3.5 W frequency-doubled fiber-based laser source at 772 nm

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A 3.5 W fiber-based laser source at 772 nm is demonstrated by using quasiphase-matched second-harmonic generation of a 40 dBm seeded ytterbium–erbium fiber amplifier in PPKTP. A 40% conversion efficiency is achieved across the entire output power range of the EDFA. No optical damage has been observed in the PPKTP over long-term high-power exposure. © 2001 American Institute of Physics. [DOI: 10.1063/1.1368181]

The key requirements for practical near-infrared wavelength range sources based on erbium-doped fiber lasers and frequency up conversion in periodically poled crystals are controlled wavelength stability, narrow linewidth, and high intensity fundamental radiation, which implies using pulsed format fiber sources. Several notable results have been achieved using the combination of periodically poled lithium niobate (PPLN) and erbium-based fiber sources. However, to date, use of PPLN has been restricted because of the limited control over the temporal and spectral characteristics of the fiber sources, and due to reduced scalability of the results to higher average powers. Such scalability was restricted because of the relatively low damage threshold of PPLN, even at raised temperatures, and limited (~100 mW) power level of fiber-based sources. Today, up to 20 W average power level erbium amplifiers have become commercially available while periodical poling of materials like KTP and LiTaO3 could offer higher than PPLN optical damage thresholds and reduced photorefractive and thermal loading.

Wide diversity in the output parameters of the erbium fiber sources, such as narrow linewidth, ultrashort pulses at selectable repetition rates, and high average saturated powers over an expansive wavelength range, could be achieved by using optical seeding of high power Er amplifiers. Combined with high photorefractive damage threshold, periodically poled ferroelectric nonlinear crystals, which have substantially relaxed requirements on raised temperature stabilization, such as KTP, would result in high average power, compact fiber-format sources capable of operating in a wide range of visible wavelengths.

Last year we proposed and demonstrated the feasibility of a PPKTP based seeded fiber-based source at 770 nm with average power up to 190 mW. In this letter, we report on a nearly 20-fold power-up scalability of the 772 nm seeded source to 3.5 W average power by employing quasiphase-matched second harmonic (SH) generation of a 40 dBm, variable pulse format, seeded erbium fiber amplifier in periodically poled KTP.

A schematic of the experimental configuration is shown in Fig. 1. A commercial 40 dBm Yb–Er doped fiber amplifier (IPG Laser) with a maximum saturated power of 10 W was employed. The control over wavelength, bandwidth, and pulse parameters was achieved using direct gain switching of the seeding DFB semiconductor laser at 1544 nm. The seed signal was preamplified and spectrally filtered using a 0.3 nm full width at half maximum fiber pigtailed tunable filter. The amplified spontaneous emission (ASE) to signal ratio was below 1% level at the input of the 40 dBm amplifier.

With adjustable repetition rates from 0.7 to 12 MHz and pulse durations from 1.6 to 2.6 ns, respectively, the duty factor (period to pulse duration ratio) of the seeding pulsed source could be varied by nearly three orders of magnitude. We found that at output peak powers above 0.5 kW, nonlinearity in the Er amplifier began to give rise to the spectral modification of the high power output (Fig. 2).

With ~1 mW input average powers, two contributions were identified. First, the ASE from unsaturated initial stages of the amplifier acted as a seed and interacted through the Kerr nonlinearity of the fiber with the high peak power, pulsed signal at 1544 nm. This lead to the appearance of the symmetrical four-wave mixing wings in the output spectrum. Second, because of the pulsed format of the amplified signal, the undersaturated cw gain led to the growth of the ASE component centred around 1565 nm. By varying the duty factor of the pulsed seeding signal and by rising the average input power level to 7 mW, over 35 dB suppression of the ASE and four-wave mixing, as well as a nearly constant peak power of ~0.4 kW were obtained across the entire adjustable output power range of the 40 dBm amplifier (Fig. 3). Under these conditions, 94% of output power was within the 2.6 nm wide quasiphase-matched bandwidth of the PPKTP crystal and allowed maximum SH conversion efficiency into 772 nm.

