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230mW of Blue Light from a Thulium-Doped Upconversion Fiber Laser

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Abstract

We demonstrate a powerful diode-pumped blue laser source, consisting of a 7W diode at 807nm that pumps a Nd:YAG laser giving 1.6W with good beam quality at 1123nm, and a thulium-doped upconversion fiber laser. The maximum output power achieved at 481nm is 230mW. We also describe the behavior of a reversible loss which is generated in the fluoride fiber during high power operation.

Introduction

BLUE LASER sources are required for a number of applications such as colour displays, printing, and data recording. Three main approaches are currently pursued. Blue-emitting laser diodes have recently been demonstrated [1], although with a number of limitations, with regard to power, lifetime, and operating temperature. Another approach is frequency-doubling of an infrared source; for example, 49mW of blue light has recently been obtained by frequency doubling the output of a diode-pumped 946nm Nd:YAG laser in a single pass through a periodically poled $LiNbO_3$ crystal [2]. Resonant doubling schemes allow higher efficiencies; 650mW at 430nm has been demonstrated [3]. Improvements are also possible by the use of intracavity second harmonic generation or a waveguide structure, apart from further improvements in the nonlinear crystals. The third approach is upconversion lasing, for which the highest reported power to date, in the blue spectral region, was 106mW from a diode-pumped thulium-doped ZBLAN upconversion fiber laser [4]. In this paper, we report a blue output of up to 230mW, achieved by using a more powerful pump laser and a ZrF_4 based fiber with modified composition, which has allowed higher power operation, although long-term operation at this highest power level is not yet possible due to creation of a reversible loss in the fiber.

Operation of blue Tm-doped fiber lasers has been demonstrated already by several groups [4]-[8]. The upper laser level ($^1G_4$) of Tm^{3+} in fluoride glass is populated by an efficient upconversion process involving the sequential absorption of three pump photons (see Fig. 1), which can be achieved effectively with a single pump wavelength. The optimum pump wavelength is around 1140nm although efficient operation is still possible at 1123nm as used in the first demonstration of this laser scheme [5] as well as in the experiments reported in this paper.

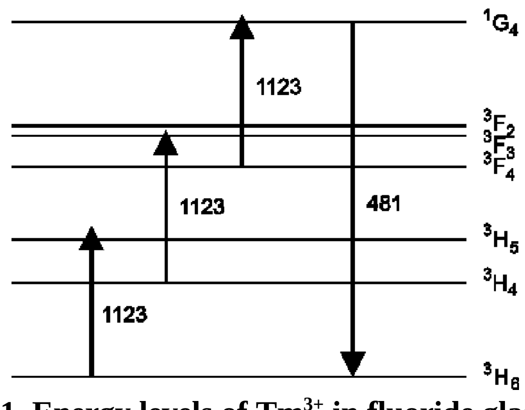

Fig. 1. Energy levels of Tm^{3+} in fluoride glass (with the definition of the numbering which we use in this paper), pump, and laser transitions (thick arrows) and all fluorescence lines which are taken into account by the model. The numbers alongside the arrows are wavelengths in nanometers.

The Experiments

We now describe our experimental setup. The pump laser (which will be described in detail elsewhere) was a Nd^{3+}:YAG laser operating at 1123nm, pumped by a 7W diode bar. Two dichroic cavity mirrors with low reflectivity at 1064nm suppressed lasing at this wavelength, for which the emission cross section is ~15 times greater than for 1123nm. A beamshaper [10] was used to transform the diode output into an approximately circular beam with beam quality factors M_x^2 = 40 and M_y^2 = 20. This beam was used to end-pump a 10mm-long Nd^{3+}:YAG rod. The laser threshold was ~800mW and the slope efficiency 33% with respect to absorbed pump power; with the maximum diode current of 10.4 A, we obtained an output power of 1.6W at 1123nm. With careful design of the laser cavity, addressing the problem posed by the strong (aberrated) thermal lens in the rod, a good beam quality could be obtained which enabled a good launch efficiency of ~50% into a single-mode fiber.

