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Near infrared and visible tunability from a diode pumped Nd^{3+} activated strontium barium niobate laser crystal

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ABSTRACT Tunable laser action from a diode pumped Nd^{3+} activated $Sr_xBa_{1-x}(NbO_3)_2$ crystal has been obtained. A wide continuous tuning range of 43 nm in the near infrared region (1050–1093 nm) has been demonstrated due to the broad $^4F_{3/2} \rightarrow {}^4I_{11/2}$ emission band present in this system. Simultaneously, 20 nm of tunability in the green region (525–545 nm), as well as 7 nm in the blue one (455–462 nm) have been achieved by tunable self-frequency conversion processes using the quasiphase matching technique, without any angle or thermal tuning of the laser crystal. The results evidence that the system is a reliable candidate for compact tunable coherent devices based on diode pumped Nd^{3+} active ions, which are of interest in many technological and scientific applications.

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1 Introduction

Over the past and present years, materials for tunable solid state lasers have been widely investigated. They constitute systems of high interest in a great variety of fields such as spectroscopy, remote environmental sensing, frequency conversion or optical networks, where a tunable and narrow spectral line is needed.

Though Nd^{3+} ions is by far, the most extensive laser ion used up to date, the tunability of Nd^{3+} ion activated laser crystals uses to be very limited since Nd^{3+} optical transitions in most laser crystals provide narrow emission lines. Thus, though tuning of the laser radiation has been demonstrated in some cases [1–3], extending that tuning range appears as a great challenge.

In this work we demonstrate continuously tunable cw laser action in a range as broad as 43 nm from a Nd doped $Sr_xBa_{1-x}(NbO_3)_2$ crystal (hereafter SBN) operating at the $^4F_{3/2} \rightarrow {}^4I_{11/2}$ transition under diode pumping. This crystal presents a tungsten-bronze structure with a high degree of cationic disorder which affects the crystal field at Nd^{3+} sites in the lattice, giving rise to very broad absorption and emission lines [4]. The large emission bandwidth associated with the $^4F_{3/2} \rightarrow {}^4I_{11/2}$ transition (more than seven times higher than that of Nd:YAG) makes this material specially suitable as gain media for a tunable laser.

Additionally, the SBN matrix is a ferroelectric and photorefractive material with large electro-optics coefficients and with relevant potential applications in the field of photonics. For instance, SBN can be used for optical memories and waveguides [5, 6]. Taking advantage of its ferroelectric character, the system can act as optical frequency converter by means of different quasi-phase matching (QPM) schemes. Thus, second harmonic generation and other different frequency mixing processes have been demonstrated by using the suitable structures of reversal ferroelectric domains [7–11]. Since the ferroelectric domain size distribution in the as grown SBN crystals (an almost random sized micro-ferroelectric needle-like shaped domains [12]) spreads over a large range, broadband non-critical QPM of multiple processes in a single crystal are possible without any angle or thermal tuning of the non linear crystal [13]. Hence, frequency conversion by QPM from a very broad band of fundamental wavelengths in the vicinity of Nd^{3+} $^4F_{3/2} \rightarrow {}^4I_{11/2}$ transition is possible. Therefore, by combining the broad emission bands of Nd^{3+} ions in SBN and the possibility of broad band non-critical QPM of multiple frequency conversion processes in a single crystal (without any angle or thermal tuning of the non linear crystal) a simultaneously tunable source in the near infrared and visible region can be obtained.

In this work, we demonstrate Nd:SBN cw laser tuning in the region 1050–1093 nm. Once that tunability in the near infrared region is shown, tunable self-frequency conversion in the visible spectral region is also achieved. In particular, tunable wavelength conversion within 20 nm in the green (525–545 nm) and 7 nm in the blue (455–462 nm) regions of the spectrum is also demonstrated in this work by using different intracavity self-frequency conversion processes from the fundamental tunable laser radiation around 1 µm provided by Nd^{3+} ions.

2 Experimental

A Nd^{3+} doped $Sr_xBa_{1-x}(NbO_3)_2$ crystal with $x = 0.6$ (congruent composition) was commercially obtained from Moltech Gmbh. Nd^{3+} ions were incorporated in a con-

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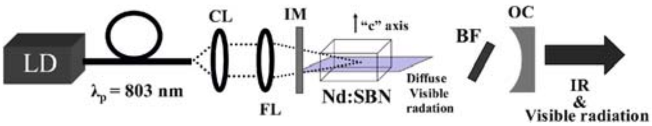

FIGURE 1 Experimental setup for tunable laser action and tunable frequency conversion

centration of 0.5 at. %. The sample used in this work was an uncoated cube ($5 \times 5 \times 5$ mm^3), with the optical *c* axis parallel to one of its faces. All faces were polished up to laser quality. Previous results from optical microscopy together with external QPM experiments performed on these same Nd^{3+}-doped SBN samples, confirmed the presence of a broad distribution of cylindrical ferroelectric domain with sizes ranging between 1.8 and 8 µm leading to external broadband second-harmonic generation in the 800–1200 nm range [14].

