Optical parametric oscillator with a 10-GHz repetition rate and 100-mW average output power in the spectral region near 1.5 μm

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We demonstrate a synchronously pumped optical parametric oscillator that emits picosecond pulses at an ~1.55-μm wavelength with a repetition rate as a high as 10 GHz and as much as 100 mW of average power. It is pumped with a diode-pumped passively mode-locked 10-GHz $Nd:YVO_4$ laser. Because of its high repetition rate and its potential for ultrabroad tunability, this kind of system is useful for telecom applications. It should be scalable to 40 GHz and higher as required for future telecom networks. © 2002 Optical Society of America

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Many applications, particularly in the field of telecommunications, require picosecond or femtosecond pulse trains with multigigahertz repetition rates. In the wavelength region near 1 μm we recently demonstrated $Nd:YVO_4$ picosecond lasers operating with repetition rates of tens of gigahertz[1] and even 157 GHz.[2] Compared to multigigahertz semiconductor or fiber lasers, these $Nd:YVO_4$ lasers offer much higher output powers. However, for telecom applications one usually prefers sources in the spectral region near 1.5 μm where the choice of gain media for passive mode locking at high repetition rates is limited. We recently demonstrated a passively mode-locked 10-GHz Er:Yb:glass laser,[3] and this approach should also work at 40 GHz. In this Letter we show that a very different concept is also suitable: An optical parametric oscillator (OPO), pumped with a 10-GHz $Nd:YVO_4$ laser, can be operated at a 10-GHz repetition rate. The highest repetition rate previously achieved with a similar device was 2.5 GHz,[4] with a semiconductor picosecond oscillator and a semiconductor amplifier for pumping. Apart from the increased repetition rate, we demonstrate a much higher signal output power, of as much as 100 mW. Scaling to 40 GHz as will be required for future telecom systems appears to be possible. Important advantages of OPOs are that they can be designed for a wide range of signal and idler wavelengths and that a single device can usually be tuned in a wide wavelength range.

The main challenge of operating an OPO in the multigigahertz regime lies in providing sufficient pump pulse energy to operate the device well above threshold. Whereas synchronously pumped OPOs near 100 MHz can easily be operated with average pump powers of the order of 100 mW, multigigahertz OPOs require higher average pump powers. Moreover, it turns out that it is more difficult to achieve high pump powers in the regime of high repetition rates. For passively mode-locked solid-state lasers this difficulty arises from the tendency for Q-switching instabilities,[5,6] the suppression of which requires design aspects that are in conflict with the optimization for high powers. We solved this problem by carefully optimizing a 10-GHz $Nd:YVO_4$ laser for relatively high output powers (as much as 2.1 W) and combining it with a low-threshold monolithic OPO.

Note that it is also possible to pump an OPO at an integer fraction of its repetition rate.[7] The required average pump power would be increased but could be more easily provided by a mode-locked solid-state laser. A disadvantage is that the output pulse energies of the OPO would then no longer be exactly equal.

Our $Nd:YVO_4$ laser is pumped with as much as 5.2 W of power incident upon the crystal from a high-power diode module (Unique Mode) at 808 nm. To avoid quenching effects at high powers we used a 0.5%-doped and 1-mm-thick $Nd:YVO_4$ crystal. The pump beam's radius of 50 μm was chosen as small as possible without severe beam divergence within the crystal length. The simple linear cavity of ~15 mm (free spectral range, 10 GHz; Fig. 1) consisted of a curved output coupler mirror (2% transmission at 1064 nm), the laser crystal, and a semiconductor saturable-absorber mirror[8] (SESAM) as a mode locker, mounted upon a piezoelectric transducer for fine tuning of the repetition rate. This laser produced

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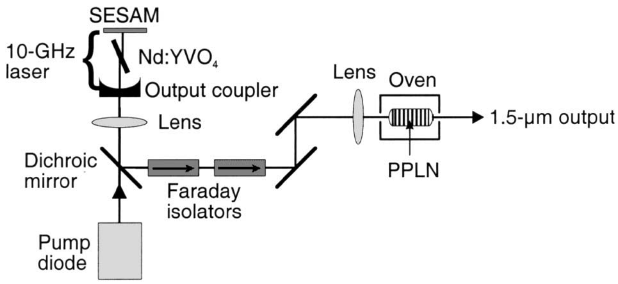

