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We present what is, to the best of our knowledge, the first diode-pumped Nd:YAG laser emitting at 899 nm and below, based on the $^4F_{3/2}-^4I_{9/2}$ transition, generally used for a 946 nm emission. A power of 630 mW at 899 nm has been achieved in cw operation and 16 mW at 884 nm with a fiber-coupled laser diode emitting 9 W at 808 nm. Intracavity second-harmonic generation in cw mode has also been demonstrated with a power of 100 mW at 450 nm by using a LiB_3O_5 nonlinear crystal.

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Blue lasers have a large number of applications, such as high-density optical data storage, flow cytometry, and fluorescence spectroscopy. Different technologies have been developed to reach the blue range: GaN laser diodes, frequency-doubled laser diodes, or diode-pumped solid-state (DPSS) lasers. Classical wavelengths of frequency-doubled DPSS blue lasers are 457 nm (Nd:YVO_4 laser) or 473 nm (Nd:YAG laser). These lasers are efficient and powerful[1,2] (up to the watt level), and it could be interesting to extend these sources to other wavelengths, in particular to deeper blue.

The lowest wavelengths ever reported with DPSS lasers based on Nd ions are 903 nm with Nd:YLF (Ref. 3) and 900 nm with Nd:ASL (Refs. 4 and 5) and recently 880 nm in Nd:YVO_4 and Nd:$GdVO_4$ (Ref. 6). Numerous other Nd-doped crystals present laser transitions in this range. In particular, the $^4F_{3/2}-^4I_{9/2}$ transition usually used in Nd:YAG for 946 nm emission can offer other possibilities at lower wavelengths (Fig. 1). For example, laser emission at 899 and 884 nm was observed in a flashlamp Nd:YAG laser in the early 1970s (Ref. 7). Yet, under diode pumping, laser emission was generally obtained at 946 nm or even at 938 nm, but never below. Our purpose in this Letter is to investigate laser oscillation between 869 and 899 nm in Nd:YAG under diode pumping. We will also examine intracavity second-harmonic generation (SHG) to reach the blue range.

With pumping at 808 nm and emission in the range of 884–899 nm, the Nd:YAG is a quasi-three-level system with a lower laser level strongly thermally populated. It is even a true three-level system for emission at 869 nm. To face the strong reabsorption at the lasing wavelength, the population inversion must be high enough.

Thus, simulations have been carried out in order to investigate whether a standard crystal (3 mm long, 0.5% doped) can be an amplifier at these wavelengths, with a classical pump laser diode of 9 W at 808 nm, with an M^2 (optical quality factor of the source) of 80, focused on a 50 μm waist radius. Thanks to a theoretical model[8] regarding the pump propagation and the equations of population of a quasi-three-level laser, we can define the small-signal gain $g_0(z)$ per unit length:

$$g_0(z) = N\frac{\sigma_{el}\sigma_P I_P(z) - \sigma_{al}A}{\sigma_P I_P(z) + A}, \qquad (1)$$

where N (cm^{-3}) is the density of neodymium ions in the crystal according to the doping percentage, σ_P (cm^{-2}) the absorption cross section at the pump wavelength (808 nm), A (s^{-1}) the inverse of the fluorescence lifetime. $I_P(z)$ is the pump intensity versus

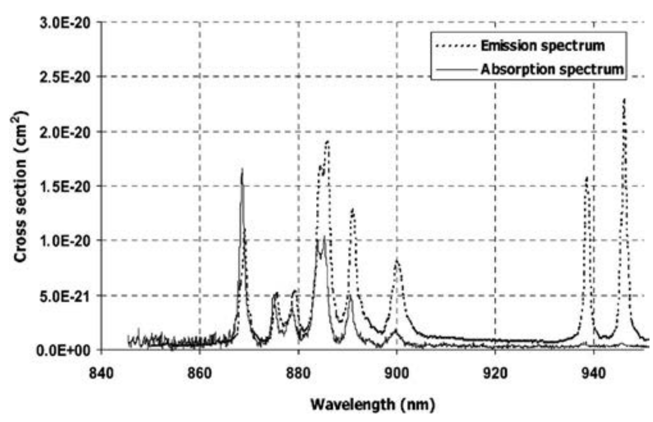

Fig. 1. Spectroscopy of Nd:YAG, centered on the $^4F_{3/2}-^4I_{9/2}$ transition.

