600 mW optical output power at 488 nm by use of a high-power hybrid laser diode system and a periodically poled $MgO:LiNbO_3$ bulk crystal

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600 mW second-harmonic blue light at 488 nm has been generated by use of a master-oscillator power amplifier diode laser system as a pump source with a maximum optical output power of 4 W in continuous-wave operation. For frequency doubling, a periodically poled $MgO:LiNbO_3$ bulk crystal was used in a single-pass configuration. A conversion efficiency of 15% and an overall wall-plug efficiency of 4% were achieved.

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Compact blue laser light sources with optical output power greater than 500 mW are required for several applications and will gain more importance in the future. In particular, 488 nm emitting laser sources are needed for spectroscopic analysis,[1] digital photofinishing, and medical applications. This wavelength has been provided mainly by gas lasers, e.g., Ar-ion lasers. Disadvantages of these devices are their large dimensions and small wall-plug efficiency at power levels above 100 mW.

An alternative way to obtain blue laser light is by second-harmonic generation (SHG) by use of high-power near-infrared diode lasers. Low cost commercially available ridge waveguide lasers with external frequency-selective Bragg gratings were used as pump sources for SHG. There an average output power of 7.5 mW at 486, 488, and 491 nm was generated in a periodically poled KTP waveguide crystal in picosecond pulses.[2] A maximum SHG output power of 60 mW at 465 nm in a single-pass configuration was demonstrated in Ref. 3. There a master-oscillator power amplifier (MOPA) system with an output power of 1.5 W was used. A conversion efficiency of 4.2% was obtained. To enhance the output power to 1 W, a nonlinear crystal can be placed in a resonant external cavity[4]; this requires a sophisticated design and control of the ring cavity. To reach a conversion efficiency of as much as 51% at a pump power of ~200 mW, Nguyen *et al.*[5] used a nonlinear crystal with an optical waveguide. Because of optical damage to the nonlinear crystal, the reliable output power is limited to ~100 mW.

Recently the output power of single-frequency near-infrared diode laser systems was increased remarkably. These diode laser systems consist of a distributed Bragg reflector laser used as a master oscillator and a tapered power amplifier (TPA). More than 3 W of power at 1060 nm was reported[6] when a distributed Bragg reflector laser was used as a master oscillator.

In this Letter we report on efficient SHG of 488 nm blue light with a MOPA system emitting at 976 nm as the pump source in a single-pass configuration. A periodically poled $MgO:LiNbO_3$ (PPMgLN) crystal was used for frequency doubling. At a pump power of 4 W a maximum output power of 600 mW at 488 nm was achieved with a conversion efficiency of 15% and an overall wall-plug efficiency of 4%. The setup for achieving the MOPA system and the single-pass configuration for the SHG is presented in Fig. 1.

The MOPA system used for these investigations consists of an InGaAs distributed-feedback (DFB) laser[7] as a master oscillator. The chip has a length of 1.5 mm and is mounted on a CuW heat spreader epi-side down on a C mount. For lateral mode confinement this laser has a 3 μm ridge waveguide structure. The laser can deliver as much as 300 mW of power in lateral and longitudinal single modes. The device was mounted on a heat sink at a temperature of $T_{DFB}=48°C \pm 0.1°C$ and was biased with a driver current of $I_{DFB}=165$ mA ± 1 mA to adjust the wavelength to fulfill the phase-matching condition. The seed power was $P_{seed}=40$ mW.

Two identical aspherical lenses, L1 and L2 (2 and 4, respectively, in Fig. 1) with focal length $f=8$ mm focused light from the master oscillator (1) onto the input facet of the tapered amplifier (5). Between these lenses a 60 dB optical isolator (3) was placed to prevent backreflection.

