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Frequency doubling of an efficient continuous wave single-mode Yb-doped fiber laser at 978 nm in a periodically-poled MgO:LiNbO$_3$ waveguide

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Abstract: A single-mode Yb-doped fiber laser producing 2 W CW at 978 nm is demonstrated with a high slope efficiency of 72%. Thanks to its narrow bandwidth, lower than 0.02 nm, and its tunability of 6 nm, it has been efficiently frequency doubled in a periodically poled MgO:LiNbO$_3$ waveguide, leading to a power of 83 mW at 489 nm and an internal conversion efficiency of 26 %.

OCIS codes: (060.2320) Fiber optics amplifiers and oscillators; (190.2620) Frequency conversion.

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1. Introduction

High power diffraction-limited continuous wave (CW) sources around 980 nm are attractive to build new blue sources around 488 nm with a nonlinear stage and realize an alternative source for Argon-ion lasers. Solutions based on frequency conversion of semiconductor devices are proposed such as extracavity frequency doubling of extended cavity laser diodes [1] or intracavity frequency doubling of an optically pumped semiconductor laser [2]. Ytterbium-doped materials have also interesting properties around 980 nm. Indeed Yb^{3+} ions present absorption around 915 nm and 980 nm, and have a strong emission cross-section around 980 nm with a true three-level behavior and a lower one around 1030 nm. Emission at 980 nm is thus difficult to obtain in Yb-doped materials, but is expected to be very efficient. Because of the true three-level nature of the transition around 980 nm in Yb^{3+} ions, the pump laser source around 915 nm must be bright enough to reach the transparency intensity of the active area and overcome the ground-state absorption. Although laser emissions at 985 nm in an Yb:S-FAP bulk crystal [3] and at 981 nm in an Yb:KYW bulk crystal [4] have recently been demonstrated with Ti:Sapphire pumping, the performances of crystals are limited by the pump intensity in the crystal. In fact, most of the reported experiments at this wavelength have been done with Yb-doped fibers, since they enable a long interaction and a good overlap of the propagating beams with the active core.

For Yb-doped fibers pumped around 915 nm, the transparency intensity is about 29 kW/cm^2 at 980 nm. With a bright pump source and a short fiber, reabsorption around 980 nm and emission around 1030 nm can be avoided. Efficient cw lasers made with single-mode Yb-doped fibers have been demonstrated at 974 nm [5] or 980 nm with a 946-nm Nd:YAG pump laser [6]. Specific double-clad fibers have been also developed for the laser emission at this transition, like jacketed-air-clad (JAC) fibers with a small inner-cladding to doped core ratio and a high numerical aperture. Although high powers have been demonstrated in laser [7] and in amplifier configurations [8], these sources suffer from a limited absorption of the pump, a high transparency power and a complex fiber structure. Specific high-brightness multimode laser diodes modules for pumping are also necessary. Alternatively, we have used commercial single-mode fibers, which benefit from an intrinsic very good overlap of the pump beam with the doped core and thus a low transparency power. For our single-mode doped fiber, described later, the overlap factor between the pump and the doped core is 77 %, leading to a transparency power as low as 7 mW. The fibers are pumped by a home-made diode-pumped Nd:YVO_4 laser emitting at 914 nm in a diffraction-limited beam, which is very close to the highest absorption wavelength in the 870-960 nm absorption band of Yb^{3+} ions.

Extracavity second harmonic generation (SHG) is the simplest way to convert a high power infrared laser beam into visible light. However highly non linear materials, like periodically poled (PP) materials, are necessary to obtain a strong conversion. For example, the SHG of an Yb-doped fiber MOPA source in a PPKTP crystal has produced a power of 18 mW at 489 nm for an incident power of 1.4 W at 978 nm [9]. Efficient extracavity SHG has also been demonstrated in PP MgO:$LiNbO_3$ (PP MgO:LN) in the visible range, thanks to its high non linear coefficient, its resistance against photorefractive damages and the capability to realize short domain periods. Moreover, a PP MgO:LN waveguide have the further advantage to provide a strong confinement of the fundamental light all along the crystal, leading to high conversion efficiency [10-12].

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We describe here the performances of a narrow-line laser source based on a commercial single-mode Yb-doped fiber with both a high efficiency, a tunability around 978 nm and a narrow linewidth suitable for the frequency doubling in a PP MgO:LN single-mode waveguide, and the results of this frequency conversion.

2. Experimental set-up

The experimental set-up is presented in figure 1. The fiber used in these experiments has a core diameter of 5 µm for a numerical aperture of 0.13. An estimation of the doping level of $4.8\text{x}10^{25}$ Yb^{3+} ions per m^3 has been experimentally determined from measurements of the pump absorption. Both fiber ends are angle-cleaved to prevent back reflections and parasitic laser effects.

