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1064 nm Nd:YVO₄ laser intracavity pumped at 912 nm and sum-frequency mixing for an emission at 491 nm

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We present for the first time a Nd:YVO₄ laser emitting at 1064 nm intracavity pumped at 912 nm by a Nd:GdVO₄ laser. We carried out a model to design the system properly, and laser performance was experimentally investigated. Intracavity sum-frequency mixing at 912 and 1064 nm was then realized in a BiBO crystal to reach the blue range. We obtained a cw output power of 155 mW at 491 nm with a pump laser diode emitting 20 W at 808 nm. © 2008 Optical Society of America

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These past few years, there has been extensive research to replace the Ar-ion laser around 488 nm [1]. One way is sum-frequency mixing between two transitions of the neodymium ion (${}^4F_{3/2}-{}^4I_{11/2}$ and ${}^4F_{3/2}-{}^4I_{9/2}$) in vanadate crystals: Nd:YVO₄ emitting at 1064 and 914 nm or Nd:GdVO₄ emitting at 1063 and 912 nm. However, dual-wavelength operation with the same laser medium in the same cavity is rather difficult at these particular wavelengths because of strong gain competition between the very efficient transition ${}^4F_{3/2}-{}^4I_{11/2}$ around 1064 nm and the quasi-three-level transition ${}^4F_{3/2}-{}^4I_{9/2}$ around 914 nm having an emission cross section 20 times lower. As demonstrated in [2], one way is to use two crystals (one for emission around 1064 nm and one for emission around 914 nm) in two different cavities sharing a common part for intracavity sum-frequency mixing. However, two pump focus points at 808 nm are needed (one for each crystal) for efficient laser action under diode pumping. This leads to an increase of the complexity of the pumping setup.

In this Letter, we propose a more simple architecture where the diode is pumping only the Nd:GdVO₄ crystal used as laser medium at 912 nm, and the 912 nm emission is pumping the 1064 nm transition (Fig. 1). Pumping a Nd:YVO₄ crystal at 912 nm is possible because the lower level of this ${}^4F_{3/2}-{}^4I_{9/2}$ transition is thermally populated, and also because the absorption is a few nanometers broad in this range as shown in Fig. 2. Even if the absorption is rather low, it can be enhanced if the crystal is put inside the cavity operating at 912 nm to take benefit from the high intracavity power.

The choice of crystals (Nd:GdVO₄ for emission at 912 nm and Nd:YVO₄ for emission at 1064 nm) was guided by laser performance. Indeed, the emission cross section at 912 nm is higher in Nd:GdVO₄ than the one at 914 nm in Nd:YVO₄ [3]. Moreover, the emission cross section at 1064 nm is higher in Nd:YVO₄.

Figure 3 gives the basic principles of this new source at 491 nm. The cavity at 1064 nm is completely included in the cavity at 912 nm. Thanks to the large confocal parameter available with a TEM₀₀ laser beam, the same focus point at 912 nm is used both for pumping the Nd:YVO₄ crystal (with an excellent overlap between pump and cavity beams) and for the sum-frequency mixing crystal, hence reducing the complexity of the overall system. In this configuration, the beams also have a very good overlap in the nonlinear crystal without any additional alignment. This “intracavity pumping” configuration has already been carried out in the middle infrared with Ho doped crystals pumped by a Tm laser [4–6], but to our knowledge, it is the first time that it is implemented in the near infrared.

One key parameter is the absorption of the intracavity pumped Nd:YVO₄ crystal. If it is too low, the absorption is not high enough, and the emission at 1064 nm will be weak. On the opposite side, if the absorption is too high, it will introduce large losses for the cavity at 912 nm, reducing laser emission at this wavelength. As we are interested in sum-frequency mixing, one has to pay attention to the product of the intracavity powers in the nonlinear crystal. Hence, to design the laser, we first carried out a simulation op-

