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491 nm generation by sum-frequency mixing of diode pumped neodymium lasers

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Abstract: We present three different dual-wavelength laser architectures to obtain cw blue radiations. They are based on diode-pumped Nd-doped crystals lasing on the ${}^4F_{3/2}$ - ${}^4I_{11/2}$ and ${}^4F_{3/2}$ - ${}^4I_{9/2}$ transitions. Blue radiations were achieved by intracavity sum frequency operation in a BiB_3O_6 crystal. We report a maximum output blue power of 303 mW at 491 nm for a pump power of 10 W.

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OCIS codes: (140.7300) Visible laser; (140.3480) Lasers diode-pumped

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1. Introduction

Lasers emitting in the visible range are useful in many fields, such as full-colour displays, astronomy or biology. Within these past few years, extensive research to find more efficient and more compact lasers with simpler architecture was carried out [1]. New solid state lasers were designed to enlarge the panel of wavelengths, for example in the yellow range, or to improve sources already used, as in the blue range. One of the greatest effort deals with the replacement of the Ar-ion laser around 488 nm.

Efficient continuous lasers in the visible range are usually based on the same principle: intracavity frequency doubling of a diode pumped solid state laser. For example, very efficient laser was obtained at 473 nm [2]. This configuration can not be directly used to reach 488 nm because of the lack of rare earth doped crystal emitting at 976 nm. However, other sources at 976 nm were explored, such as laser diode [3], vertical-extended-cavity surface emitting semiconductor laser [4], optically pumped semiconductor laser [5] or co-doped Pr-Yb fibre laser [6]. The most powerful configuration offers a cw power of 15W at 488 nm [7] for a pump power of 80 W, but most of other solutions offer a power around 50 mW of blue power [8].

Another solution to reach 488 nm is to use sum frequency operation instead of simple second harmonic generation. This has already been demonstrated to reach the yellow range [9]. In our case, the transitions ${}^4F_{3/2}$ - ${}^4I_{11/2}$ and ${}^4F_{3/2}$ - ${}^4I_{9/2}$ of the neodymium ion produce radiations around 1060 nm and 900 nm respectively. By sum-frequency operation between these two radiations, blue emissions can then be achieved around 488 nm.

In this paper, we propose to explore more into details this solution. We present three architectures, all based on intracavity sum-frequency in a BiB_3O_6 (BiBO) crystal [10]. The first configuration is based on a dual-wavelength laser at 912 nm and 1063 nm. Both laser lines were produced in the same Nd:GdVO₄ laser crystal. Although dual-wavelength operation between two four level systems is a concept widely used, dual-wavelength operation between a four level system and a quasi-three level one has first been presented only few months ago in Nd:YAG [11]. Indeed, in a quasi-three level system, a lower effective emission cross-section and reabsorption losses lead to a smaller gain, and hence a line competition more complex to manage than in the case of two four-level-transitions. The second configuration is based on two laser crystals, Nd:YLF (1047 nm) and Nd:GdVO₄ (912 nm), to avoid line competition. They are placed in the same cavity and pumped by the same diode laser. Finally the last architecture is based on two separate lasers linked by a common arm, where the non-linear crystal is placed.

2. Dual-wavelength operation in a single Nd:GdVO4 laser crystal

We propose to obtain continuous blue radiation around 488 nm by sum-frequency mixing the waves from two transitions of the neodymium (${}^4F_{3/2}$ - ${}^4I_{11/2}$ and ${}^4F_{3/2}$ - ${}^4I_{9/2}$). The simplest architecture is to use a single laser crystal, operating at the two wavelengths. The main disadvantage of this configuration is the line competition in the laser crystal. To quantify this competition, we propose, both theoretically and experimentally, to investigate it.

To achieve the dual-wavelength oscillations, a key parameter is the gain coefficient (cm^{-1}) at each wavelength. In four and quasi three level systems it can be written as [13]:

$$g_{1063} = \sigma_{1063} f_b N_2 \quad (1)$$

$$g_{912} = \sigma_{912} f_b N_2 - \sigma_{912} f_a N_1 \quad (2)$$

where g_{1063} and g_{912} are the gain coefficients at 1063 nm and 912 nm respectively and σ_{912} and σ_{1063} are the emission cross sections at these wavelengths. f_a and f_b represent the fraction of the ${}^4I_{9/2}$ and ${}^4F_{3/2}$ populations that reside in the Stark component used as the lower and upper laser level of 912 nm respectively. N_1 and N_2 are the population of the ${}^4I_{9/2}$ and ${}^4F_{3/2}$

levels respectively. The relative populations of the levels are given by a Boltzman distribution.

