6-W Average power green light generation using seeded high power ytterbium fibre amplifier and periodically poled KTP

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Abstract

Up to 6 W average power, green laser source is demonstrated using a combination of laser-diode-seeded ytterbium fibre amplifier and quasi phase-matched second harmonic generation in periodically poled KTP. The source is used as a pump for a femtosecond Ti:Sapphire laser. © 2000 Elsevier Science B.V. All rights reserved.

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As a result of improved fibre formats and novel parallel diode pumping schemes remarkable progress has been made in high power, single transverse mode, cladding-pumped fibre lasers, in that cw powers in excess of 40 W devices are now commercially available. Research on considerably lower power amplifiers using V-groove side pumping has been also reported elsewhere [1]. In addition to the very compact nature of the packaging the most notable characteristic is the overall efficiency of such lasers. Consequently high power fibre lasers, and in particular Yb and Yb:Er based systems operating broadly around 1 μm and 1.5 μm respectively, are beginning to replace conventional arc lamp pumped and diode pumped solid state lasers in many applications. At the power levels available and with the all-fibre versions schemes has allowed added wavelength versatility. For example, stimulated Raman scattering, where conversion efficiencies of up to 70% have been achieved and average powers in excess of 5 W at any wavelength up to 1.5 μm demonstrated [2]. On the other hand, a combination of the seeded fibre amplifier, with its efficient, compact and relatively high average power performance, with periodically poled crystals for harmonic or parametric generation appears as the natural combination for source diversity in a compact package.

With high saturation powers possible from cladding pumped fibre amplifiers one highly flexible and efficient configuration is that of the seeded or master oscillator-power fibre amplifier (MOPFA) [3]. The high gain of the systems allows weak seed signals from diode lasers or fibre lasers in all-fibre coupled formats to achieve high power saturated outputs with extensive diversity in the output parameters of the total source, from single frequency operation [4] to ultrashort pulses at selectable repetition

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rates with selectable duration over large wavelength ranges. Over the past few years there has been renewed interest in quasi phase matched non linear conversion in periodically poled crystalline materials where impressive progress has been made in the achievable grating lengths and in the scale of minimum feature allowing harmonic generation at shorter wavelengths. The combination of the master oscillator power fibre amplifier and the periodically poled material [5] provides a compact and highly efficient means for non-linear conversion and expansive wavelength conversion in a configuration that also requires minimal operator attention.

In this paper, we report the highly efficient, up to 6 W average power, second harmonic generation in periodically poled KTP using a seeded, all-fibre format ytterbium amplifier. The experimental configuration is shown in Fig. 1. The commercial PPKTP sample provided by Isorad was 10 mm long with a 0.5 x 5.0 mm aperture and was placed in a temperature-controlled oven with the temperature stabilisation better than 0.1°C. The crystal had a poling period of 9.0 μm with 50% duty cycle grating which provided for the first order second harmonics quasi-phase matching at 1064 nm at about 40°C.

The pump source consisted of a seeding semiconductor diode and IPG-Lasers Yb-doped fibre amplifier with a maximum saturated power of 10 W. The gain switched Fabry–Perot EG & G laser diode had external cavity and was locked to the central wavelength of 1064 nm using a fibre Bragg grating. In mode-lock regime, the diode provided 0.6–0.8 mW average output power which was above the 0.5 mW saturation level the high power Yb-doped amplifier. The output of the fibre amplifier coupled to a grin lens, GL, provided a collimated beam with the quality $M^2 < 1.05$. A simple 75 mm focal length convex lens, $L_1$, provided optimal focusing conditions with the waist radius of $W_{min} = 18$ μm. The polarisation state of the output of the amplifier was adjusted using a polarisation controlling loop, PC, and was set to provide a linear polarisation with the extinction ratio better than $10^{-7}$ parallel to the c-axis of the PPKTP sample. The seeding semiconductor laser was operating in different regimes, from cw to picosecond with repetition rates up to several gigahertz, depending on the drive frequency and configuration. In picosecond operation mode, the optical bandwidth of the laser source was less than 0.2 nm which did not exceed that of the PPKTP phase-matching bandwidth, and allowed maximum conversion efficiency into the second harmonic signal.