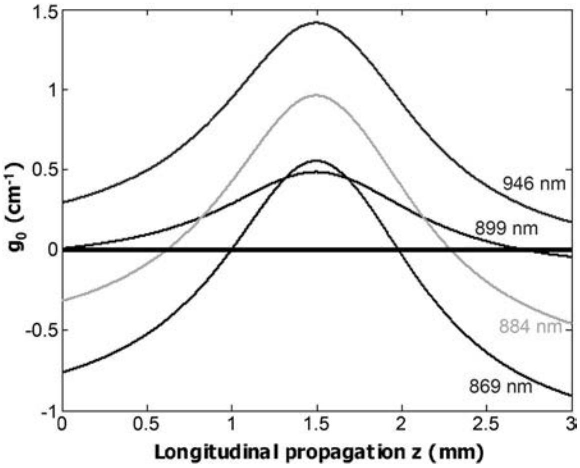

Fig. 2. Evolution of the small-signal gain versus z for different short wavelengths.

Table 1. Calculated Effective Gain at Maximum Pump Power and Verification of the Oscillation Condition

Wavelength (nm)	946	938	899	884	869
$G_0(\lambda)$	1.24	1.16	1.06	1.06	0.93
$T(\lambda)$	0.47	0.71	0.038	0.02	0.015
$G_0^2(\lambda)(1-L(\lambda))$	0.81	0.39	1.08	1.10	0.84

the longitudinal abscissa in the crystal, and σ_{el} and σ_{al}, respectively, are the emission and absorption cross sections at the lasing wavelength.

Figure 2 gives the theoretical g_0 for a pump beam focused at the center of the crystal: the medium is absorbent for a negative small-signal gain and is an amplifier for a positive one. As expected, the medium presents gain around the focus point, but reabsorption is predominant at the two extremities of the crystal, where the effects of the pump defocus are the strongest.

To know whether the crystal was an amplifier, we have calculated (Table 1) the effective gain defined as follows:

$$G_0 = \exp\left(\int_0^L g_0(z)\mathrm{d}z\right). \tag{2}$$

Despite strong reabsorption, the crystal can be a laser amplifier down to 884 nm; yet, under our conditions at 869 nm it seems theoretically impossible to obtain laser oscillation with this 3 mm long crystal. Nevertheless, simulations have shown that with a 1.5 mm long crystal, 0.5% doped, the calculated effective gain would be 1.03 at 869 nm, demonstrating the feasibility of laser operation with a true three-level laser in Nd:YAG.

Thus, the gain simulations show that laser oscillation below 938 nm should be possible; however, we have to face strong line competition, in particular, the gain at 946 nm is much higher. So the cavity must use some spectral elements to avoid laser oscillation at 946 nm or even 938 nm.

The experimental setup used is described in Fig. 3 (Case A). The pump source was a 0.22 numerical aperture, 100 μm core diameter fiber-coupled laser diode, emitting at 808 nm, up to 9 W. The pumping beam output was imaged with two doublets (60 mm focal length) into the Nd:YAG crystal with a waist radius of 50 μm inside. Directly coated on the Nd:YAG crystal, the first mirror of the cavity is highly transparent at the pump wavelength and highly reflective at approximately 900 nm. The second mirror is highly transparent at 1064 nm, to suppress the parasitic emission, and highly reflective at approximately 900 nm. Finally, the third mirror is an output coupler whose transmission curve is given in Fig. 3. This coupler is the key of the lasing oscillation below 938 nm in Nd:YAG.

