Red, blue, and green laser-light generation from the NYAB nonlinear crystal

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Abstract. Continuous wave red, green, and blue laser light are generated under IR-pumping crystals of $\text{Nd}^{3+}:\text{YAl}_3(\text{BO}_3)_4$ by a Ti:sapphire laser. The red (669-nm) and green (532-nm) radiations are obtained by self-frequency doubling of the fundamental laser lines at 1338 nm ($^4F_{3/2} \rightarrow ^4I_{13/2}$ channel) and 1062 nm ($^4F_{3/2} \rightarrow ^4I_{11/2}$ channel), respectively. Blue laser radiation (458 nm) is achieved by self-sum-frequency mixing of the main laser line at 1062 nm and the pumping radiation at 807 nm. The main spectroscopic and nonlinear properties of this crystal are included. In addition, a simple model devoted to optimizing the blue radiation is provided. © 1999 Society of Photo-Optical Instrumentation Engineers. [S0091-3286(99)00211-1]

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1 Introduction

Currently there is much interest in compact lasers emitting in the visible range of the spectrum for a great variety of applications.¹ Semiconductor diode lasers have not been able to provide full coverage of the requirements in every field of science, technology, and industry, especially those requiring a combination of long operational lifetimes at room temperature, continuous wave operation, narrow spectral linewidth, and good beam quality at moderate to high powers. Alternatively, IR intracavity frequency-converted diode-pumped solid state lasers can be used to achieve these properties. A great effort in the study of new diode-pumped solid state lasers has been made in recent years, and many new laser systems have been developed.

Among these lasers, crystals activated with Nd^{3+} ions have been studied most extensively. Nd^{3+} -doped crystals are of great interest since they show strong optical absorption around 800 nm and therefore can be easily pumped by commercial laser diodes. Laser action around 900, 1060, and 1300 nm has been demonstrated in a variety of Nd^{3+} -doped laser crystals, corresponding to optical transitions from the metastable state ($^4F_{3/2}$) to lower Stark states $^4I_{9/2}$, $^4I_{11/2}$, and $^4I_{13/2}$, respectively.²

Together with the technological interest of these laser lines, there is the attractive fact that they can be used to generate visible laser radiation. The introduction of a nonlinear crystal inside the laser cavity can be used to generate visible laser light from a Nd^{3+} -activated crystal. It is then possible to achieve blue, green, and red laser radiation by second-harmonic generation of these laser lines. Nevertheless, the use of an intracavity optical element results in some inconveniences such as an increase in the optical losses (and therefore in laser threshold) and a reduction in the device compactness.

Nonlinear crystals used as laser host media provide the opportunity to achieve compact devices. In such cases, the fundamental laser radiation and its second harmonic (vis-

ible) are produced in the same medium, so that additional intracavity elements are not necessary.

Because of its high nonlinear coefficient together with the good laser properties of Nd^{3+} ions, Nd^{3+} -doped LiNbO_3 was first used for this purpose.³ Nevertheless this material has some disadvantages, due to pump- (and second-harmonic) radiation-induced photorefractive damage. The photorefractive damage can be avoided by increasing the crystal temperature or by codoping with oxides such as MgO, ZnO, and Sc_2O_3 (Ref. 4). Codoping with these oxides, however, leads to low-optical-quality crystals and to a decrease in the Nd^{3+} content in the crystal. Low Nd^{3+} concentration inside the crystal leads to a low absorbed pump power, and therefore a low pump-to-visible conversion efficiency.

During the last 10 yr, considerable scientific effort has been made in searching for new nonlinear host crystals for rare-earth ions.² Almost all these efforts have been focused on Nd^{3+} doped systems. Self-frequency doubling (SFD) from the IR to the visible has been demonstrated only in a few laser crystals.⁵⁻⁹

Among these laser crystals, the highest efficiency in green laser light generation by SFD has been demonstrated so far in Nd^{3+} -doped yttrium aluminum borate¹⁰ (NYAB). Since the first experimental observation of SFD in NYAB, efficient green laser light generation has been demonstrated by using a great variety of schemes.^{11,12} Although almost all the scientific effort with this material has been made on the green laser light generation, the high content of Nd^{3+} ions makes NYAB an excellent candidate for blue and red laser light generation as well.