The ratio of the gains, from Eq. (1) and Eq. (2) can be expressed as:

$$\frac{g_{912}}{g_{1063}} = \frac{\sigma_{912}}{\sigma_{1063}} \left(1 - \frac{f_a N_1}{f_b N_2} \right) \quad (3)$$

Equation (3) shows that the ratio of the emission cross section is a key parameter. To choose the laser crystal, we estimated this ratio for most common Nd-doped crystals emitting around 900 nm. The results are presented in the Table 1.

Table 1. Comparison between different Nd-doped crystals emitting around 900 nm.

Crystal	Nd:YAG	Nd:GGG	Nd:YAIO ₃	Nd:YLF	Nd:YVO ₄	Nd:GdVO ₄
λ_1^a (nm)	1064	1062	1079	1047	1064	1063
λ_2^a (nm)	946	937	930	908	914	912
$\lambda_1 + \lambda_2$ (nm)	501	498	499	486	492	491
$\frac{\sigma_2}{\sigma_1}$	0.09	0.28	0.09	0.06	0.04	0.06

^aIndex 1 corresponds to the four level system, index 2 corresponding to the quasi-three level system

Despite a favourable emission cross section ratio, Nd:YAG, Nd:GGG and Nd:YAIO₃ lead to a sum frequency emission too far away from 488 nm. Nd:YLF and Nd:GdVO₄ present the same ratio of emission cross section. We finally chose the Nd:GdVO₄ crystal because its absorption is greater at 808 nm, corresponding to a standard wavelength for high power laser diodes and for its better thermal properties.

The experimental setup for the two fundamental wavelength laser operation is shown in Fig. 1. The pump source was a fibre-coupled diode at 808 nm with a core diameter of 100 μ m, a numerical aperture of 0.22 and provided a maximal power of 10 W. The fibre output was relay-imaged into the crystal by two doublets to obtain a pump spot diameter of 170 μ m. The gain medium was a 4-mm thick 0.2 % doped Nd:GdVO₄ crystal placed into a copper mount. This mount was water cooled and regulated with a Pelletier thermoelectric cooler to set its temperature at 18 °C. Both sides of the rod were AR coated at 808 nm, 912 nm and 1063 nm. The mirrors M4 and M5 were used to control the relative intensity between the two laser lines and to adjust the waist of the beam at 1063 nm in the crystals. In the gain medium, the size of the waist was 70 μ m at 912 nm and could be adjusted from 70 μ m to 105 μ m at 1063 nm. In the non-linear crystal, the waist was 70 μ m at 1063 nm and 69 μ m at 912 nm. The non-linear crystal was a BiB₃O₆ (BiBO). It was 10-mm-long with both sides AR-coated at 912 nm and 1063 nm.

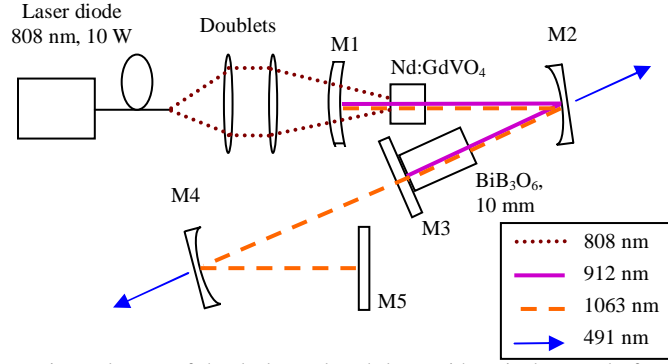


Fig. 1. Experimental setup of the dual-wavelength laser with a single crystal of Nd:GdVO₄. M1: HT@808 nm, HR@912 nm, RoC=50 mm, R= 77% @1063 nm, M2: HR@912 nm + 1063 nm, RoC=100 mm, M3: HR@912 nm, HT@1063 nm, M4: HR@1063 nm, RoC=200 mm, M5: T=6 % @1063 nm

To adjust all the experiment parameters, such as the beam waist at 1063 nm in the gain medium or the influence of gain competition between the two wavelengths on intracavity intensities and power, a precise modelization was required.