The Tm-doped fluoride fiber we used, produced by Le Verre Fluoré, had a thulium concentration of 1000 ppm (by weight), a numerical aperture of 0.2, and a core diameter of 3µm, corresponding to a cutoff wavelength of 800nm. A fiber length between 2.1 and 3 m was used in all experiments. Both fiber ends were butted against dielectric mirrors. The input mirror had a high reflectivity for the blue light and high transmission, 90%, for the 1123nm pump light which was launched through this mirror into the fiber core using an aspheric lens. Tests with a nonabsorbing silica fiber (with very similar NA and cutoff wavelength) showed that the launch efficiency, defined as launched power divided by power incident on the lens, was between 50% and 60%, varying somewhat with changes in mode quality.

Initially, we used an output coupler which had an optimized design: the reflectivity for the blue light was ~50% while 98% of the residual pump light was reflected back. With this configuration, we achieved a threshold around 100mW and a high slope efficiency of 25% with respect to incident power. However, at output powers of a few tens of mW the output end of the fiber was destroyed very rapidly, subsequently showing strong scattering of the blue fluorescence. Restoration of lasing could then be achieved only by recleaving the fiber end. This behavior was first observed while using an index matching fluid at both fiber ends; however, without the fluid, the problems at the output end were significantly worse. Although the physical origin of this problem is not clear, it turned out that much more reliable operation could be achieved by using other output couplers which do not reflect back the residual pump light; in this case dry fiber ends gave the most reliable performance. The slope efficiency achieved with an output coupler of 63% reflectivity for the blue light was now reduced to 19%; this lower value is mainly caused by the loss of unabsorbed pump light. The transmitted pump power (above threshold) was around 30%-40% of the launched power. We expect that the problems with the fiber ends could be entirely eliminated by using mirror coatings which are evaporated onto the fiber ends, replacing the butted mirrors; it should then be possible to use an output coupler that reflects the pump and thus allows an even better performance.

At higher power levels (above 100mW output power) we observed a fast degradation of the fiber laser performance so that one could not reach the output powers expected from linear extrapolation of the results at lower pump power: the output power dropped significantly within a few seconds, and it was then found that the threshold and slope efficiency (also at lower powers) had deteriorated. Recleaving the fiber ends did not restore the previous performance. By comparing the fiber's transmission of white light (measured with a halogen lamp and an optical spectrum analyzer) with that of an unused piece we found that the fiber had developed a broad-band loss that rises sharply toward shorter wavelengths and was typically a few dB/m at 480nm. However, this loss appeared to be entirely reversible: when the fiber laser was operated at a lower power level (with, e.g., 40mW output power) this would eventually lead to a full restoration of the previous performance. The required duration of this treatment for full restoration increased with the duration of previous high power operation; up to 1 hour of low-power operation was required after operation at the highest powers.

We also note that the generated loss seems to increase significantly after the laser is turned off; one piece of fiber that had lased up to the end of the experiments on one day could not be made to lase on the next day, even with a high reflector in place of the output coupler.

The observed effects are strongly reminiscent of earlier reports by several groups [7], [9], [11], [12] of a broadband induced loss, which is induced especially in fibers with high thulium concentration when pumped with wavelengths around 1120-1140nm. The exact mechanism of this effect is not yet known, but it is believed that the excitation of high lying levels of the thulium (above the $^1G_4$) via energy transfer processes leads to the creation of color centers [9], [13]. Our experiments indicate that some significant loss is also generated by laser operation at high powers, although the population in the upper laser level (integrated over the length of fiber) should be no higher than during operation just above threshold. This suggests that not only the population of higher levels but also the presence of high intracavity blue power (or possibly the high pump power) can induce loss although as mentioned before a moderate blue power level appears to eliminate the loss.

It is interesting to note that a broad-band loss both in the blue spectral region and around 800nm was previously observed by us [9] in an earlier fiber from the same source (Le Verre Fluoré) as well as by another group [11], the latter using fibers from Galileo Electro-Optics Corporation; the new fiber used in the experiments we describe here (with slightly modified composition) as well as another fiber from Le Verre Fluoré (see [12]) again displayed the loss in the blue region but not around 800nm. Apparently there are two different kinds of color center, one of which has now been eliminated by a slight change of the fiber composition. This gives hope that further modifications may be found which also eliminate the other color center which strongly affects the laser performance at present.