Red laser light can be generated by SFD its fundamental laser line around 1.3 μm , corresponding to the $^4F_{3/2} \rightarrow ^4I_{13/2}$ channel. In fact, NYAB was first used to produce red laser radiation under pulsed pump conditions and recently continuous wave red radiation was reported for this material.¹³

Blue laser light could be obtained by SFD its fundamental laser line around 890 nm, corresponding to the ${}^4F_{3/2} \rightarrow {}^4I_{9/2}$ transition. Since the terminal state is now the ground state, the operation scheme is close to a three-level laser system. Thus, the laser threshold is higher than that obtained for the other laser channels. Furthermore, an additional increase in laser threshold is caused by the self-absorption of laser radiation due to the spectral overlap between emission and absorption bands. The effect of self-absorption can be reduced using short samples or by crystal cooling. However, short samples lead to a weak interaction between fundamental and second-harmonic radiations and crystal cooling reduces the device compactness.

Self-sum-frequency mixing of pump and laser radiation seems to be a better choice for blue laser light generation. Recently, tunable blue laser radiation was demonstrated¹⁴ by self-sum-frequency mixing of pump (750–820 nm) and fundamental laser radiation around 1060 nm in NYAB. The blue laser threshold is given by the laser properties of the ${}^4F_{3/2} \rightarrow {}^4I_{11/2}$ efficient laser channel. Absorbed pump thresholds as low as 7 mW have been observed in NYAB. Thus, in principle, blue laser light can be generated by pumping NYAB crystals with commercial low-current laser diodes. In fact, Risk et al.¹⁵ demonstrated this blue light generation by using KNbO_3 nonlinear crystal placed inside a diode-pumped $\text{Nd}^{3+}:\text{YAG}$ cavity. Nevertheless, NYAB is the first material in which this sum-frequency mixing phenomenon is carried out in the same material. Thus NYAB, pumped by a commercial low-current diode, emerges as the first material capable of generating three fundamental colors without the use of any additional crystal.

In this paper, we study the conditions necessary to obtain red, green, and blue laser radiation from NYAB crystals. The most recent results obtained by our group on this crystal are also summarized. Thus, this paper involves a variety of results on NYAB, including a spectroscopic study of the laser channels, laser oscillation experiments under Ti:sapphire pumping in the IR, external second-harmonic generation experiments, and visible laser light generation by self-sum-frequency mixing and SFD experiments.

2 Results and Discussion

2.1 Spectroscopic Characterization of IR Laser Channels

The energy level diagram of Nd^{3+} ions in YAB was studied in detail in a previous work.¹⁶ Figure 1 shows a simplified energy level diagram of Nd^{3+} ions in YAB, in which only the metastable (${}^4F_{3/2}$) and the terminal states are indicated together with the states involved in the pump processes.

The fluorescence lifetime measured for the metastable state¹⁶ ($\approx 60 \mu\text{s}$) is low compared to that of other Nd^{3+} -doped laser materials, such as YAG (230 μs). This low fluorescence lifetime was explained¹⁶ as a consequence of the high nonradiative multiphonon deexcitation rate. A quantum efficiency as low as 26% was measured by photoacoustic methods.¹⁷ This low quantum efficiency produces crystal heating under pumping. This effect influences both laser and nonlinear efficiencies.

Fig. 1 Simplified energy level diagram of Nd^{3+} ions in YAB; pump and laser channels are indicated.

