Frequency-Doubled Fiber-Based Continuous Wave Orange Laser Radiation at 590 nm

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(Received April 1, 2004)

Generation of 0.5 W of cw orange laser radiation at 590-nm by single-pass frequency doubling of 1180-nm high-power Raman-shifted Yb-doped fiber laser in a 20-mm long periodically poled MgO doped lithium niobate (PP-MgO:LN) crystal with internal frequency doubling efficiency of 3.3% is presented. At the low-power level where the laser linewidth was close to the acceptance bandwidth of the PP-MgO:LN crystal, frequency doubling efficiency of 1.36%/W was obtained.

Key Words: Quasi-phase-matching, Frequency doubling, Medical applications, Fiber lasers

Visible laser light sources are of great interest in the fields of spectroscopy, printing technology and medical applications. However, there is none or a few conventional laser sources in the yellow-orange region of the visible spectrum. Especially, in medical community, there is a great demand of efficient, compact, and maintenance-free visible laser source at 590-nm, a wavelength that coincides with an absorption band of hemoglobin and is of particular interest for a range of medical applications.¹⁾ Laser retinal treatment generally requires 0.1-1.5 W of continuous wave (cw) power. In the yellow-orange region of the spectrum, ion and dye lasers are currently used in medical applications, which are bulky, inefficient, and cumbersome to maintain. There has been other approaches to making laser source in the yellow-orange region of the spectrum that include resonant extracavity sum-frequency generation,²⁾ single-pass extracavity sum-frequency generation,³⁻⁵⁾ and frequency doubling (SHG) of an intracavity Raman-shifted Nd:YAG laser.^{6,7)} Most of these approaches are complex, and could suffer from beam degradation on scaling to produce a higher output power.

Advancement in Quasi-phase-matched (QPM) nonlinear crystal technology has generated great interest in generation of visible output by single-pass frequency doubling of fiber laser sources.^{8,9)} QPM crystals are very attractive nonlinear devices for external single-pass frequency doubling because of their high nonlinear coefficients. For example, the nonlinear coefficient d_{33} of periodically poled lithium niobate crystal is 28 pm/V.¹⁰⁾ Combined with Raman Stokes-shifted Yb-doped fiber laser system, such components allow development of compact, highly portable, and maintenance-free laser source at wavelengths for which there are none or a few high-power cw laser sources, for example, a 590-nm laser source.

In this letter, generation of 0.5 W of cw orange laser radiation at 590-nm by second harmonic generation of 1180-nm fiber laser source in a PP-MgO:LN crystal is reported. A PP-MgO:LN crystal was used because it has high resistance to photorefractive damage in comparison to a periodically poled lithium niobate (PPLN).¹¹⁾

A schematic drawing of the experimental set up is shown in Fig. 1. A commercial Raman-shifted Yb-doped fiber laser (IPG Photonics Model PYL-20-1180-LP) producing up to cw 20 W of collimated linearly polarized output beam with $M^2 = 1.05$ at 1180-nm was used in the experiment. The output fiber of the cw fiber laser source was rotated so that the laser field is aligned with the z-axis of the PP-MgO:LN crystal placed inside an oven with temperature controller. In the experiment, the PP-MgO:LN sample (manufactured by HC Photonics Corp.) was 20-mm long, 0.5-mm thick, with 9.21 μm domain period chosen for first-order second harmonic quasi-phase-matching (QPM) at 1180-nm, and two end facets were polished without antireflection coating. A focusing lens was used for focusing the fundamental beam into the center of the PP-MgO:LN crystal. At the output of the crystal a second lens was used for collimating the beam. A dichroic beamsplitter that reflects 99.5 % of 590-nm radiation and transmits >95 % of 1180-nm radiation was used along with an IR filter to separate 590-nm laser beam from the fundamental laser beam. A calibrated silicon detector (Coherent model LM-2) was used to measure the orange power at values up to 20 mW and a thermal detector (OPHIR model 30A) was used to measure the orange power at values above 20 mW. A thermal detector (OPHIR model 150A) was used to measure the fundamental power and a spectrum analyzer (Advantest model TQ8345 with 0.1-nm resolution) was used to measure its linewidth.

Fig. 1 Schematic drawing of the experimental set up.