Laser gain experiments were performed by using an end-pumping quasi-hemispherical cavity (schematically shown in Fig. 1) with a flat dichroic input mirror (IM). The crystal was placed on a copper sample holder as close as possible to the input mirror with the optical axis perpendicular to the propagation of the pump beam. The output coupler (OC) was 10 cm radius of curvature with a transmittance of 0.2%. End pumping was performed by using 100 µm 10-W fiber coupled diode laser (LD) operating at around 803 nm. The fiber output was collimated and focused using two lenses (L) giving a minimum pump beam radius at the laser crystal of 90 µm. Tuning of laser radiation was accomplished by inserting a 1.5 mm single plate quartz birefringent filter (BF) oriented at Brewster's angle inside the cavity. The optimum cavity length for tunable laser operation was around 9.8 cm. The near infrared laser power was measured by using a thermopile. The visible converted radiation generated into the cavity was detected perpendicularly to the axis of the laser cavity since, due to its diffuse character, it propagated in all directions of the plane perpendicular to the c axis. The spectral distribution of both (visible and near infrared) output radiations was coupled into a fibre and dispersed by a 0.5 M Spex monochromator (0.01 nm resolution). The detection was performed by a cooled photomultiplier.

3 Results and discussion

Some spectroscopic properties of Nd^{3+} ion in SBN crystals including the absorption and emission spectra and lifetime measurements have been previously reported [4]. Here, the emission cross-section spectra, as useful information to asses the laser performance of a laser media, have been obtained. Figure 2 shows the spectral dependence of the $^4F_{3/2} \rightarrow {}^4I_{11/2}$ polarized emission cross-section ($\sigma_{\mathrm{em}}^{\sigma,\pi}$) for our crystal. These spectra have been obtained from the polarized emission spectra, $\mathrm{I}^{\sigma,\pi}(\lambda)$, by using the expression:

$$\sigma_{\mathrm{em}}^{\sigma,\pi}(\lambda) = \frac{3\lambda^5 \beta_{JJ'} I^{\sigma,\pi}(\lambda)}{8\pi n_{\sigma,\pi}^2 c\tau_{\mathrm{r}} \int \lambda\,(2I^{\sigma}(\lambda) + I^{\pi}(\lambda))\,\mathrm{d}\lambda} \qquad (1)$$

where the superscripts σ and π stand for the spectra with the electric field of the light perpendicular and parallel to the c axis of the crystal, respectively; $n_{\sigma,\pi}$ corresponds to

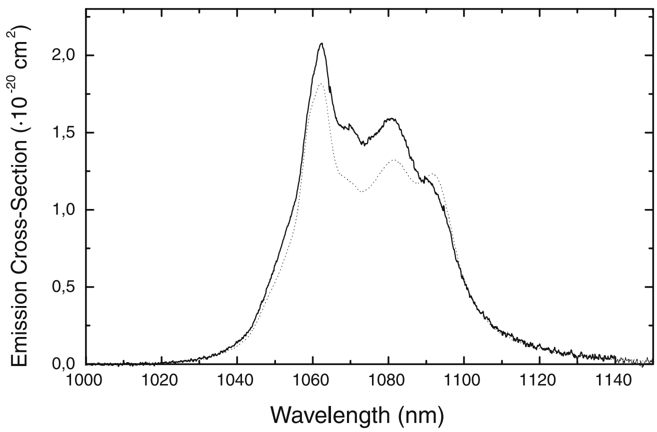

FIGURE 2 Room temperature emission cross section spectra of Nd^{3+}:SBN in σ (*solid line*) and π (*dotted line*) polarization

the ordinary and extraordinary refractive indexes and τ_{r} is the radiative lifetime of the $^4F_{3/2}$ metastable state which according to [4] was 257 µs. $\beta_{JJ'}$ is the branching ratio of the $^4F_{3/2} \rightarrow {}^4I_{11/2}$ transition which has been estimated by using the Judd–Ofelt theory to be 0.5 [15].