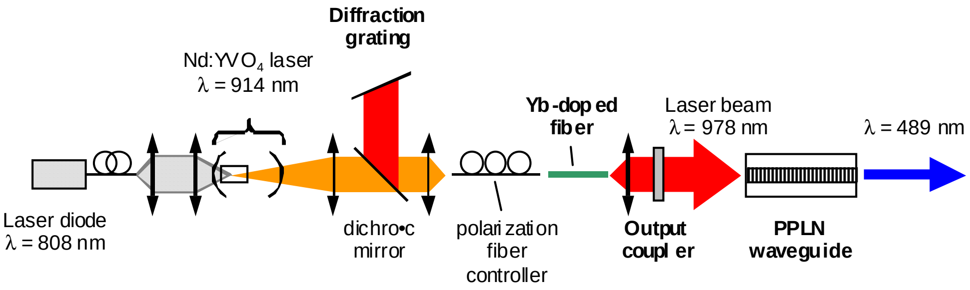

Fig. 1. Experimental set-up for the infrared laser source and its frequency doubling stage

We have developed a diffraction-limited diode-pumped Nd:YVO_4 laser emitting at 914 nm to pump our fibers [13]. A 5-mm-long Nd:YVO_4 crystal with a doping level in Nd^{3+} ions of 0.1 %, is inserted in a concave-concave cavity and pumped with a 200-µm-fiber-coupled laser diode at 808 nm, which is focused in the crystal in a beam of 200 µm of diameter. The input mirror has a radius of curvature of 50 mm, and the output coupler of 100 mm. Its transmission is 3% at 914 nm. The cavity mirrors and the crystal are anti-reflection coated at 1064 nm to prevent laser emission on this very intense line. The laser threshold is obtained for a pump power of 8.5 W. The laser emits a cw power of 4 W for a 22-W incident pump power at 808 nm with a slope efficiency of 27 % with respect to the incident pump power, in a linearly polarized beam (Fig. 2.). The beam profile is nearly diffraction-limited with a M^2 close to 1.1 at the highest laser power. Within these conditions, the coupling efficiency of the laser beam in the single-mode fiber is 75%, leading to a power of about 3 W at 914 nm at the Yb-doped fiber input.

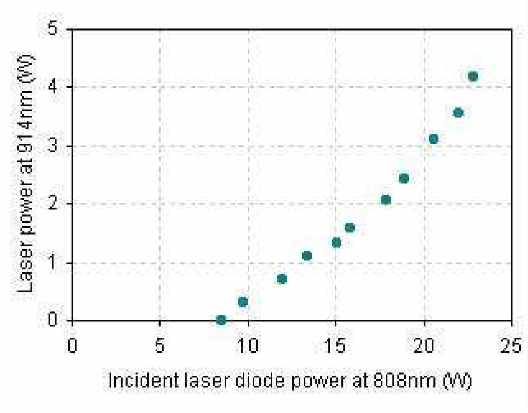

Fig. 2. Output power at 914 nm versus the incident laser diode power at 808 nm.

The fiber laser cavity is formed at one end by a diffraction grating of 1200 lines/mm in Littrow configuration. Since our fibers are APC connectorized, a glass plate plays the role of a broadband ~4 % output coupler (Fig. 1.). The bandwidth of the reflection from the grating into the fiber is estimated to 0.4 nm. The reflection coefficient is about 70 % for the selected bandwidth, taking into account the 92 % efficiency of the grating in the first order.

Extracavity frequency doubling is realized in a ridge-type PP MgO:LN TEM_{00} waveguide, with a grating period of about 5 µm for a length of 8.3 mm. The faces of the crystal are angle-polished to suppress back reflections, but uncoated. The mode field diameters of the waveguide are 3 µm x 5 µm at 978 nm. The infrared beam is matched to the elliptical mode profile of the waveguide with a prism, and focused at the input of the non-linear crystal. The temperature of the waveguide is set to 50°C with a Peltier cooler.