The rate equation for the lower manifold, using previous notations, can be expressed as:

$$\frac{dN_1}{dt} = -\sigma_p I_p N_1 - \sigma_{912} I_{912} f_a N_1 + A N_2 + \sigma_{1063} I_{1063} f_b N_2 + \sigma_{912} I_{912} f_b N_2 \quad (4)$$

where σ_p is the effective absorption cross section for the pump transition, I_p is the pump intensity, I_{912} and I_{1063} are the intracavity intensities at 912 nm and 1063 nm respectively and A is the spontaneous emission rate.

By solving Eq. (4) in the steady-state regime and defining the total population density N by $N=N_1+N_2$, we find:

$$N_1 = N \frac{A + \sigma_{912} I_{912} f_b + \sigma_{1063} I_{1063} f_b}{A + \sigma_{912} I_{912} (f_b + f_a) + \sigma_{1063} I_{1063} f_b + \sigma_p I_p} \quad (5)$$

A linear relationship between the intracavity intensities, I_{912} and I_{1063} , can be derived from Eq. (3) and Eq. (5):

$$I_{912} = -\left(\frac{g_{912}}{g_{1063}}\right)^{-1} I_{1063} + K \quad (6)$$

where K is a parameter dependent on g_{1063} , g_{912} , σ_{912} , σ_{1063} , σ_p , A , f_a , f_b and I_p but independent on I_{1063} . The ratio g_{912}/g_{1063} being low, the slope is great.

To investigate the line competition more precisely, we compute the emission at 912 nm as a function of the emission at 1063 nm.

The gain coefficient at 912 can be derived from Eq. (2) and Eq. (4):

$$g_{912} = N \frac{\sigma_p I_p f_b \sigma_{912} - A f_a \sigma_{912} - \sigma_{1063} I_{1063} f_b f_a \sigma_{912}}{A + \sigma_{912} I_{912} (f_b + f_a) + \sigma_{1063} I_{1063} f_b + \sigma_p I_p} \quad (7)$$

The final expression of the gain G per double pass integrated over the whole crystal can be expressed as [14]:

$$G = \left[1 + \int_0^l dz \int_0^{r_c} \frac{4g(r, z)}{w_c^2(r, z)} \exp\left(\frac{-2r^2}{w_c^2(r, z)}\right) r dr \right]^2 \quad (8)$$

where l is the crystal length and r_c is the crystal radius.

To achieve laser oscillation, the round-trip gain has to be equal to the round-trip losses. Assuming low intracavity losses, we can write:

$$G = \frac{1}{1 - T_{\text{out}} - L} \quad (9)$$

where T_{out} is the transmission of the output coupler and L are the cavity passive losses.

Equation (9) was numerically solved, adapting the model presented by Auge et al. to our configuration [13]. This model takes into account the profiles of the beams, considered to be circular Gaussian, the pump beam quality through its M^2 factor and the propagation of the beams in the laser crystal. The local temperature in the crystal is also computed using the quantum defect and the thermal conductivity of Nd:GdVO₄. For a pump power of 10 W and for several values of intracavity power at 1063 nm and several waists in the laser crystal of the beam at 1063 nm, we obtained the curves presented in the Fig. 2.