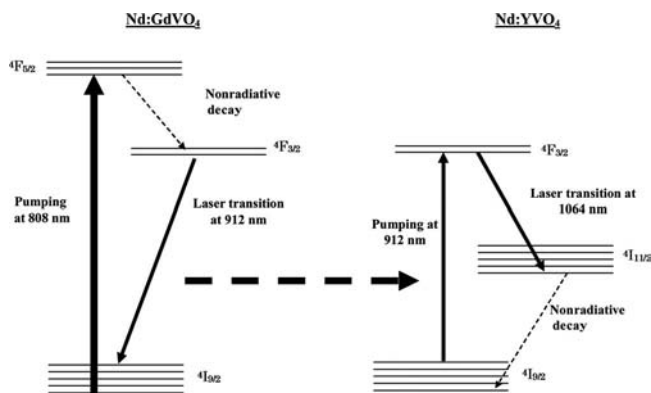


Fig. 1. Principle of the cascade pumping.

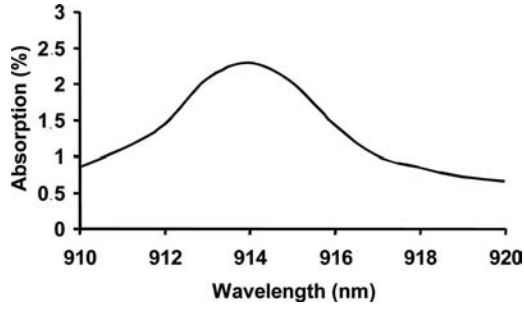


Fig. 2. Absorption in a Nd:YVO₄ crystal at room temperature (5 mm long, 0.1% doping level) around 914 nm.

timizing this parameter versus the absorption of the Nd:YVO₄ crystal.

For that purpose we use a model derived from the one proposed by Augé *et al.* [7]. It calculates the gain per double pass at 912 nm G_{912} integrated over the whole crystal, knowing the gain coefficient G_{912} at each point in the crystal. Signal and pump beam propagations are taken into account, as well as the temperature profile in the laser crystal. To achieve laser oscillation, this gain has to equal the round-trip losses. As we used a high reflective cavity, the round-trip losses include only the passive losses L_{912} and the absorption at 912 nm in the second laser crystal (Nd:YVO₄). We can then write

$$G_{912} = \frac{1}{(1 - L_{912})e^{-2\sigma_a^{912}Nl}}, \quad (1)$$

where σ_a^{912} is the effective absorption cross section at 912 nm, N is the total population density in the Nd:YVO₄ crystal, and l is its length. As described in [7], G_{912} is a decreasing function of the intracavity intensity at 912 nm I_{912} . Hence, Eq. (1) is solved by adjusting the value of I_{912} .

The same method is used to calculate the intracavity intensity I_{1064} at 1064 nm, coming from laser emission in the Nd:YVO₄ crystal. This time, the laser transition is on four levels. The gain coefficient can then be written as

$$G_{1064} = \sigma_e^{1064}N \frac{\sigma_a^{912}I_{912}}{\sigma_a^{912}I_{912} + 1/\tau + \sigma_e^{1064}I_{1064}}, \quad (2)$$

where σ_e^{1064} is the emission cross section of Nd:YVO₄ at 1064 nm.

The gain per double pass integrated over the whole crystal, G_{1064} , can be found using [8] knowing Eq. (2). As the second cavity oscillates at 1064 nm, G_{1064}

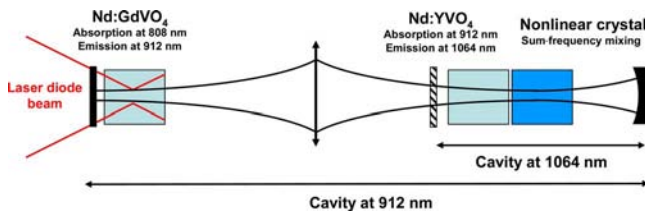


Fig. 3. (Color online) Principle of the intracavity pumping and sum-frequency mixing.

must equal the round-trip losses at 1064 nm following Eq. (3). In our case, the cavity at 1064 nm is also a high reflective cavity with losses denoted as L_{1064} ,

$$G_{1064} = \frac{1}{(1 - L_{1064})}. \quad (3)$$

The calculations were carried out for a Nd:GdVO₄ crystal optimized for laser emission at 912 nm having a length of 4 mm and a doping concentration of 0.2% [2] and with a pump power of 20 W coming from a fiber-coupled laser diode (200 μ m core diameter, NA 0.2).