The uncoated 6 mm long PPKTP sample had a 23 μm poling period and was temperature stabilized at 75 °C. An optimized confocal focusing with a 40 μm beam waist diameter was arranged. The polarization controlling loop provided better than 102 polarization extinction ratio at the PPKTP input.

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Figure 4 illustrates the internal average SH conversion efficiency of the PPKTP at different fundamental power levels and duty factors of the seeding signal. The 3.5 W power level of the SH at 772 nm was achieved with 2.6 ns pulses at 10.4 MHz repetition rate. This corresponds to an internal peak power conversion efficiency in the PPKTP of $P_{2\omega}/P_\omega = 40\%$.

In our experiment, the value of the Boyd–Kleinman confocal focusing parameter $\xi = \lambda L/(2\pi W_{\text{min}}^2 n_\omega)$ was 0.5. Here $\lambda$ is the fundamental wavelength, $L$ is the crystal length, $W_{\text{min}}$ is the minimum waist diameter, and $n_\omega$ is the refractive index of the PPKTP at 1544 nm. The normalized SH conversion efficiency can be estimated as

$$\eta = \frac{P_{2\omega}}{L P_\omega} = \frac{2\omega^3 d_{\text{eff}}^2 \xi}{\pi n_\omega^2 \beta_2 n_\omega^2 \varepsilon_0 c^4},$$

where $P_{\omega}$ and $P_{2\omega}$ are peak powers of the fundamental and SH, $\omega$ is the fundamental's frequency, $d_{\text{eff}}$ is the effective nonlinearity of PPKTP, $c$ is the speed of light, and $\varepsilon_0$ is free-space permittivity. The experimental value of $\eta = 82 \times 10^{-3} \text{ (cm W)}^{-1}$ yields $d_{\text{eff}} = 13 \text{ pm/V}$ which is in good agreement with the values reported elsewhere. Taking into account the pump depletion, the estimated value of $d_{\text{eff}}$ would come to 14 pm/V.

The quasiphase-matching acceptance bandwidth of the 6 mm long PPKTP was 2.6 nm and indicated a nearly ideal periodically poled structure with the effective length of the crystal of $L_{\text{eff}} = 5.1 \text{ mm}$, which relates to the acceptance bandwidth $\Delta \lambda$ as

$$L_{\text{eff}} = \frac{0.44 \lambda^2}{\left[n_{2\omega} - n_\omega + \lambda \frac{d}{d \lambda} n_\omega - \frac{\lambda}{2} \frac{d}{d (\lambda/2)} n_{2\omega}\right] \Delta \lambda}.$$  

No significant thermal loading was observed in the PPKTP. The thermal load was increasing at the rate of 0.3 deg W$^{-1}$ and amounted to 2.8 deg level at the maximum power density of 0.6 MW/cm$^2$ at 9.6 W average power level at 1544 nm. This led to about 10% shift of the 26° wide temperature quasiphase-matching bandwidth of the PPKTP and was compensated by adjusting the temperature of the PPKTP sample. No long-term photorefractive damage in the PPKTP sample was observed.

With a 15 mm long PPKTP sample, we estimated that up to 56% efficient SH generation is possible which would lead to ~4.5 W average power generation at 772 nm. The main restriction of the current configuration, the peak and saturation power dependent nonlinear modification of the output spectrum at 1544 nm, can be overcome by filtering out the unsaturated ASE component within the high-power Er amplifier.

In conclusion, we have demonstrated power scalability of the frequency doubled seeded 40 dBm erbium fiber source to 3.5 W of average power. This compact and robust variable pulse format source at 772 nm is based on 40% efficient quasiphase-matched SH generation in PPKTP and offers high average and peak powers and excellent short-long term power stability.

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