Two maximum cross-section peaks, $\sigma_{\mathrm{em}} = 2 \times 10^{-20}$ cm^2 at 1062 nm and $\sigma_{\mathrm{em}} = 1.6 \times 10^{-20}$ cm^2 at 1081 nm were obtained for the σ polarized emission spectrum (electric field perpendicular to the ferroelectric axis). For π polarization (electric field parallel to the optical axis of the crystal) values of $\sigma_{\mathrm{em}} = 1.8 \times 10^{-20}$ cm^2 and $\sigma_{\mathrm{em}} = 1.3 \times 10^{-20}$ cm^2 were obtained at 1062 nm and 1081 nm, respectively. The spectra of Fig. 2 show that emission-cross section values are high enough for laser action in the range 1050–1095 from a four level system in a cavity with low internal losses.

Figure 3 shows the laser gain curve obtained for this system under diode pumping. Free running laser operating at the $^4F_{3/2} \rightarrow {}^4I_{11/2}$ transition is obtained with a slope efficiency of 3% and a threshold value of 250 mW for a 0.2% transmitance OC. The low laser efficiency and the relatively

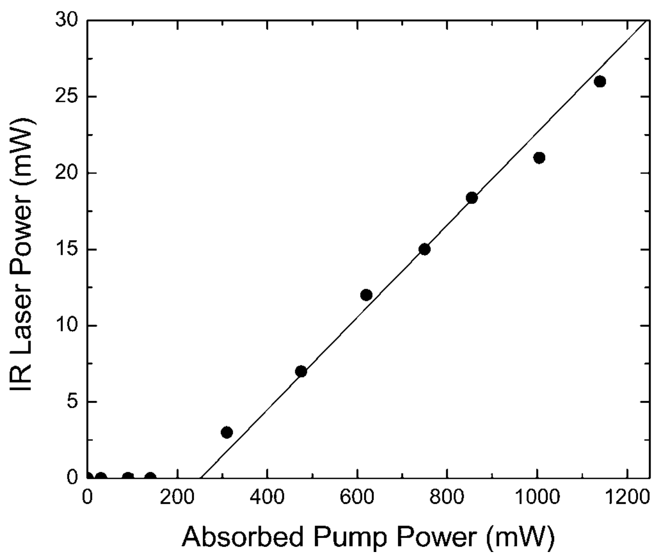

FIGURE 3 Performance of the diode pumped Nd^{3+}:SBN cw laser for a 0.2% transmission output coupler

high threshold value are consequence of the inhomogeneous line broadening of the emission bands induced by the Nd^{3+} multicenter distribution in Nd:SBN crystals. In fact, the laser efficiency here reported is similar to that previously obtained under Ti:Sapphire pumping [9]. In our case, we have obtained that for pump powers lower than 400 mW the system free runs at 1063 nm. When higher pump powers are used, multiline oscillation at 1063 and 1081 nm is observed, in good agreement with the emission cross section values here presented. The spectral linewidth (FWHM) for free running conditions at 1063 was 2 nm. Under this diode pumping free running conditions, self-frequency doubling (SFD) and self-sum frequency mixing (sum mixing of laser and pump radiation) (SFM) processes leading to diffuse green (531.5 nm) and blue (458 nm) radiations, are also observed.

Figure 4 shows the tuning range obtained when an intracavity single birefringent quartz filter plate is used. The absorbed pump power, fixed at 803 nm, was around 1.2 Watt. As shown, a continuous tuning range of 43 nm, from 1050 to 1093 nm, (exceptionally broad for a Nd^{3+} based laser crystal) was obtained under our diode pumping conditions. This result is in agreement with the cross section spectra of Fig. 2. A maximum output power of around 25 mW is obtained by using a 0.2% transmission OC. Under the same conditions, the laser without birefringent filter delivered 29 mW.

It is important to remark that the same tuning range was obtained for incident pump powers close to the threshold value due to the four level laser operation scheme of Nd^{3+} ion. This constitutes an advantage over tunable Yb^{3+} doped laser crystals (with tuning ranges in the same spectral region), which require higher pump powers to obtain similar tuning ranges due to their quasi-three level operation scheme.

In our experiments the infrared tuned laser radiation is forced to oscillate with its polarization parallel to the ferroelectric optical axis of the crystal (π polarization). The aim is to fulfil the requirements for frequency conversion by QPM, which imposes that the electric field is parallel to the optical axis allowing the access to the d_{33} component of the second order nonlinear tensor. Thus, during the experiments of tunability in the near infrared region, visible light generated by SFD and SFM is simultaneously achieved with a state of polarization parallel to the optical axis. The spatial distribution of the visible light shows a diffuse character spreading out in all directions of the plane perpendicular to the ferroelectric c axis (see Fig. 1), in accordance with previous works on SBN [9, 12]. Consequently, although the spectral distribution of tunable green and blue laser radiation was easily recorded, the output power could not be measured.