The inset in Fig. 3 shows that M_3 transmission rapidly increases after 900 nm. We define the cavity losses by L:

$$L(\lambda) = L' + T(\lambda), \tag{3}$$

where L' is the term corresponding to the passive losses of the cavity, estimated at $\sim 1\%$, and $T(\lambda)$ the transmission of M_3. To reach the oscillation threshold, the gain and losses at the wavelength λ must verify

$$G_0^2(\lambda)(1 - L(\lambda)) > 1. \tag{4}$$

Table 1 shows that oscillation threshold can be obtained at 899 and 884 nm, and avoided at 946 and 938 nm.

Experimentally, laser oscillation was obtained only at 899 nm with the mirror M_3 as output coupler. The laser performance is presented in Fig. 4. M_3 had transmission of 2.8% at 899 nm; the laser threshold was ~ 3 W of incident pump power, and the maximum cw output power was 630 mW nonpolarized, corresponding to a slope efficiency of 11% with respect to the incident pump power.

Despite a product $G_0^2(\lambda)(1-L(\lambda))$, nearly equivalent at 884 and 899 nm, laser oscillation was not observed at 884 nm. This can be understood by means of Fig. 5, which shows the evolution of the effective gain with respect to the incident pump power at 899 and 884 nm. For low incident power, there is a higher gain at 899 nm, involving the start of the emission at this wavelength, using all the available gain, and preventing other wavelengths from oscillating.

Laser emission at wavelengths other than 899 nm can be achieved by inserting a 25 μm Fabry–Perot etalon into the cavity. Thus, lasing oscillation has been demonstrated at 891, 885, and 884 nm without line competition. The measured output power varied from 16 mW at 884 nm to 325 mW at 899 nm.

As the best performance was obtained at 899 nm, we tried SHG at this wavelength. We modified the cavity to reduce the cavity losses and to add a second waist. A highly reflective concave mirror at 899 nm with high transmission at 946 and 938 nm replaced the output coupler (Fig. 3, Case B). This architecture