The optimal absorption of the second crystal will be derived from the simulations. To be independent of the beam size in each crystal, Fig. 4 displays the intracavity powers P_{912} and P_{1064} instead of the intracavity intensities I_{912} and I_{1064} . The relationship between the power and the intensity at 912 nm (assuming a Gaussian beam shape) at a given position is

$$P_{912} = \frac{h\nu\pi w_{912}^2}{2} I_{912}, \quad (4)$$

where ν is the frequency corresponding to 912 nm. The same expression can be given for P_{1064} . As we use low-loss cavities, the intracavity powers are the same whatever the position in the resonators. Hence P_{912} and P_{1064} represent the intracavity power in the nonlinear crystal. Figure 4(a) gives P_{912} and P_{1064} versus the losses induced by the Nd:YVO₄ crystal. As expected, the greater the absorption, the weaker the intracavity power at 912 nm, whereas P_{1064} reaches a maximum value.

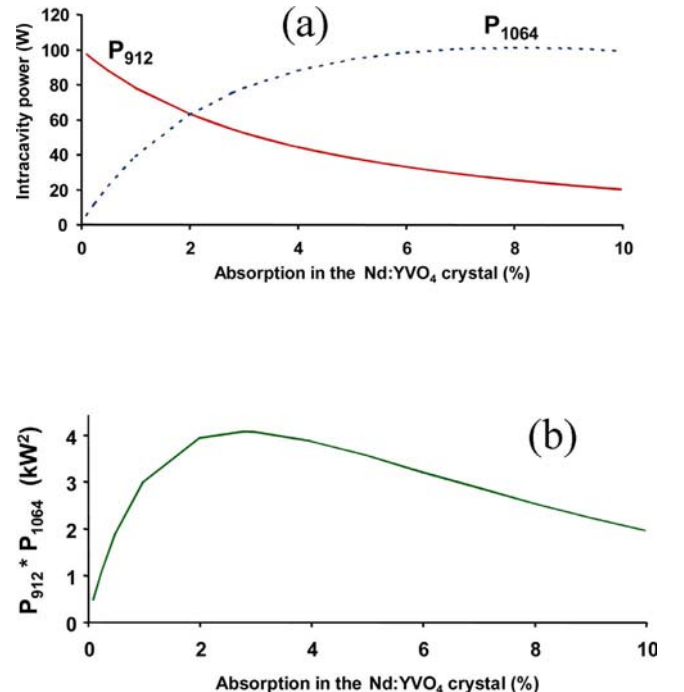


Fig. 4. (Color online) (a) Simulated intracavity powers at 912 and 1064 nm and (b) product of intracavity powers $P_{912} \times P_{1064}$ versus absorption in the Nd:YVO₄ crystal.

Figure 4(b) presents the product of the intracavity powers $P_{912} \times P_{1064}$. It is maximum for a double-pass absorption in the Nd:YVO₄ of 2.8% at 912 nm. This value is very low, but as the intracavity power is on the order of 50 W, the absorbed pump power for the Nd:YVO₄ can reach the watt level, leading to high intracavity power at 1064 nm.

This low absorption can be achieved by standard crystals. For example, Fig. 2 shows the absorption spectrum for a 5 mm long 0.1% doped Nd:YVO₄ crystal around 914 nm. This transition is wide enough to induce approximately 1.2% losses at 912 nm for a single pass. Hence the double-pass losses (2.4%) are close to the calculated optimum [2.8%, see Fig. 4(b)]. The experimental setup is illustrated by Fig. 5. The pump source (fiber-coupled laser diode) and the Nd:GdVO₄ crystal characteristics are the ones described in the simulations. The pump fiber output was relay imaged into the first Nd:GdVO₄ laser crystal by two doublets to obtain a pump spot diameter of 200 μm . Following the computer simulations, we used a weakly doped (0.1%) and short (5 mm) Nd:YVO₄ crystal for laser emission at 1064 nm. Both vanadate crystal faces were antireflection (AR) coated at 912 and 1064 nm. The crystals were mounted in a water-cooled copper heat sink. The nonlinear crystal was a BiBO [9], 10 mm long and both sides AR coated at 912 and 1064 nm. It was cut for room temperature type I phase matching ($\theta=164.1^\circ$, $\varphi=90^\circ$).

