Compact Hybrid Master Oscillator Power Amplifier With 3.1-W CW Output Power at Wavelengths Around 1061 nm

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***Abstract*—A hybrid master oscillator power amplifier (MOPA) laser source has been realized by coupling a single-mode three-section distributed Bragg reflector (DBR) laser as master oscillator and a tapered power amplifier with a single lens only. A maximum continuous-wave optical output power of 3.1 W was achieved. The emission spectrum was completely determined by the DBR laser. Single longitudinal mode operation at a wavelength of $\lambda = 1061$ nm was maintained over the whole power range. Up to an output power of 1.8 W, the beam propagation factor M^2 was less than 1.6.**

***Index Terms*—Distributed Bragg reflector (DBR) laser, high-power hybrid laser, master oscillator power amplifier (MOPA), tapered amplifier.**

I. Introduction

DIFFRACTION-LIMITED high-power laser diodes are very attractive for their possible applications as pump sources in erbium-doped fiber amplifiers [1], in communication systems, for ultraviolet or visible light generation by frequency-doubling or tripling [2], for medical applications [3], and for optical printing techniques.

Various types of semiconductor lasers have been designed to achieve high output power in diffraction-limited beams [4]. High-brightness high-power diode lasers based on single emitter chips suffer from low efficiency like α distributed feedback (DFB) lasers [5] or from longitudinal mode instabilities like monolithically integrated master oscillator power amplifiers (MOPAs) [6], [7]. A high optical output power with a beam propagation factor $M^2 < 2$ can be achieved with tapered lasers. However, their spectral properties are poor, because there are no frequency-selective elements incorporated. Very attractive configurations for high-brightness high-power laser light sources are hybrid MOPA combinations, where the output of a single-mode master oscillator (MO) is coupled into a power amplifier (PA). The highest output power of 5 W using a hybrid arrangement has been achieved by O'Brien *et al.* [8]. Up to now, only a sophisticated mounting scheme including an optical isolator on a relatively large arrangement was reported. For the generation of a high optical output power with a small spectral linewidth, the MOPA has to contain frequency selective elements either integrated into the MO (distributed feedback or distributed Bragg reflector (DBR) lasers) or coupled externally (grating reflectors [9]). In [10], a hybrid MOPA combining an α—DFB—laser and a broad-area PA, coupled by two lenses on a compact submount, reached 1.4-W output power with $M^2 = 2$ and a sidemode suppression ratio of the longitudinal modes of higher than 18 dB.

In this letter, we report about the realization of a hybrid MOPA by coupling a three-section DBR laser as MO to a tapered PA with only one gradient-index lens (GRIN-rod lens) without any optical isolator.

II. Device Structures and Experimental Setup

The active layers of the MO as well as the PA consist of a compressively strained InGaAs single quantum well embedded in a AlGaAs waveguide layer, grown by metal–organic vapor-phase epitaxy.

The complete layer structure and electrooptical properties of the DBR laser, emitting at an wavelength of $\lambda = 1061$ nm, are described in [11]. The total length of the three-section DBR laser is 2000 μm with a gain section of 1300 μm, a phase section of 200 μm, and a DBR section of 500-μm length. The DBR laser has a ridge waveguide (RW) structure for lateral mode confinement. The width of the ridge is 3 μm to reach fundamental mode emission, with a lateral full-width at half-maximum (FWHM) of the beam of $\Theta_{\|} = 10°$ and a vertical FWHM of $\Theta_{\perp} = 30°$. The front and rear facets are antireflection coated to 10% and 1% reflectivity, respectively. In [13], it was shown that those lasers have a linewidth smaller than 10 MHz. With this multi-section type of DBR, short pulses at high repetition rates can be generated. After amplification, these might be very useful in frequency conversion.

The layer structure of the amplifier is similar to the laser structure published in [12]. The tapered amplifier has a length of 4000 μm and is divided in an index-guided 500-μm straight section and a gain-guided 3500-μm tapered section. Index guiding in the straight section is achieved by an RW of 3-μm width. The RW section and tapered section have separate contacts. The full taper angle is $\varphi_R = 4°$. The front and rear facet of the tapered amplifier are antireflection coated with a reflectivity $<10^{-3}$.

Both chips were mounted p-side up on AlN heat sinks and attached to temperature-controlled copper plates.