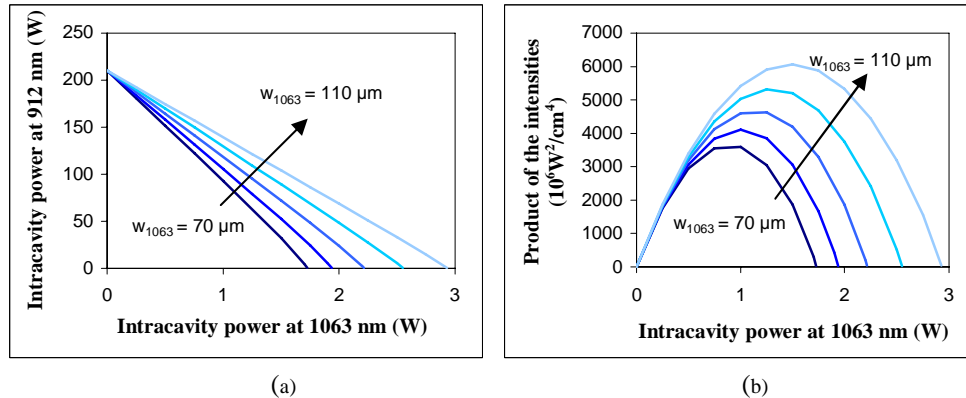


Fig. 2. Influence of the waist size of the laser at 1063 nm in the Nd:GdVO₄ crystal on the gain competition (a) Evolution of the intracavity intensity of the 912 nm radiations versus the intracavity intensity of the 1063 nm radiations – (b) Product of the two intracavity intensities in the non-linear crystal).

We can see that the intracavity powers of the two laser lines are linearly dependent. Figure 2(a) shows that to achieve high intracavity power at 912 nm, intracavity power at 1063 nm must be kept at a very low level: only a few watts at 1063 nm are necessary to vanish the 912 nm line.

This figure also shows that the larger the waist at 1063 nm, the weaker the line competition between 912 nm and 1063 nm. This can be explained by a worse overlap between the beam at 1063 nm and the pump beam when its waist increases from 70 μm to 110 μm (the pump beam radius remaining at 85 μm). The gain at 1063 nm can thus be decreased.

The efficiency of non-linear operations strongly depending on the product of the intracavity intensities in the non-linear crystal, this product must be as high as possible. Figure 2(b) shows this product versus the intracavity power at 1063 nm for different waists of the beam at 1063 nm in the laser crystal. For a given size of the beam at 1063 nm in the non-linear crystal, by increasing the waist at 1063 nm in the laser crystal, the product of the intracavity intensities can be considerably improved.

In the final experiment setup, we set the waist of the beam at 1063 nm in the Nd:GdVO₄ crystal at 105 μm and its waist in the BiBO crystal at 70 μm. The waist in the BiBO was then close to the one of the beam at 912 nm.

First, we investigated experimentally the gain competition. The mirror M5 was quite highly reflective at 1063 nm (T=6%). By misaligning this mirror, the intracavity losses were adjusted to modify the intracavity power at 1063 nm from 0 W to 2.8 W. As predicted, one can see in Fig. 3(a) a strong competition between the two laser lines revealed by an intracavity power decrease at 912 nm versus intracavity power at 1063 nm.

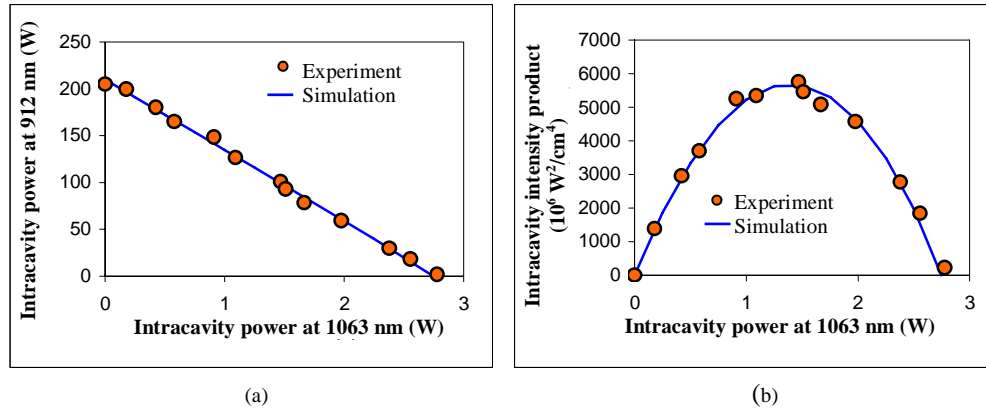


Fig. 3. (a) Evolution of the intracavity intensity of the 912 nm radiations versus the intracavity intensity of the 1063 nm radiations –(b) Product of the two intracavity intensities in the non linear-crystal.

As predicted by the simulations, the two powers were linearly dependent. From 1063 nm intracavity power higher than 2.77 W, the 912 nm radiation vanished. This strong limitation was due to the difference of emission cross sections ($12.5 \times 10^{-19} \text{ cm}^2$ at 1063 nm and only $0.7 \times 10^{-19} \text{ cm}^2$ at 912 nm [15]) and to the re-absorption losses undertaken by the quasi-three level system at 912 nm.