Figure 2 shows measured linewidth of the 1180-nm fiber laser source as a function of 1180-nm power. The linewidth of 1180-nm fiber laser source is 0.2 nm at 1.5 W, which is close to the acceptance bandwidth of a 20-mm long PP-MgO:LN crystal. However, the linewidth of the 1180-nm fiber laser source broadens with the increase in the fundamental power as shown in Fig. 2.

For determination of phase-matching characteristics and effective nonlinear coefficient, 1.5 W of 1180-nm fiber laser was loosely focused into the 20-mm long PP-MgO:LN crystal placed inside the oven with temperature controller with temperature accuracy of 0.1 °C (HC Photonics Corp.). The loose focusing ensures approximately constant phase matching condition throughout the crystal. An $f = 340$ -mm lens with antireflection coating at 1180-nm was used to focus fundamental beam into the center of the crystal to the waist radius of 56- μ m. The QPM phase matching temperature was found to be 179.5 °C with temperature width of 2.0 °C. The normalized second harmonic conversion efficiency was found to be 1.36 %/W for the 20-mm long PP-MgO:LN sample, where the measured power levels were corrected on the basis of the Fresnel reflection losses. These losses amount to 13.4 % for fundamental radiation at the input facet and 14.4 % for the second harmonic radiation at the output facet of the uncoated sample. The power level for second harmonic radiation at 590-nm was also corrected for losses due to beamsplitter and IR filter used for separating 590-nm radiation from the 1180-nm radiation. Using conventional equation¹²⁾ for normalized conversion efficiency, we calculated the effective nonlinear coefficient to be 9.5 pm/V, 53 % of the value for an ideal first-order QPM grating. This lower value of effective nonlinear coefficient might have resulted from imperfection in poling process and deviations in the duty cycle and the period.

We next performed the single-pass frequency doubling of 1180-nm fundamental laser radiation at higher power levels. An $f = 200$ mm focusing lens with antireflection coating at 1180-nm was used to focus fundamental beam into the center of the 20-mm long PP-MgO:LN sample to the waist radius of 33- μ m. The value of Boyd-Kleinman confocal focusing parameter¹²⁾ $\xi = \lambda L / (2\pi\omega_0^2 n_F)$ was 1.6. Here λ is the fundamental wavelength, L is the crystal length, ω_0 is the waist radius; and n_F is the refractive index of the crystal at 1180-nm wavelength. The measured

Fig. 2 Linewidth of 1180-nm fiber laser source as a function of the fundamental power.

dependence of the orange power at 590-nm and the internal second harmonic conversion efficiency on the fundamental power is shown in Fig. 3 (a) and (b), respectively. All powers are internal to the sample and corrected for losses due to Fresnel reflection at the end facets of the sample, the beamsplitter, and the IR filter. The linewidth of 1180-nm fiber laser source increases with the increase in the fundamental power (Fig. 1). As a result linewidth of 1180-nm fiber laser source at high power levels is significantly broad in comparison to the acceptance bandwidth, 0.19-nm, of a 20-mm long PP-MgO:LN crystal, which causes overall conversion efficiency to saturate at high input powers as shown in Fig. 3 (b). A maximum cw orange output power of 0.5 W has been achieved at 15 W of the fundamental power, corresponding to the internal second harmonic (SHG) conversion efficiency of 3.3 %. No evidence of photo-refractive damage was observed.

In conclusion, generation of 0.5 W of cw orange laser radiation at 590-nm by single-pass frequency doubling of 1180-nm fiber laser source in a 20-mm long periodically poled MgO doped lithium niobate crystal with internal second harmonic conversion efficiency of 3.3 % has been presented. This is the highest cw orange power at 590-nm wavelength reported so far, by single-pass frequency doubling of 1180-nm fiber laser source in bulk QPM crystal. In the present experiment, orange power has been limited to 0.5W because of the broad bandwidth of the 1180-nm fiber laser source at high power levels and significantly low ef-

Fig. 3 Measured (a) cw orange power at 590-nm internal to the exit face of the PP-MgO:LN sample, and (b) the internal second harmonic conversion efficiency as a function of 1180-nm power internal to input face of the PP-MgO:LN sample.

fective nonlinear coefficient (53 % of the ideal value) of the PP-MgO:LN sample used. In the future, there is a plan to generate 1.5 W of orange power with conversion efficiency of more than 10 % by limiting the linewidth of 1180-nm fiber laser source to ≤ 0.5 nm and using PP-MgO:LN crystal with better poling and effective nonlinear coefficient, and to perform characterization of the orange output beam.

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