The phase-matching curves of the PPKTP sample were recorded in cw regime and are shown in the Fig. 2. The temperature and wavelength FWHM phase-matching bandwidths of the PPKTP sample were $\Delta_T = 5.5°C$ and $\Delta_\lambda = 0.31$ nm respectively. Neglecting the thermal expansion of the crystal over $\Delta_T$ range, the effective length of the second harmonic generation near the quasi-phase matching maximum can be estimated as

$$L_{eff} = \frac{5.6\lambda}{(4\pi\Delta_f(\delta n_{2\omega}/\delta T - \delta n_{\omega}/\delta T))}$$

where $\lambda$ is the fundamental wavelength. The values of temperature derivatives of the refractive index of KTP at second harmonic and fundamental wavelengths, $\delta n_{2\omega}/\delta T$ and $\delta n_{\omega}/\delta T$, were taken from Ref. [6]. The measured effective length corresponded to 9.1 mm which was close to the 10 mm physical
length of the crystal indicating a nearly ideal periodically poled structure.

In pulsed operation, 8.2% $W^{-1}$ average power conversion into second harmonic was achieved with 200 ps pulses at 100 MHz repetition rate. Fig. 3 shows the variation of the second harmonic conversion efficiency with fundamental average and peak powers. At a peak power of 350 W, 55% of the pump power was converted into the green allowing up to 6 W at 532 nm for a 10 W saturated amplifier output. We attribute the slight roll off of the efficiency to the depletion of the pump and to the local heating effects at higher average powers. In fact, with the rise of fundamental power, the temperature of the PPKTP sample had to be adjusted within 1 to 2° to compensate for the heating effects. For 70 ps pulses at 675 MHz repetition rate and an average pump power of 5.5 W, 22% conversion into the second harmonic signal was obtained.

The normalised conversion efficiency of the PPKTP sample in quasi-cw operation is conventionally estimated as

$$
\eta = \frac{P_{\text{2nd}}}{P_{\text{1st}}} = \frac{8 \alpha^3 d_{\text{33}}^2 \xi}{\pi^2 n_{\text{s}} n_{\text{2nd}} v_0 c^3}
$$

where $L$ is the crystal length, $P_{\text{2nd}}$ and $P_{\text{1st}}$ are second harmonic and fundamental beam peak powers, $\omega$ is the frequency of the fundamental beam, $\xi$ is the Boyd–Kleinman focusing factor [7], $n_{\text{s}}$ and $n_{\text{2nd}}$ are refractive indices at the fundamental and second harmonic wavelengths, $\varepsilon_0$ is permittivity of the free space, and $c$ is the speed of light. For the experimental focusing conditions, the Boyd–Kleinman factor $\xi = \lambda L/(2\pi W_{\text{1st}} n_{\text{s}}) = 0.755$. The measured normalised conversion efficiency was $1.7 \times 10^{-3}$ cm/W. This corresponds to a $d_{\text{33}}$ value of 15.6 pm/V which is in a good agreement with the common value $d_{\text{33}} = 16$ pm/V [8,9].

The reported visible laser source showed high reliability with no detectable grey tracking developed in the PPKTP sample at 40°C after many hours (>100) of continuous operation. The versatility of this compact and efficient source was demonstrated in its application as a pump source for a self starting KLM Ti:Sapphire laser. Operating at 100 MHz, the Ti:Sapphire source reached threshold for 0.8 W 532 nm pump. At 1.5 W pump level, self starting KLM with unoptimised pulse duration of about 100 fs was observed. Mode-locking was achieved through synchronous operation, however on establishing femtosecond operation the Ti:Sapphire laser cavity length could be varied without loss of minimum pulse operation, indicating the dominance of the passive mode-locking mechanism.

In conclusion, we have demonstrated an efficient, up to 6 W average power, versatile visible source based on an all-fibre format seeded high power ytterbium amplifier and bulk periodically poled KTP quasi-phase matched in the first order. Through incorporating additional non linear processes, tunable operation throughout the visible is possible. Absence of grey tracking problem and insignificant roll-off of the SHG efficiency curve allow for scalability of the system to higher output powers as commercial fibre amplifiers with up to 40 W output power become available. The source can also be readily applied to pumping of Ti:Sapphire lasers and optical parametric oscillators. This compact and efficient source will readily replace commercial large frame Nd:YAG and ion argon lasers in many applications.

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References