Figure 2 shows the wavelength dependence of the polarized stimulated emission cross section departing from the metastable state in the 800- to 1500-nm range. YAB is a uniaxial crystal, so that light can propagate with its polarization vector parallel to the crystal optical axis (π polarized) perpendicular to the optical axis (σ polarized). The polarized stimulated emission cross section [$\sigma_e^p(\lambda)$, where p indicates the polarization state] was calculated from the polarized fluorescence spectra, the radiative lifetime of the metastable state, and the branching ratios for the radiative transitions from this metastable state to the final laser states¹⁶ ($J=9/2, 11/2, 13/2$, and $15/2$). The branching ratios were experimentally determined from calibrated emission spectra of 0.47, 0.46, 0.07, and 0 to the terminal states ${}^4I_{9/2}$, ${}^4I_{11/2}$, ${}^4I_{13/2}$, and ${}^4I_{15/2}$, respectively.¹⁶

Table 1 gives the peak cross sections obtained from Fig. 2 for both polarizations and for the three laser channels. Note here that as the peak cross section values depend on both polarization and emission wavelength, the oscillating line inside the experimental cavity will depend on the relative orientation of optical and cavity axis.

Fig. 2 Wavelength dependence of the polarized emission cross section.

Table 1 Emission cross section peaks for both polarizations and for the three laser channels.

Laser Channels	Polarization	Emission Cross Section
${}^4F_{3/2} \rightarrow {}^4I_{9/2}$	σ	$0.50 \times 10^{-19} \text{ cm}^2$ at 883 nm
	π	$0.32 \times 10^{-19} \text{ cm}^2$ at 879 nm
${}^4F_{3/2} \rightarrow {}^4I_{11/2}$	σ	$1.11 \times 10^{-19} \text{ cm}^2$ at 1062 nm
	π	$1.18 \times 10^{-19} \text{ cm}^2$ at 1061 nm
${}^4F_{3/2} \rightarrow {}^4I_{13/2}$	σ	$0.24 \times 10^{-19} \text{ cm}^2$ at 1338 nm
	π	$0.25 \times 10^{-19} \text{ cm}^2$ at 1338 nm

Since absorbed pump power at the threshold of laser action is proportional to the inverse of the stimulated emission cross section,¹¹ laser oscillation corresponding to ${}^4F_{3/2} \rightarrow {}^4I_{11/2}$ channel is associated to the lowest pump threshold. As we see in next section, the absorbed pump power at threshold obtained for the ${}^4F_{3/2} \rightarrow {}^4I_{13/2}$ channel is also low enough to enable efficient pumping by low-current diodes.

2.2 IR Laser Gain Experiments

Some physical parameters of great relevance on laser dynamics, such as optical losses factor (δ), can be determined by laser gain experiments. The factor of optical losses associated with IR laser radiation at 1062 and 1338 nm in NYAB were already determined in previous works.^{11,13}

Laser experiments were performed in a quasihemispherical cavity consisting of a flat dichroic input mirror (we used three different input high-reflectance mirrors at laser wavelengths 900, 1062, and 1338 nm) and output couplers of 10-cm radius of curvature. A schematic diagram of the experimental setup is shown in Fig. 3. Several output mirrors of different transmittances at laser wavelengths were available. End pumping was performed by a cw Ti sapphire tunable laser (Spectra Physics model 3900). The pump beam was focused into the crystal by a 5-cm single-focus lens. The polarization character of the oscillating laser line was analyzed using a calcite polarizer.

The crystals used in laser experiments were a 5-mm-long prism cut $\theta = 30$ deg with respect to the optical axis for green laser light generation (fundamental wave at 1062 nm), a 5-mm-long prism cut $\theta = 27$ deg with respect to optical axis for red laser light generation (fundamental wave at 1338 nm), and a 2-mm-long prism cut $\theta = 36$ deg with respect to optical axis for blue laser light generation (fundamental wave at 900 nm). As mentioned earlier, due to self-absorption of laser radiation, short samples must be used for laser light generation at 900 nm.

Fig. 3 Schematic of the experimental setup used for laser gain experiments; θ refers to the phase-matching angle. **Fig. 4** Laser curves for minimum threshold (a) and maximum slope efficiency (b).