Figure 5 shows as an example, several spectra recorded for green and blue radiations obtained when tuning the infrared laser emission under the above mentioned conditions. A continuous range of 20 nm in the green region (525–545 nm) and 7 nm in the blue one (455–462 nm) are simultaneously obtained for a pump wavelength fixed at 803 nm without any angle or thermal tuning of the laser crystal. The FWHM resulted to be around 0.5 nm for the green emission and about 2 nm for the blue. The green linewidth is in good agreement with that obtained in the infrared case. The broader FWHM obtained for the blue radiation is a consequence of the spectral linewidth of the pumping diode around 1.5–2 nm, since blue radiation is generated by sum mixing of laser and pump radiation. Although the spectral distribution of tunable green and blue laser radiation is easily recorded, the output power could not be measured. This is basically due to the diffuse character of the converted radiation and its low conversion efficiency [9, 13]. Indeed, the broadband non-critical QPM as well as phase-matching of multiple non linear processes in a single crystal has been possible due to the relatively broad distribution in domain sizes found in this host crystal which provides very high spectral and angle tolerances at the expense of the maximum efficiency since the area under the detuning curve should be conserved [16]. This reduction in the maximum efficiency could be a restriction for frequency conversion outside a cavity but it is not a limitation for intracavity frequency conversion, due to the high circulating intracavity fundamental laser intensity.

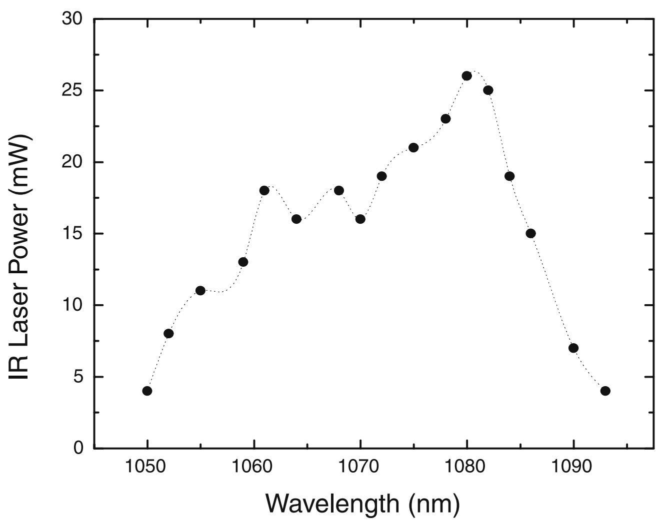

FIGURE 4 Tunning curve of the near infrared laser radiation under diode pumping

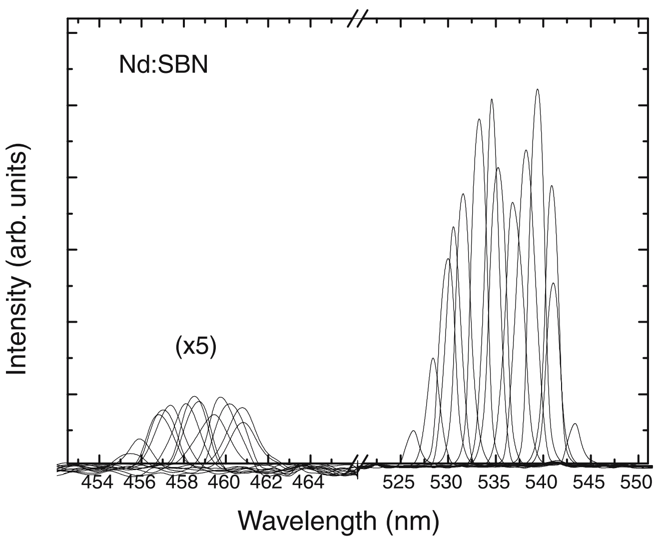

FIGURE 5 Self-converted visible spectra obtaining by tuning the near infrared laser radiation

4 Conclusions

In this work, the multi-functional character of SBN as optical material is extended by the demonstration of continuous tunable laser action from a diode pumped Neodymium activated SBN crystal in three different spectral ranges of great technological interest: near infrared, green and blue. On one side the cationic disorder imposed by the host crystal allows 43 nm of continuous laser tunability in the $^4F_{3/2} \rightarrow {}^4I_{11/2}$ channel of Nd^{3+} active ions. On the other side, the broad distribution in ferroelectric domain sizes, provides the mechanism for tunable near infrared-to-visible frequency conversion by non-critical QPM without any angle or temperature stabilization of the crystal. The system could be an alternative to Yb^{3+} activated tunable lasers and allows to envisage additional spectral tuning ranges around other Nd^{3+} laser channels (such as those around 1.3 μm or around 0.9 μm). The results constitute an interesting approach to develop compact tunable coherent systems based on diode pumped Nd^{3+} active ions, which are of interest in many technological and scientific applications.

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