The power amplifier is an InGaAs single-quantum-well tapered laser structure with an antireflection coating on both facets ($R \leqslant 5 \times 10^{-4}$). The tapered amplifier has a total length of 4000 μm and consists of an index-guided 1350 μm straight section and a gain-guided 2650 μm tapered section. The full tapered angle is $\varphi=6°$. The chip was mounted on a CuW heat

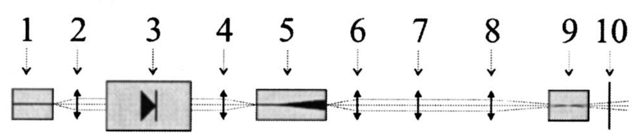

Fig. 1. Setup of the laser diode system: 1, DFB ridge waveguide laser; 2, lens L1; 3, optical isolator; 4, lens L2; 5, TPA; 6, lens L3; 7, lens L4; 8, lens L5; 9, PPMgLN bulk crystal; 10, short-pass filter.

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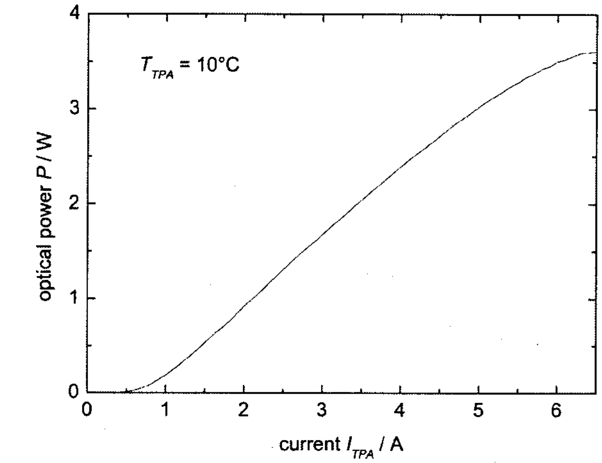

Fig. 2. Power current characteristic of the MOPA emitting at 976 nm for $T_{\mathrm{TPA}}=10°\mathrm{C}$.

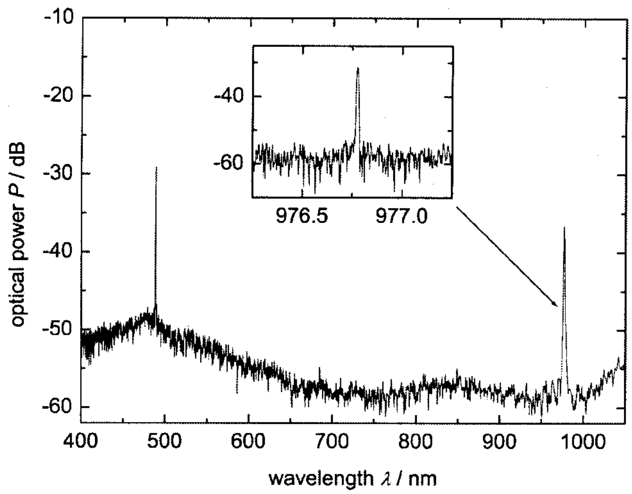

Fig. 3. Spectra of the MOPA at 2.3 W and 300 mW second-harmonic blue light.

spreader p side down on a C mount. In Fig. 2 the power current characteristic of the MOPA system at a heat sink temperature $T_{\mathrm{TPA}}=10°\mathrm{C}$, of the amplifier is presented. At a current of 6.5 A a maximum output power of 3.6 W was reached for the MOPA.

The output beam from the tapered amplifier was shaped for optimal focusing in the 30 mm long nonlinear crystal.[8] The fast axis radiation of the output beam of the MOPA was collimated by aspherical lens L3 (6, Fig. 1; $f=8$ mm). An additional cylindrical lens L4 (7) ($f=150$ mm) was used for slow-axis collimation and astigmatic compensation. To focus the collimated beam into the PPMgLN crystal a spherical lens L5 (8) ($f=175$ mm) was used. The elliptical beam waist inside the crystal is approximately 100 μm $\times$ 60 μm in diameter, which is optimum for the given crystal length.[8] To overcome the likelihood of photorefractive damage a SHG crystal (9, HC Photonics Corporation) was placed within an oven at a temperature of $\sim 70°\mathrm{C}$. It is antireflection coated on both facets for infrared light and the second harmonic. The dimensions of the nonlinear bulk material are 0.5 mm $\times$ 2 mm $\times$ 30 mm. To measure the generated optical power at 488 nm a short-pass filter (10) was used to suppress the infrared light that passed through the crystal.