The efficiency of non-linear operations is proportional to the intracavity intensity product of the two fundamental wavelengths. Figure 3(b) representing this product versus the intracavity power at 1063 nm, clearly shows that there was an optimal between the two intracavity powers. This optimum was obtained for 1.5 W at 1063 nm and 101 W at 912 nm, corresponding to intracavity intensities of $8.5 \times 10^3 \text{ W/cm}^2$ at 1063 nm and $675.3 \times 10^3 \text{ W/cm}^2$ at 912 nm in the non-linear crystal.

Using these results, we performed a second experiment using an optimal output coupler (M5) with a transmission of 74% at 1063 nm. The non-linear BiBO crystal was cut for room temperature type I phase matching ($\theta=164.1^\circ$, $\phi=90^\circ$). We demonstrated a total power of 30 mW at 491 nm for two output beams. This blue power was limited by the low power at 1063 nm and by the gain competition. To avoid this gain competition, and thus to increase the power in the blue, one alternative may consists in using two different laser crystals, one for each wavelength.

3. Dual-wavelength operation in Nd:GdVO₄ and Nd:YLF crystals

To avoid gain competition inside a single crystal, we explored a second configuration based on two different laser crystals, one for each wavelength. We chose a Nd:GdVO₄ crystal for the emission around 900 nm because it has a broad absorption around 808 nm and its emission cross section at 912 nm is greater than the one of the Nd:YVO₄ crystal. The second laser crystal had to be transparent at 912 nm. To reduce losses in the cavity, it also needs to have an emission wavelength at which the Nd:GdVO₄ crystal is transparent. For these reasons, we

chose a Nd:YLF crystal, operating at 1047 nm. The blue radiation resulting from the sum-frequency operation was thus at 487 nm. Because of reabsorption losses in the quasi-three level system laser, the pump absorption in the laser crystal must be low to access high population inversion. Only 40 % of the pump power was then absorbed by the Nd:GdVO₄ crystal. The remaining 60 % were used to pump the Nd:YLF crystal. As the quasi-three level system laser presented a lower gain, and was more sensible to intracavity losses, we chose to limit the number of intracavity components at 912 nm, penalizing the radiations at 1047 nm.

Figure 4 illustrates the experimental setup. The pump scheme for both crystals was the same as in the previous experiment, leading to a pump spot diameter of 170 μm in the Nd:GdVO₄ crystal. This crystal was 4 mm thick and with a neodymium concentration of 0.1 %. In the copper mount, we also placed the Nd:YLF crystal. It was 8 mm long and had a neodymium concentration of 1 %. Both sides of the rod were AR-coated at 808 nm, 912 nm and 1047 nm. As the mirrors have a high reflection at 1047 nm but also at 1063 nm, a prism was inserted in the 1047 nm cavity to avoid emission at 1063 nm in the Nd:GdVO₄ crystal.

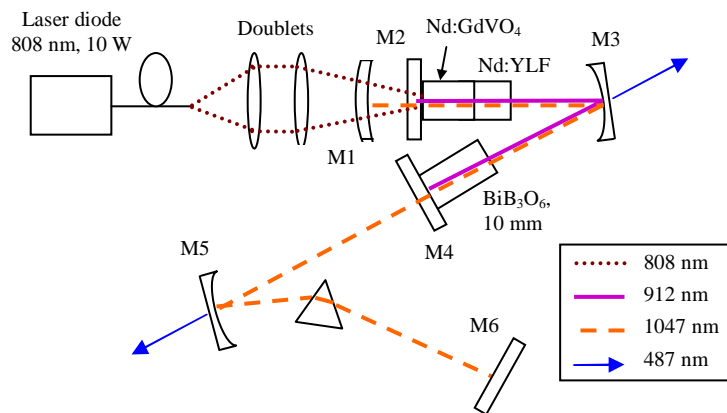


Fig. 4. Experimental setup of the dual-wavelength laser in two laser crystals (Nd:GdVO₄ and Nd:YLF). M1: HT@808 nm, HR@1047 nm, RoC=50 mm, M2: HR@912 nm, HT@808 nm + 1047 nm, M3: HR@912 nm + 1047 nm, RoC=150 mm, M4: HR@912 nm, HT@1047 nm, M5: HR@1047 nm, RoC=1 m, M6: HR@1047 nm.

