Thesis, Colorado School of Mines, 1992.

[4] E. C. Cheung, J. G. Ho, H. Injeyan, M. M. Valley, J. G. Berg, R. L. Byer, and Y. Huang, "A Solid State Raman Laser for Sodium D2 Line Resonant Excitation," OSA Technical Digest, Adaptive Optics Topical Meeting, Vol. 13, July 1996.

[5] R. K. Watts and W. C. Holton, "New intermediate gain laser material: $Y_3(Al_{1-x}Ga_x)_5O_{12} : Nd$", J. of Applied Phys., Vol. 45(2), pp. 873-881., Feb. 1974.

[6] Norman P. Barnes, Keith E. Murray, Elka B. Ertur, Brian M. Walsh and Ralph L. Hutcheson, "Compositionally Tuned Solid State Lasers", in OSA Technical Digest, Advanced Solid State Lasers, Vol. 1, pp. 522-525, 1996.

[7] Alexander A. Kaminskii, Laser Crystals, Springer Verlag, p.335, 1989.