Fig. 1. Experimental setup: a monolithic periodically poled lithium niobate (PPLN) OPO, pumped with the diode-pumped 10-GHz $Nd:YVO_4$ laser.

pulses with as much as 2.1 W of average power, diffraction-limited beam quality, and pulse durations of 14–20 ps. The repetition rate was tunable from 9 to 11 GHz (without significantly changing the pulse parameters). The design guidelines for this kind of laser are discussed in Ref. 2. Two Faraday isolators in the output beam eliminated destablizing reflections from the OPO.

First experiments were carried out with an OPO made from a 6.65-mm-long crystal of periodically poled $LiNbO_3$ with a 29.6-μm poling period. The signal round-trip time was ≈100 ps, corresponding to a 10-GHz repetition rate. Dielectric coatings were evaporated onto the curved end faces (with a 5-mm radius). The input face was coated for high transmission at 1064 nm (pump) and high reflectivity at 1550 nm (signal). The output face had a high reflectivity at 1064 nm (for a double pass of the pump light to be achieved) and an output coupler transmission of 0.05–0.3% at 1550 nm. Both faces had >70% transmission for the idler wave. For temperature tuning and to avoid photorefractive effects, the crystal was mounted in an oven kept at 100–200 °C.

With an optimized pump repetition rate of 10.33 GHz, the pump threshold was reached for 620-mW average pump power incident upon the OPO. This device could be stably operated only up to ≈700-mW pump power because strong thermal effects appeared to affect the stability at higher powers. These effects might result either from signal absorption in the crystal or idler or from idler absorption in the coatings. With the crystal at 150 °C and using 700 mW of incident pump power in 13.6-ps pulses, we obtained signal pulses at 1561.6 nm with 5-mW average power, 5.9-ps duration (from a sech^2 fit of the autocorrelation), 0.47-nm spectral width, and a time–bandwidth product of 0.35.

For further experiments we used a 3× longer (20.8-mm-long) OPO crystal, which we still pumped at a 10-GHz repetition rate. We then obtained a 10-GHz repetition rate of the signal output with three pulses circulating in the OPO cavity. The radius of curvature of the end faces increased to 15 mm such that the focusing parameter was the same as for the first device. For constant focusing parameter and pump power, the parametric gain scales linearly with the crystal length.[9] We therefore used an increased output coupler transmission of 1%. The pump threshold was measured to be 330 mW with 20-ps pump pulses, and a signal output power of 100 mW was reached for 580-mW pump power, resulting in a slope efficiency of 40%. To prevent damage to the coatings, we did not yet apply more pump power. Autocorrelation and optical spectrum of the signal output pulses with 100-mW average power are shown in Fig. 2. We cannot now explain the reason for the small pedestals in the autocorrelation for 100 mW and note that for 82 mW of output power the pedestals go significantly weaker. At 100 mW the signal-pulse duration was 12.7 ps and the spectral width was 0.23 nm, corresponding to a time–bandwidth product of 0.37.

By varying the crystal temperature from 100 to 190 °C we could tune the signal wavelength of a similar device (20.8-mm length, output coupler transmission 0.05–0.3%) from 1535 to 1578 nm, corresponding to idler wavelengths of 3468 to 3267 nm. The required pump repetition rate of the OPO varied over 35 MHz for the full temperature range. Tuning of the OPO with a higher output coupler transmission has not been tried but should work similarly despite the higher threshold, as sufficient pump power is available. Modified poling periods (with different crystals) would allow the signal wavelengths to be varied in a much wider range. A nonmonolithic OPO concept would even permit the use of a single crystal with multiple gratings, with access furnished by translation of the crystal, but the pump threshold would be higher owing to increased losses.