In this configuration, and with the same non-linear crystal, we obtained 120 W of intracavity power at 912 nm and 7.5 W of intracavity power at 1047 nm, leading to a total blue power of 93 mW for the two output beams.

Thanks to the wavelength shift of neodymium in the two different matrices, gain competition was avoided in this scheme. However blue power was still limited by low intracavity power at 1047 nm. Firstly, the maximum of absorption in Nd:YLF is around 792 nm. To optimize the absorption in Nd:GdVO₄, we chose a laser diode at 808 nm, decreasing the absorption in the Nd:YLF crystal. Secondly, the pump beam was focused in the Nd:GdVO₄ crystal and the laser crystals were much longer than the confocal parameter of the pump beam. The pump beam diameter in the Nd:YLF varied thus from 282 μm to 1154 μm . Finally, additional losses, like the mirrors M4 and M2 or the prism, are present in the cavity at 1047 nm, limiting the laser efficiency.

To improve the efficiency of the two lines, a solution is to build two independent cavities and to link them by a common arm in which the non-linear crystal could be placed. Thus, all the constraints on the wavelength shift in the two laser crystals disappear, and a more efficient crystal at 1064 nm can be used.

4. Dual-wavelength operation in Nd:GdVO₄ and Nd:YVO₄ crystals

One way to reduce the constraints on the second laser crystal is to remove it from the cavity generating the 912 nm. There are thus two independent cavities with a common arm including

only the non-linear crystal. This concept was already presented by Kretschmann et al. [15] in order to produce red radiation. As the two laser crystals are not placed within the same cavity, there is no need in using two crystals with wavelength shifts in their lasing transitions. Indeed, the gain competition is easily avoided. We chose a more efficient crystal lasing at 1064 nm, a Nd:YVO₄ crystal, to replace the Nd:YLF crystal. Its emission cross section at 1064 nm is greater than the one of Nd:YLF at 1047 nm and it has absorption peak at 808 nm. As in the previous experiment, all the pump power was not absorbed by the Nd:GdVO₄ crystal. The remaining pump power was recycled to pump the Nd:YVO₄ crystal.

The experimental setup is shown in Fig. 5. The Nd:YVO₄ crystal is 0.5% doped and 6-mm-long. One of the rod faces is coated AR at 808 nm and high reflecting at 1064 nm; the other face is AR coated at 808 nm and 1064 nm. The same non-linear BiBO crystal was used.

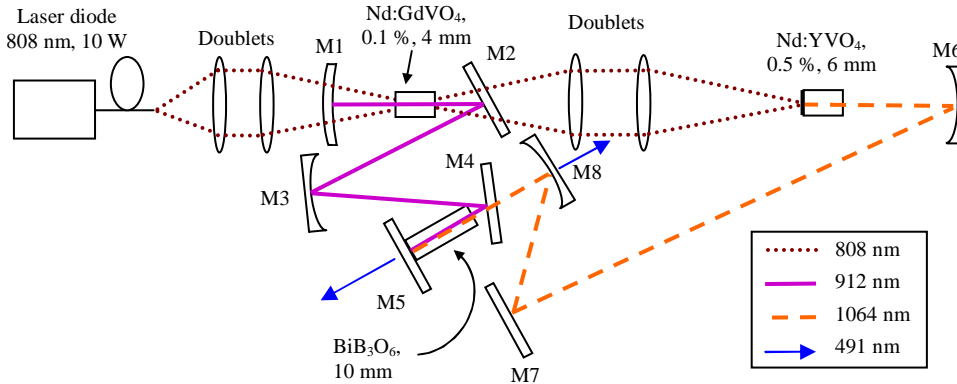


Fig. 5. Experimental setup of the dual-wavelength laser in two laser crystals (Nd:GdVO₄ and Nd:YVO₄). M1: HT@808 nm, HR@912 nm, RoC=50 mm, M2: HR@912 nm, HT@808 nm, M3: HR@912 nm, RoC=200 mm, M4: HR@912 nm, T=96% @1064 nm, T=52% @491 nm, M5: HR@912 nm+1064 nm, T=77% @491 nm, M6: HR@1064 nm, RoC=500 mm, M7: HR@1064 nm, M8: HR@1064 nm, T=85% @491 nm, RoC=350 mm.