Figure 4(a) shows laser curves for the minimum threshold obtained for laser oscillation at 1060 and 1338 nm. A 0.36% transmittance output coupler mirror was used in both cases. For these experiments, the cavity length was set as close as possible to the stability limit of our cavity (≈ 10 cm). In both cases, only ordinary radiation was oscillating inside the cavity, so that all the intracavity power of IR radiation could be converted to the second harmonic by a type I phase-matched process. This is in contrast to other SFD materials³ such as LiNbO₃, where the laser gain associated with extraordinary radiation is higher than that associated with ordinary radiation. This forces the introduction of an intracavity element to avoid laser oscillation in extraordinary polarization, which is not useful for SFD.

The observed absorbed pump thresholds are 10 and 45 mW for laser action at 1062 and 1338 nm, respectively. The ratio between absorbed pump thresholds at 1338 and 1062 nm is 5.6, very close to the value predicted by mode overlap formalism¹⁸ together with the cross section estimated by spectroscopic measurements.¹⁶ The ratio between pump thresholds is mainly given by the ratio between emission cross sections. This indicates that the optical losses are similar for both laser radiations.

Laser action at 900 nm was tried by using both input and output mirrors of high reflectance ($>99\%$) at 900 nm. In these experimental conditions, no laser action was achieved at 900 nm. In fact, laser action was observed at 1062 nm as predominant in spite of the fact that the mirror transmittances at 1062 nm were higher than 50%.

Figure 4(b) shows the laser curves obtained when 3% transmittance output couplers are used. Since the factor of optical losses is very similar for both laser wavelengths, the difference in the laser slope efficiency is associated with the different quantum defect (ratio between pump and laser photon frequencies). The slope efficiencies obtained with these transmittance output couplers are 50 and 30% for the laser transitions at 1062 and 1338 nm, respectively.

2.3 External Second-Harmonic Generation

In this section, we report external second-harmonic generation experiments that were performed to estimate fundamental nonlinear properties of NYAB, such as angle acceptance ($\Delta\theta \cdot L$) and thermal acceptance ($\Delta T \cdot L$) for incident

Fig. 5 SH intensity as a function of sample temperature (a) and misalignment angle (b).

radiation at 1062 and 1338 nm. Angle acceptance is a very important parameter since it indicates how precise the crystal orientation should be. Crystals with a high angle acceptance can be oriented without requiring a high-precision method. In crystals with low angle acceptance, a slight deviation in sample orientation from the phase-matching direction causes a drastic decrease in second-harmonic power. In addition, thermal acceptance is a parameter of particular relevance in this crystal, since heating by pump radiation occurs because of the low quantum efficiency.

An optical parametric oscillator (OPO; Spectra Physics MOPO 730) was used as a source to generate laser radiation at 1062 and 1338 nm. The MOPO provides 10-ns pulses with a 10-Hz repetition rate. The average pulse energy was 20 mJ. The sample was mounted on a goniometer placed inside the oven, so that both sample orientation and temperature could be controlled. The OPO beam was driven through the sample by two folding mirrors. A calcite polarizer was placed between the mirrors and the sample so that incident OPO radiation into the sample was 100% polarized. A silicon detector was used to detect the second-harmonic (SH) intensity. A second calcite polarizer with its axis perpendicular to the first one, enabled us to filter the fundamental radiation (at 1338 or 1062 nm), since the polarization of the SH beam is perpendicular to the polarization of fundamental beam.

Figure 5(a) shows the SH intensity as a function of temperature for input wavelengths of 1062 and 1338 nm. As expected,¹⁹ both curves fit well to a sinc^2 form (dotted lines). From this figure, thermal acceptances of 30 and 55°C cm were obtained for SH generation at 1062 and 1338 nm, respectively.