The response of these devices to changes of the pump repetition rate (Fig. 3) is somewhat peculiar as the result of a complicated but well-understood interplay of

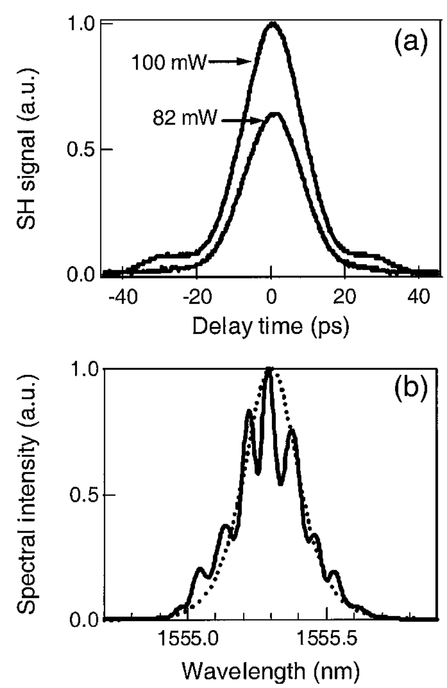

Fig. 2. (a) Autocorrelation for the signal output with 100- and 82-mW average power. The pulse widths are 12.7 and 11.8 ps, respectively. SH, second-harmonic. (b) Optical spectrum for 100-mW output power (solid curve). The spectral width is 0.23 nm (dotted sech^2 fit).

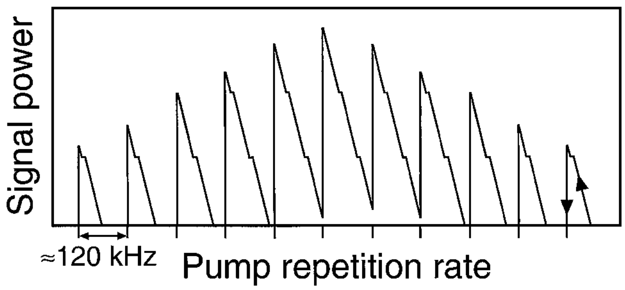

Fig. 3. Schematic of the evolution of the signal power at a pump power of 580 mW when the pump repetition rate is varied (starting from high values). This behavior can be explained by an interplay of residual idler feedback, thermal effects, and a shift of the longitudinal modes of the pump laser (see text).

residual idler feedback and thermal effects: The idler cannot be completely eliminated by the mirror but has a round-trip loss only of the order of 10 dB, and the absorption of signal and (or) idler power heats the crystal. When the pump repetition rate is slowly reduced, starting from too high a value, the signal (and idler) power builds up. As a result of the heating, the resonance is pushed away, i.e., toward an even lower pump repetition rate, so we are in a self-stabilizing situation. When the maximum is reached, the signal power suddenly drops but rises again with further reduction of the pump repetition rate. The maximum is reached with typically two pronounced steps (for the 20.8-mm 1% output coupling crystal). These steps are caused by jumps between different clusters of signal modes (defined by the condition that both signal and idler are resonant) and are accompanied by signal wavelength changes of approximately 0.25–0.4 nm. They always occur at nearly the same signal output power (Fig. 3). For constant cavity length, the equilibrium is found within a few seconds. When the global maximum is reached and the pump repetition is still decreasing, the signal power suddenly vanishes. If the device is pumped well above threshold (580-mW pump power, as much as 100 mW of signal power), the whole pattern as described above is repeated in a similar form with a period of ≈120 kHz (for a 20.8-mm-long crystal) in terms of the repetition rate. This occurs because, by tuning the repetition rate of the pump laser by ≈120 kHz, we also tune the optical frequencies of its longitudinal modes by 3.3 GHz, i.e., the free spectral range of the OPO cavity, so the mode clusters are moved by one period. If the idler feedback could be totally suppressed, we would expect to have a range of pump repetition rates of a few-hundred-kilohertz width in which the signal power would vary quite smoothly. This would significantly enhance the long-term stability of the system, which is currently limited by drifts of the repetition rate of the pump laser. Also, it should allow the signal wavelength to be tuned by adjustment of the pump repetition rate.[10] Similar thermal effects with a doubly resonant OPO with a high-Q cavity were reported in Ref. 11.

In conclusion, we have demonstrated that a synchronously pumped OPO, emitting picosecond pulses near 1.5 μm, can be operated with a 10-GHz repetition rate. We achieved this result by combining an optimized 10-GHz Nd:YVO_4 pump laser with a low-threshold monolithic OPO cavity. We believe that this approach will also be suitable for repetition rates of 40 GHz and higher.

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