3. Description and optimization of the Yb-doped fiber laser at 978 nm

The laser performances can be conveniently predicted from a simple theoretical model based on the resolution of the propagation equations in the fiber without taking into account the amplified spontaneous emission [14]. Analytical expressions of the threshold power P_{th} (1), the slope efficiency η (2) and the output power P_{laser} (3) are deduced in terms of experimental parameters : the reflectivity R_1 and R_2 of the cavity mirrors, the transmissions of the optics at the both ends of the fiber T_1 and T_2 including the coupling efficiencies, the input pump power P_{pump} and the fiber length L.

$$P_{th} = \frac{h\,c}{\lambda_p} P_s^{sat} \frac{\alpha_s L - \ln(T\,R)}{1-(G_{max}\;T\,R)^{-\delta}} \tag{1}$$

$$\eta = \frac{\eta_q T_2 (1 - R_2)}{T_{eff}} \left[1-(G_{max}\;T\,R)^{-\delta}\right] P_{laser} = \eta\left(P_{pump} - P_{th}\right) \tag{2}$$

$$P_{laser} = \eta\left(P_{pump} - P_{th}\right) \tag{3}$$

In these expressions, λ_p and λ_s are respectively the pump and laser wavelengths, $\eta_q = \lambda_s / \lambda_p = 0.94$ is the quantum efficiency. $P_p^{sat} = 8.8$ mW and $P_s^{sat} = 1.2$ mW are the saturation powers at the pump and laser wavelengths and δ is the ratio of these two powers $\delta = P_s^{sat} / P_p^{sat} = 0.14$. G_{max} is the maximum gain which could theoretically be obtained when the population inversion is maximal along the fiber $G_{max} = \exp((\alpha_p / \delta - \alpha_s) L)$, where $\alpha_p = 27\ m^{-1}$ and $\alpha_s = 88\ m^{-1}$ are the small-signal absorption coefficient at the pump and laser wavelengths. The calculations use an effective reflectivity of the cavity $R^2 = R_1 R_2 = 0.03$, an effective transmission of the cavity $T = T_1 T_2 = 0.73$, and an effective output transmission $T_{eff} = (1-T_2^2R_2) + (1-T_1^2R_1)\ T_2^2R_2 / (TR) = 1.07$. All these numerical values have been experimentally determined.

For this three-level transition, the critical parameter for the optimization of the laser operation is the fiber length. Indeed the laser power is maximal for the residual pump power equal to the transparency power to avoid any reabsorption of the laser emission. The following analytical expression of the optimum length (4) is obtained by differentiating the laser power with respect to the fiber length.

$$L_{opt} = \frac{1}{\alpha_p - \delta\alpha_s} \ln\left[\frac{\lambda_p}{h\,c} \frac{P_{pump}}{P_s^{sat}} \frac{\alpha_p - \delta\alpha_s}{\alpha_s \left(T\,R\right)^{\delta}}\right] \tag{4}$$

With our set-up, and a pump power of 3 W, this optimal length is evaluated to 42 cm. For this length, a slope efficiency η of 71 % for a maximal output P_{laser} of 2.1 W at 978 nm, and a threshold pump power P_{th} of 47 mW are expected. Experimentally, a maximal output power of 2 W for an input pump power of 3 W is obtained with a fiber length equal to 40 cm (Fig. 3.). The slope efficiency of the laser emission is 72% with respect to the input pump power.

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The laser threshold is 40 mW (Fig. 3.), and the pump absorption is 98 % for the maximal pump power. Without any adjusting parameters, a good agreement between the theoretical and the experimental results is thus observed. The shorter fiber with a length of 30 cm has an insufficient absorption resulting in a lower efficiency. On the contrary, the residual pump power is not high enough to avoid the reabsorption with longer fiber (L = 50 cm). Moreover, a parasitic emission at 1030 nm begins to appear, that decreases the laser efficiency for fibers longer than the optimal length. This decrease is faster than predicted by our model, which does not take into account this 1030-nm line.

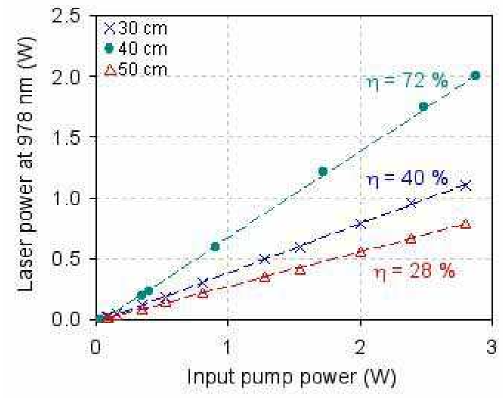

Fig. 3. Output laser power versus the input pump power, with their linear fit and experimental slope efficiency for three different fiber lengths.

For the 40-cm-long fiber, the output beam is linearly polarized with an extinction ratio of 50:1 thanks to the slight dependence of the grating efficiencies with polarization and the intracavity polarization fiber controller. The residual amplified spontaneous emission around 1030 nm is 30 dB lower than the laser emission. The laser wavelength is tunable from 975 nm to 981 nm with a power higher than 1 W on this range (Fig. 4.). We have measured a laser linewidth shorter than 0.02 nm (FWHM), i.e. limited by the resolution of our optical spectrum analyzer.