Figure 5(b) presents the SH intensity as a function of angle misalignment ($\Delta\theta$) with respect to the phase-matching direction. Points represent the experimental data and dotted lines represent the best fitting of experimental points to the theoretical sinc^2 expression.¹⁹ The maximum SH intensity occurs in both cases when $\Delta\theta = 0$. It indicates that crystals are properly oriented (27 and 30 deg) for SH generation at 1338 and 1062 nm, respectively. The angle acceptances are obtained to be $\Delta\theta \cdot L = 0.7$ mrad cm (1062 nm) and $\Delta\theta \cdot L = 1.3$ mrad cm (1338 nm). Thus, special care must be taken in crystal orientation for green laser light

Fig. 6 Green output power as a function of absorbed pump power.

generation for which the angle acceptance is lower. Nevertheless, the possible influence of an incorrect laser element orientation can be avoided by using antireflection coatings at the fundamental wavelengths. This would enable a fine alignment of the crystal inside the laser cavity without decreasing output IR power.

For external self-sum-frequency mixing experiments, two collinear beams of different wavelengths are required. Due to the wavelength dependence of the refractive indices, these two beams propagate at different directions inside the crystal for nonperpendicular incidence. The spatial overlap between both beams is therefore reduced when the sample is not perpendicular to the propagation direction of the incident beams. Hence the variation of frequency mixing intensity with sample orientation will be given not only by phase mismatch but also by spatial overlap reduction. Nevertheless the angle acceptance can be estimated by using the reported refractive indices.¹⁴ We estimated an angle acceptance width of 0.9 mrad cm for a 807-nm pump wavelength. Unfortunately the temperature dependence of refractive indices has not yet been studied so that we are not able to estimate the thermal acceptance width for a self-sum-frequency mixing processes.

2.4 Visible Laser Light Generation

In this section the most relevant results for visible laser light generation obtained in our laboratory are presented and discussed.

2.4.1 Ti-sapphire laser pumping

Green laser light generation. Figure 6 shows the green output power obtained by SFD versus absorbed pump power in a 5-mm-long NYAB crystal for type I phase matched generation. An output mirror of 0.36% transmittance at 1062 nm and of 75% transmittance for SH was used. Up to 115 mW of green power were obtained at 1 W of absorbed pump power. In this experiment, only ordinary radiation was oscillating at 1062 nm, so that all the IR circulating power was contributing to green light generation. The optimum cavity length was found to be 9.6 cm, corresponding to a laser beam waist of about 60 μm . The pump was focused to a 15- μm beam waist located at the input face of the crystal. At low absorbed pump powers, the green output intensity increased quadratically with the ab-

Fig. 7 Red output power as a function of absorbed pump power.

sorbed pump power. For absorbed powers above 500 mW, this dependence became linear. This effect was formerly attributed to power depletion of the fundamental beam.¹⁰ In this regime, intracavity SH generation is high enough to act as a loss source for the IR beam.¹⁰ In Fig. 6, the experimental points corresponding to low pump powers are fitted to a quadratic expression and those corresponding to high pump powers are fitted to a line (solid lines).

Red laser light generation. Figure 7 shows the laser power at 669 nm as a function of absorbed pump power obtained by SFD the laser line at 1338 nm. The output mirror used in this experiment had 1% transmittance for fundamental laser radiation and 80% transmittance for the red laser radiation. Although output power was not higher than 1 mW, this value can be improved using an output mirror of higher reflectance at the laser wavelength. In the same experimental conditions (same laser crystal and focusing conditions), more than 10 mW are expected if a 0.36% transmittance output coupler is used (as in case of SFD experiments for green generation). The pump was focused in the same way as for green laser light generation experiments. The optimum cavity length was found to be 9.7 cm, giving a laser beam waist of about 80 μm .

Blue laser light generation. As mentioned, blue laser light was obtained by self-sum-frequency mixing of pump and laser radiations. Figure 8 shows the blue laser output power (at 455 nm) as a function of absorbed pump power.

Fig. 8 Blue output power as a function of absorbed pump power.

Fig. 9 Visible laser light power as a function of absorbed pump power from a diode laser.

The optimum cavity conditions were found to be the same as for green generation. The output blue power obtained is of the order of microwatts, resulting in a very low conversion efficiency. The 1.7-mm-long sample used in these experiments was Nd^{3+} doped with 5.5% and cut 35 deg with respect to optical axis.¹⁴ As we shall see these are not the optimum conditions for blue laser light generation.