We obtained the best performance with a 2.2m piece of the currently available fiber by first operating it with about 20mW output power for a few minutes and then increasing the pump power rapidly to the maximum available power of about 1.6W (incident on the aspheric lens) within about 15 s, while taking a rapid recording of input and output power with a computer-controlled setup. The results are shown in Fig. 2. The maximum

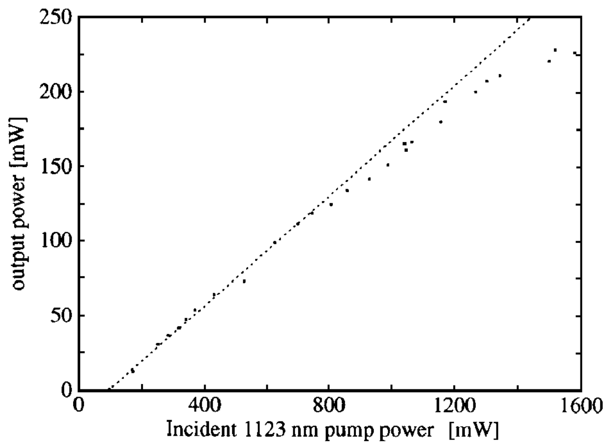

Fig. 2. Output versus incident input power for 2.2m-long laser, recorded within 30 s after lasing at low powers for a few minutes. Dotted line: linear interpolation at lower powers, indicating 18.5% slope efficiency.

achieved output power was ~230mW. The slope efficiency was 18.5% for an output power of up to 120mW; for higher pump powers we obtained slightly less power than expected from linear extrapolation, probably because some loss had already been induced.

Later, we tried operation for longer times at various power levels. Fig. 3 shows the time dependence of the output over 5 min. The first measurement (lowest curve) was done with 465mW of incident pump power and delivered a fairly constant output of 65mW. At higher pump power levels (733, 963, and 1610 mW) the output power dropped significantly in the beginning but seemed to settle down at some lower level after a few minutes. The noise on the curves in Fig. 3 was caused by optical feedback to the pump laser (a suitable Faraday isolator was not available). We confirmed that an output power of about 140mW could be sustained over longer periods (at least 20 min). After this treatment, the slope efficiency had settled down at a level of 14%, but after 1 h of low-power lasing at ~20mW output the fiber performance recovered to 18% slope efficiency again.

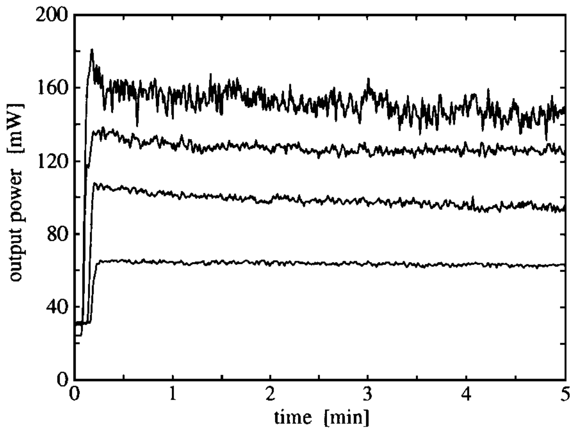

Fig. 3. Output power versus time of a 2.3m-long laser, with 465, 733, 963, and 1610mW of incident pump power. (In the first few seconds, the pump power was about 290mW.)

Conclusion

The combination of a high-power diode-pumped 1123nm pump laser with an optimized fiber laser has allowed us to generate up to 230mW of blue light. At these high-power levels the fiber laser performance degrades quickly, but we have found that it can recover fully as a result of operation at lower power for some time. Further work aimed at eliminating the color centers by other modifications of the fluoride glass composition should enable more stable operation at higher output powers. Stable operation with hundreds of milliwatts of blue output may become possible in the near future.

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