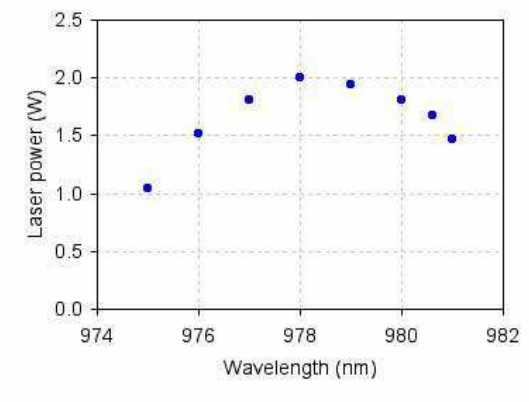

Fig. 4. Tunability of the laser source for a fiber length of 40 cm and a pump power of 3 W.

4. SHG in PP MgO:LN waveguide

The nearly diffraction-limited infrared beam is then coupled into the PP MgO:LN waveguide. The coupling efficiency is measured out of the phase-matching conditions, at the output of the waveguide. Taking into account the 14 % reflection at the input end and the propagation losses of 0.3 dB.cm^{-1} at 978 nm, we evaluate that 48 % of the infrared incident beam is actually coupled into the waveguide for non-linear conversion. Figure 5 shows the evolution

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of the power at 489 nm with respect to the incident power at 978 nm as well as the theoretical parabolic behavior of the SHG conversion.

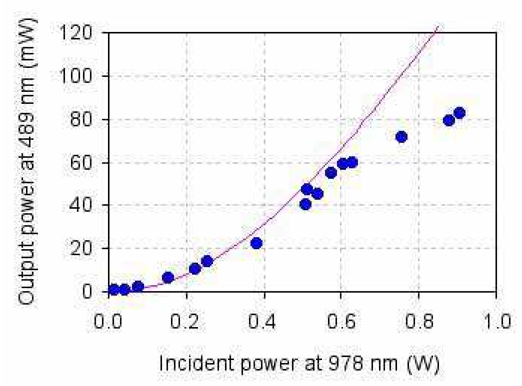

Fig. 5. Output power at 489 nm vs the incident fundamental power at 979 nm and the theoretical parabolic fit.

For an incident infrared power of 910 mW, corresponding to a coupled power of 370 mW, we have obtained a maximal output power of 83 mW at 489 nm in an elliptical gaussian beam. This value corresponds to an internal conversion efficiency of 26 % with respect to the blue and infrared powers inside the waveguide. The normalized efficiency of the SHG process is evaluated to 137 %/W for incident infrared power lower than 0.6 W, from a parabolic fit of the experimental blue versus infrared power, inside the waveguide. We have observed a saturation of the blue power for incident infrared powers higher than 900 mW that limits the conversion efficiency. We assume that it is due to an absorption linked to the correlated evolution of 978 and 489 nm in the PP MgO:LN. It leads to a temperature gradient along the waveguide, which can not be corrected by an adjustment of the crystal temperature. The thermal acceptance of the PPLN waveguide has been measured to about 2.4 °C and its spectral acceptance to 0.14 nm. The spectral bandwidth of our fiber laser is thus well suited for this low spectral acceptance. In comparison, Soh *et al.* [9] reported a lower efficiency of the frequency doubling of the 978-nm laser source based on JAC fibers. This is partly due to the fact that the spectral bandwidth of their source (0.6 nm) was higher than the spectral acceptance of the PPKTP crystal they used (0.2 nm). Bulk PPKTP has also a lower non linear coefficient than PPLN, and is less efficient than PPLN waveguide for frequency conversion.

5. Conclusion

In conclusion, we have demonstrated a very efficient fiber laser source emitting on the three-level transition of Yb^{3+} ions at 980 nm, based on a commercial single-mode Yb-doped fiber. Its narrow bandwidth, as well as its high beam quality, enables an efficient second harmonic generation in a PP MgO:LN waveguide in single-pass extracavity configuration, with an internal conversion efficiency of 26 % at the highest 489-nm power. The overall optical-to-optical efficiency of the source is mainly limited by the low efficiency of the $Nd:YVO_4$ laser at 914 nm. In order to have a full diode pumped fiber laser source, it could be interested to use newly demonstrated Nd-doped double-clad fiber laser emitting around 930 nm [15] instead of the $Nd:YVO_4$ laser, and thus to develop an all fiber source.

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