The coupling scheme is shown in Fig. 1. The DBR laser as MO ensures longitudinal and lateral single-mode emission and is coupled into the tapered PA by the GRIN rod lens (GRINTECH Ltd). The length of this lens is l = 4.42 mm with a diameter of $d = 1$ mm, having a working distance of $wd = 150$ μm.

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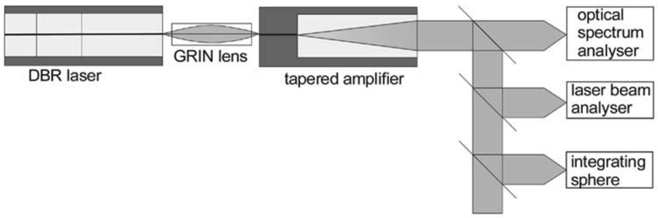

Fig. 1. Scheme of the experimental setup.

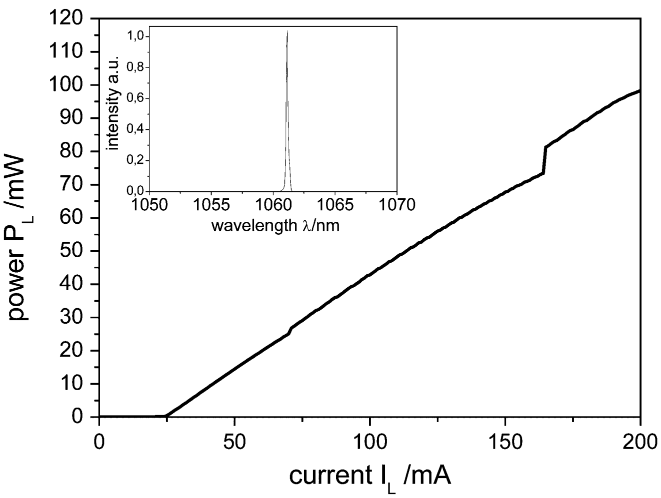

Fig. 2. P–I characteristic of the DBR laser. Inset shows optical spectrum at $I_L = 200$ mA, linear scale.

An integrating sphere was used for measuring the power–current (P–I) characteristic. The longitudinal mode spectrum was measured with an optical spectrum analyzer (Spex270 M) with a resolution of about 0.2 nm. The near- and far-field patterns are measured with a charged-coupled device (CCD) camera of the laser beam analyzer system LBA-100A (Polytec Ltd).

III. Results

First, the DBR laser and tapered PA were investigated independently. In Fig. 2, the P–I characteristic of the DBR laser is shown. The threshold of the laser is 24 mA and the slope efficiency $\eta = 0.56$ W/A. The kinks in the P–I characteristic correlate to longitudinal mode hops due to a thermal detuning of gain and DBR section. The inset shows the spectrum at a drive current of $I_L = 200$ mA according a power of $P_L = 98$ mW. A spectral FWHM of 0.2 nm was measured, limited by the resolution of the grating spectrometer. At an output power of $P_L = 98$ mW, the emission wavelength of the DBR laser at a submount temperature of $T = 21$ °C is 1061 nm.

Fig. 3 shows the P–I characteristic of the unpumped PA. The RW section of the amplifier was biased with various currents I_{RW} between 0 and 225 mA. A maximum power of nearly 450 mW was reached at $I_A = 3.3$ A amplifier current through the tapered section. At a higher current level, the output power decreases caused by thermal rollover. The inset of Fig. 3 shows the optical spectrum at $I_A = 3$ A. The FWHM of the spectrum is 10 nm. The maximum of the spectral distribution is at

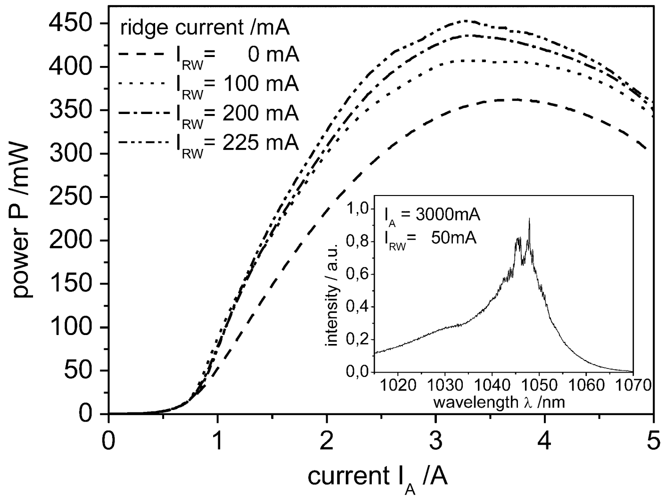

Fig. 3. P–I characteristic of the amplifier at various currents through the RW section. The inset shows optical spectrum at an amplifier current of 3 A and a current through the RW section of 50 mA.