Figure 6 shows the intracavity powers at 912 nm and 1064 nm incident on the non-linear crystal versus the pump power. The maximum intracavity power was 106 W at 912 nm and 27 W at 1064 nm for an incident pump power of 10 W on the Nd:GdVO₄ crystal, leading to an intensity product more than three times greater than in the previous configuration. The remaining pump power incident on the Nd:YVO₄ crystal was 4.7 W. The maximum total output blue power at 491 nm was 303 mW for the two output beams, as shown in Fig. 7.

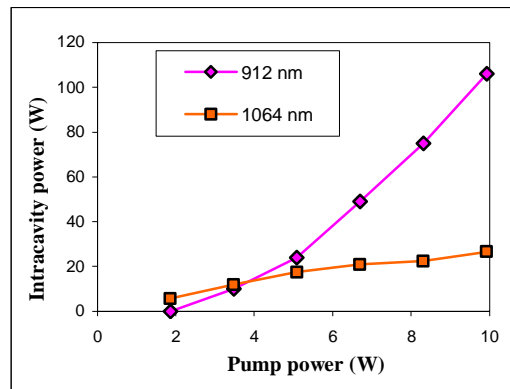


Fig. 6. Intracavity power at 912 nm and 1064 nm versus pump power at 808 nm.

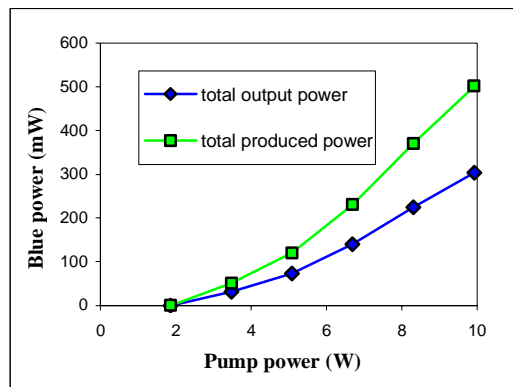


Fig. 7. Total output power and total produced power (see text) at 491 nm versus pump power at 808 nm.

All the mirrors used had not a high transmission at 491 nm. We also present in Fig. 7 the predicted blue power produced in the BiBO crystal if the mirrors were 100 % transmitting in the blue range. The maximum produced blue power would be 501 mW.

The efficiency at 1064 nm is mainly limited by the transmission of the mirror M4, which has a reflection coefficient of 4 % at this wavelength, introducing important losses in the 1064 nm cavity. More blue power could also be obtained by using a more efficient non-linear crystal, such as KNbO₃ or ppKTP. This last configuration is the most complex out of the three presented in this paper, but is also the most efficient.

5. Conclusion

In conclusion, we have presented several architectures producing continuous wave blue radiation. They were based on diode pumped neodymium doped crystals emitting at two wavelengths. Blue radiations were obtained by intracavity sum-frequency operation in a BiBO crystal.

The simplest architecture was based on a dual-wavelength Nd:GdVO₄ laser at 912 nm and 1063 nm. We obtained 20 mW at 491 nm. We demonstrated, theoretically and experimentally, that this configuration is not efficient enough around 488 nm using the existing crystals. However, it could give interesting results at 498 nm, using Nd:GGG. Indeed, this crystal presents an emission cross section ratio more favourable.

The most powerful configuration presented was based on two separate cavities linked in a common arm where the non-linear crystal was placed. We obtained a total output power of 303 mW. This solution has the advantage to avoid gain competition. However, its main drawback is the number of components.

For the moment, the most powerful solution explored to produce a blue radiation to replace Ar-ion laser was the optically pumped semiconductor lasers, with a maximum power of 15 W at 488 nm for a pump power of 80 W [7]. The other diode pumped laser solutions produce less than 50 mW of blue power. Our last solution, using only standard components, with more than 300 mW at 491 nm represents a middle way. Furthermore, the output blue power could again be increased by using more efficient non-linear crystals such as KNbO₃ or ppKTP, or by using a more powerful pump diode. This solution offers a promising alternative to the watt power level continuous blue lasers around 488 nm.