2.4.2 Diode laser pumping

To investigate the viability of a diode-pumped RGB laser based on NYAB, we have developed preliminary experiments under diode laser pumping. The diode used in our experiments was a 0.5-W Optopower AlGaAs cw laser. The same cavity as for Ti-sapphire pumping was used. The pump focusing system was slightly changed so that two lenses were used: a 0.5-cm-focal-length lens was used to collimate the diode beam, which was focused into the sample by a 5-cm-focal-length lens. Figures 9(a), 9(b), and 9(c) show the input-output RGB power curves. Although the obtained efficiencies are lower than those corresponding to Ti-sapphire pumping, these experiments strongly suggest that a RGB device based on NYAB pumped by low-current diodes can be realized.

3 Self-Frequency Mixing Sum Mixing Optimization

Certain parameters, such as crystal length and Nd^{3+} concentration, are of great importance for efficient self-sum-frequency mixing. In this section, we investigate the best conditions for sum-frequency mixing of the fundamental laser and pump radiations. The low pump to blue efficiency obtained in the previous section is also explained.

For red and green laser light generation by SFD the optimum Nd^{3+} concentration has already been determined in the literature. Due to the low factor of internal losses associated with the fundamental laser lines, the laser threshold is almost invariant with crystal length and the

pump-to-visible conversion efficiency increases with crystal length. However, the maximum length is limited to 5 mm due to the growth method. For this crystal length, the optimum Nd^{3+} concentration has been determined²⁰ to be in the range 4 to 6%.

In self-sum-frequency mixing, the situation is different. The blue intensity generated is proportional to both pump and laser intensities. For a given pump power, the absorbed pump power will depend on the absorption coefficient at pump wavelength and on the crystal length. Thus, to increase the pump intensity inside the crystal, a low Nd^{3+} concentration must be used or, alternatively, the pump wavelength must be tuned to a low absorption coefficient. On the other hand, low values of absorbed pump power will lead to low IR laser intensities circulating inside the cavity. Thus, to optimize the sum-frequency mixing intensity a trade-off is necessary between high pump and circulating laser intensities.

For the general case, a NYAB crystal (cut along phase-matching direction for frequency sum mixing of pump and laser radiation) of length L is pumped with an intensity I_0 . The pump wavelength and the Nd^{3+} concentration are such that the absorption coefficient is equal to α . The amplitude of the electric field associated to the pump radiation at a distance x with respect to the input face $E_0(x)$ is given by

$$E_0(x) \propto E_0 [\exp(-\alpha \cdot x/2)], \quad (1)$$

where E_0 is the electric field amplitude of pump radiation at the input face of the crystal ($x=0$). Let us assume that the electric field associated with the laser radiation at a distance x , $E_L(x)$, can be considered constant along the crystal and is given by

$$E_L(x) = E_L \propto (I_{\text{abs}} - I_{\text{th}})^{1/2}, \quad (2)$$

where I_{abs} is the total absorbed pump intensity and I_{th} is the absorbed pump intensity at threshold. Equation (2) can be also written in terms of the absorption coefficient:

$$E_L(x) = E_L \propto I_0^{1/2} \left(1 - e^{-\alpha L} - \frac{I_{\text{th}}}{I_0} \right)^{1/2}. \quad (3)$$

The electric field associated with the generated sum-frequency beam by a differential element of the crystal (dx long) located at a position x , $E_{\text{FS}}(x)dx$, can be calculated by combining Eqs. (1) and (3):

$$E_{\text{FS}}(x)dx \propto E_L(x)E_0(x)dx \\ \propto \left(1 - e^{-\alpha L} - \frac{I_{\text{th}}}{I_0} \right)^{1/2} [\exp(-\alpha \cdot x/2)]. \quad (4)$$

Then the final amplitude of this field E_{FS} is given by

$$E_{\text{FS}} \propto \int_0^L \left(1 - e^{-\alpha L} - \frac{I_{\text{th}}}{I_0} \right)^{1/2} [\exp(-\alpha \cdot x/2)] dx \\ = \left(1 - e^{-\alpha L} - \frac{I_{\text{th}}}{I_0} \right)^{1/2} \left[\frac{1 - \exp(-\alpha \cdot L/2)}{\alpha/2} \right]. \quad (5)$$

Fig. 10 Sum-frequency mixing efficiency as a function of absorption coefficient and crystal length. The efficiency corresponds to the ratio P_{FS}/P_0 .