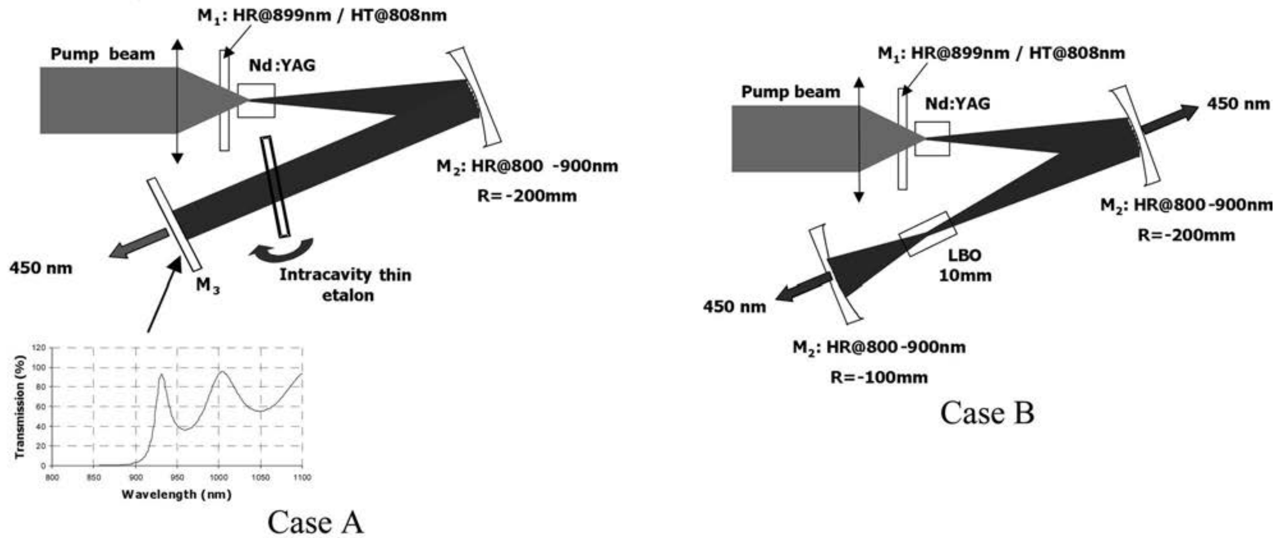

Fig. 3. Experimental setup. M_1, HT at 808 nm, HR at 899 nm; M_2, HR at 800–900 nm, radius = −200 mm. Case A: M_3, flat mirror, T = 2.8% at 899 nm and 46% at 946 nm. Case B: M_3: concave mirror, HR 800–900 nm, radius = −100 mm.

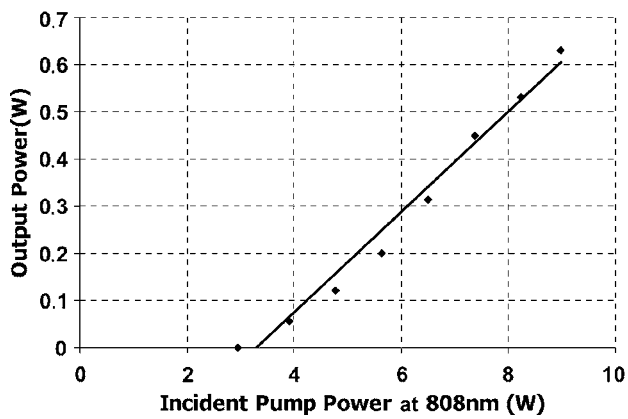

Fig. 4. Laser performances in cw operation with a 2.8% output coupler at 899 nm.

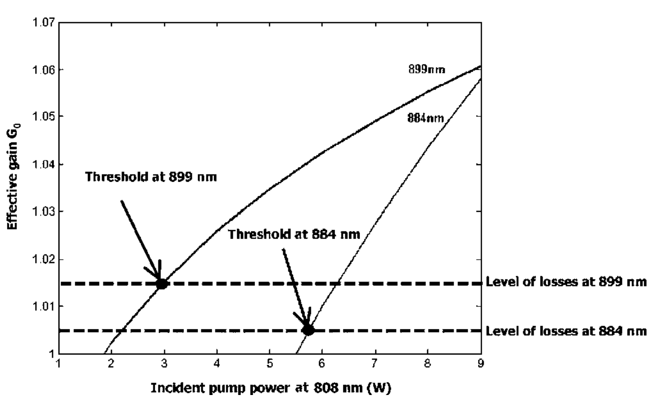

Fig. 5. Evolution of the effective gain G_0, with respect to the incident pump power.

increases the intensity into the nonlinear crystal and thus efficiency of the nonlinear conversion.

The largest blue power obtained was with a 10 mm long type-I phase-matched ($\theta = 90°$, $\varphi = 22.86°$) LiB_3O_5. With only 25 W of intracavity power at 899 nm (due to the passive losses induced by the mirrors), we achieved in cw operation a total output blue power of 100 mW on two output beams.

We have demonstrated for the first time, to the best of our knowledge, laser emission at 899 nm and below in Nd:YAG crystal. For the 899 nm emission, with a 3 mm long, 0.5% doped crystal, a cw output power of 630 mW was achieved, to be compared with 580 mW at 903 nm for 9 W of incident pump power in Nd:YLF.[3] After the SHG, a total power of 100 mW at 450 nm was obtained on two output beams. Thus, this experiment opens a new way to reach deepest wavelengths in the blue range. Further improvements of the spectral selectivity of the cavity and the crystal length should allow us to reach the zero line transition at 869 nm and the use of more efficient nonlinear crystals, such as BiBO or $KNbO_3$, should increase the blue power. Moreover, integration in microchips configuration with lower level of losses will be explored in order to improve the efficiency of the architecture.

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