Four mirrors composed the cavity operating at 912 nm (M1, M2, M3, and M5). M1, M2, and M3 were coated for high reflection (HR) at 912 nm and high transmission (HT) at 1063 nm to prevent any gain competition in the first Nd:GdVO₄ crystal. M2 is a folding mirror used to increase the losses at 1063 nm. The Nd:GdVO₄ was placed at the first cavity waist (calculated diameter 180 μm); the Nd:YVO₄ crystal was at the second waist plane (calculated diameter 180 μm). The 1064 nm cavity consisted of two mirrors, M4 and M5, having a HR coating at 1064 nm. Mirror M4 was thus inside the 912 nm cavity. Despite a transmission measured at 83% at 912 nm, the insertion losses of M4 were estimated to be only 3.1% (by measurement of the intracavity power with or without M4). These lower than expected losses are due to etalon effects, as M4 is a plane and parallel

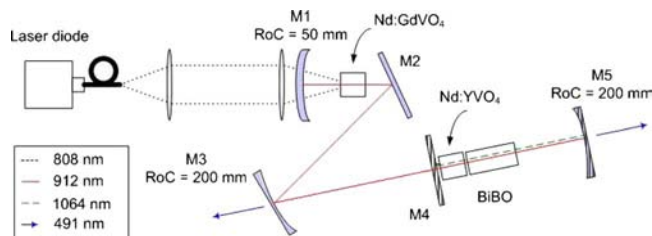


Fig. 5. (Color online) Experimental setup. M1, M2, M3, and M5 are HR at 912 nm and define the cavity at 912 nm. M4 and M5 are HR at 1064 nm and define the cavity at 1064 nm. M1 is HT at 808 nm. M2 and M3 are also HT at 1064 nm. The distance M1–M3 is 240 mm. The distance M3–M5 is 395 mm.

plate perpendicular to the optical axis. M4 is put very close to the Nd:YVO₄ crystal and the BiBO. The calculated beam diameter at 1063 nm was around 200 μm in the BiBO.

With this configuration, we recorded an oscillation threshold at 18 W incident on mirror M1 (pump power at 808 nm). This high threshold level is related to high intracavity losses in the 912 nm cavity (induced by mirror M4 and the Nd:YVO₄ crystal). At 20 W, we obtained an intracavity power of 54 W at 912 nm and 75 W at 1064 nm. We achieved a power of 155 mW at 491 nm (sum of the two outputs through mirrors M3 and M5), corresponding to an optical–optical efficiency of 0.77%. The beam mode was TEM₀₀.

Schellhorn *et al.* [6] have noticed a pulsed mode behavior while intracavity pumping a Ho:YAG rod with a Tm:YLF laser. We recorded temporal waveforms for emission at 912 and 1064 nm with a fast photodiode (1 ns rise time), and pulsed behavior has not been observed. Indeed, the Nd:YVO₄ crystal did not act as a saturable absorber. This is mainly due to a high saturation intensity caused by a great difference between the emission cross section at 912 and 1064 nm in this crystal. The upper emitting level in Nd:YVO₄ also has a much shorter lifetime (100 μs) than the one for Ho:YAG (10 ms).

In conclusion, we present for the first time to our knowledge a Nd:YVO₄ laser at 1064 nm pumped on the $^4F_{3/2}$ – $^4I_{9/2}$ transition at 912 nm. Computer calculations allowed us to determine the optimal conditions to perform sum-frequency mixing to reach blue range at 491 nm; in our conditions of pumping, we demonstrated that the absorption in the Nd:YVO₄ crystal must be weak, around 2.8%. We experimentally validated this new pumping concept by realizing a blue laser source with an output power of 155 mW at 491 nm. Considering the high intracavity powers (more than 50 W at both wavelengths), it would be possible to produce more blue with a more efficient nonlinear crystal, such as KNbO₃ or ppKTP.

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