For efficient SHG the spectral width of the pump laser had to be smaller than the acceptance bandwidth of the nonlinear crystal. The acceptance bandwidth of a 30 mm long PPMgLN crystal as given by the supplier (HC Photonics Corporation) is $\Delta\lambda = 0.04$ nm. Optical spectra of the MOPA and the second-harmonic blue light obtained with an Advantest Q8347 spectrometer are presented in Fig. 3. The inset shows the spectrum of the MOPA measured with a spectral resolution of 0.003 nm. It shows a spectral width of 0.01 nm at a FWHM of the MOPA at 2.3 W, which is well below the acceptance bandwidth of a 30 mm PPMgLN crystal and guarantees high conversion efficiency for SHG.

In Fig. 4 the output power P_{out} for the second-harmonic blue light as a function of pump power P_{MOPA} is presented. Optical output power P_{out} was measured for several pump power levels of the MOPA. As expected, a quadratic dependency between the pump power and the second-harmonic generated light could be observed. At a pump power of 3.6 W we achieved 550 mW output power for the second-harmonic blue light following the quadratic fit, which resulted in a $P_{\mathrm{out}}/P_{\mathrm{MOPA}}$ conversion efficiency of 15% and an overall wall-plug efficiency of 4% including the electrical power of the master oscillator and the power amplifier.

A maximum output power P_{out} of 600 mW for the second-harmonic blue light was reached at 4 W of optical output power of the MOPA. To obtain this optical pump power we reduced the heat sink temperature of the power amplifier to $T_{\mathrm{TPA}}=0°\mathrm{C}$.

For the beam waist dimensions given above a power density of 3.2 kW/cm^2 at 488 nm was estimated. This is far below the damage threshold of 1.7 MW/cm^2 at 488 nm for PPMgLN bulk material given by the supplier. We assume that the deviation of the second-harmonic output power of 600 mW from the quadratic fit is caused by degradation of the beam quality at high output power of the pump laser, as shown in Ref. 9. Nevertheless this results in a con-

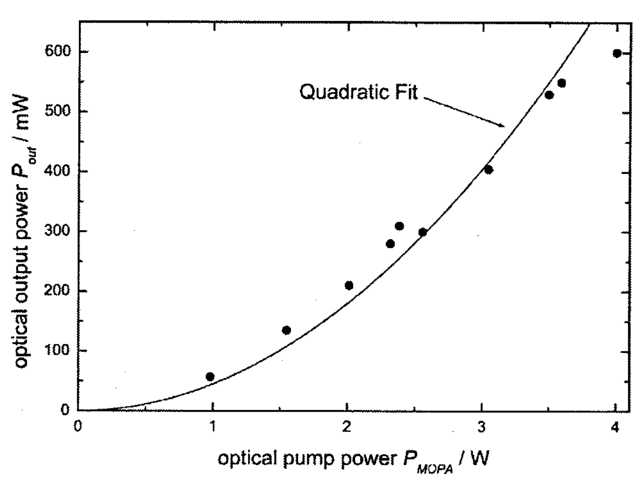

Fig. 4. Optical output power P_{out} at 488 nm versus P_{MOPA} at 976 nm.

version efficiency of 15% and an overall wall-plug efficiency of 4%.

In summary, efficient frequency doubling in a single-pass configuration has been demonstrated. A MOPA emitting at 976 nm with a maximum output power of 4 W was used as a pump source for SHG, and 600 mW second-harmonic blue light at 488 nm was generated with a PPMgLN bulk crystal.

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