Finally, the intensity of the sum-frequency beam I_{FS} is given by

$$I_{\text{FS}} \propto E_{\text{FS}}^2 \propto \left(1 - e^{-\alpha L} - \frac{I_{\text{th}}}{I_0} \right) \left[\frac{1 - \exp(-\alpha \cdot L/2)}{\alpha/2} \right]^2. \quad (6)$$

It can be observed that I_{FS} is not proportional to L^2 , as it is for a SFD process. The term I_{th}/I_0 is equal to P_{th}/P_0 , where P_{th} is the absorbed pump power at threshold and P_0 the incident pump power at $x=0$. The variation of P_{th} with crystal length can be estimated if we know the optical loss factor and the value of the absorbed pump power at threshold for a given output coupler transmittance. Absorbed pump powers at thresholds as low as 10 mW are reported in this work using 5 mm crystal length and 0.36% transmittance output coupler. In those experiments, the factor of optical losses was $1\% \text{ cm}^{-1}$. Then, the absorbed pump power at threshold (for a fixed output mirror transmittance of 0.36%) can be estimated for different crystal lengths by¹²

$$P_{\text{th}}(L) \approx 20L, \quad (7)$$

where L is given in centimeters and P_{th} in milliwatts. Combining Eqs. (7) and (6) the pump-to-visible conversion efficiency ($P_{\text{FS}}/P_0 = I_{\text{FS}}/I_0$) can be estimated (in arbitrary units) as a function of both crystal length and absorption coefficient.

Figure 10 shows the pump-to-visible conversion efficiency for an input pump power $P_0 = 1 \text{ W}$. In this figure, we considered crystal lengths only up to 5 mm (maximum crystal length available for NYAB). As can be observed, the conversion efficiency increases with crystal length. Long crystals provide a high interaction between pump and laser radiations. Nevertheless, for each crystal length there is an optimum absorption coefficient α .

There are two ways of achieving the optimum absorption coefficient. The first is wavelength tuning. In some practical applications, such as high brightness displays, it could be advantageous to generate the three fundamental

colors in the same crystal. As was said before, high conversion efficiencies for red and green generation require high Nd^{3+} concentrations. For green laser light generation, the optimum Nd^{3+} concentration inside the crystal has been determined²⁰ to be 5.5% for a crystal length of 5 mm. Let us then analyze the optimum pump wavelength for blue generation in this crystal. From Fig. 9, the optimum absorption coefficient is found to be 2.3 cm^{-1} . Considering the absorption coefficient (ordinary polarization) of this crystal in the diode-pumping spectral region,¹¹ this absorption coefficient value occurs at two wavelengths: 800.2 and 808.5 nm.

In the second method, Nd^{3+} concentration tuning, it is desirable to use the same pump source, and therefore the same pump wavelength, for all the crystals. In fact, for green and red laser light generation by SFD 807 nm is the most efficient pump wavelength.^{11,13} The absorption coefficient at this wavelength is a function of Nd^{3+} . If we denote the Nd^{3+} concentration in atomic percent by C , then the absorption coefficient at 807 nm is given by²⁰

$$\alpha(C) = 0.93C, \quad (8)$$

so that it is now possible to find the optimum concentration for blue generation by inspection of Fig. 9. For an input power of 1 W at 807 nm and a 5-mm crystal length, the optimum Nd^{3+} concentration would be 2.5%, which is half of the optimum concentration obtained for green laser light generation. Thus, this simple model partially explains the low efficiency obtained for blue generation (see Fig. 8 in Sec. 2.4)

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