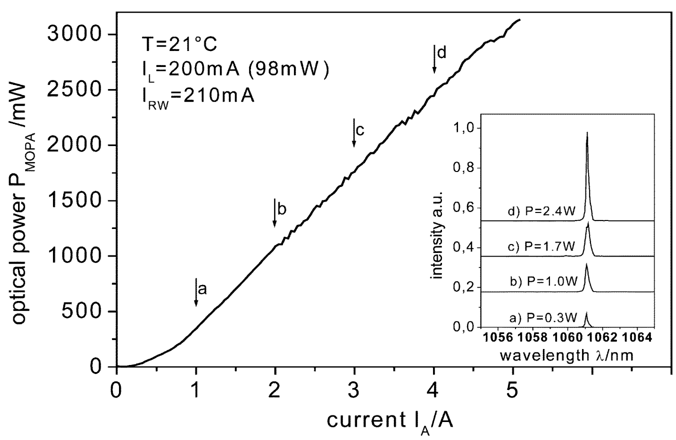

Fig. 4. P–I characteristic of the MOPA at $T = 21$°C. The arrows (a)–(d) indicate amplifier currents at which the longitudinal mode spectra were measured (inset).

$\lambda = 1050$ nm. Thus, the DBR pump laser works at the low energy side of the amplifier optical spectrum. Due to the fact that the gain spectra of the amplifier shifts to lower energy at higher currents (higher temperature), the overlap of the gain curve of the amplifier and the DBR wavelength is enough in our experiments.

Second, the MOPA arrangement was characterized after the illustrated configuration. To realize the hybrid MOPA, the beam emitted by the DBR laser was coupled into the RW part of the tapered PA. The lens was adjusted with a three-axis translation stage to reach a maximum of coupled intensity. The adjustment had to be performed with high precision in the range of 0.5 μm. The power characteristic of the MOPA depending on current through the tapered section is shown in Fig. 4. The output power of the DBR laser was fixed at $P_L = 98$mW. The RW section of the amplifier was biased with $I_{\mathrm{RW}} = 210$ mA to ensure transparency for this section on the one hand and to preamplify the pump beam on the other hand.

The slope efficiency, obtained by a linear fit between 1- and 4-A current through the tapered section, has a value of 0.7 W/A. A maximum output power of 3.1 W is achieved at an injection

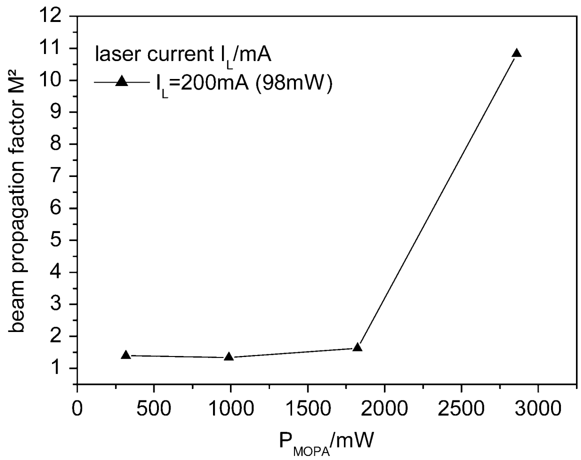

Fig. 5. Beam propagation factor versus optical power of the hybrid MOPA. Line is used as guide for the eyes only.

current through the tapered section of $I_A = 5$ A. The light roughness of the curve for currents greater than 2 A is according to some feedback effects.

Assuming that all light emitted by the oscillator is coupled into the amplifier, an amplification factor of nearly 15 dB can be estimated. In comparison with the stand-alone amplifier, thermal rollover was not observed up to a current of $I_A = 5$ A due to the higher conversion efficiency due to stimulated emission. Under the current experimental condition, the maximum amplifier current is limited by the heat transport by the peltier cooler. At currents higher than 5 A, thermal rollover was observed and the amplifier got damaged.

Longitudinal mode spectra were taken at various continuous-wave (CW) output powers of the amplifier [see inset of Fig. 4(a)–(d)]. The emission spectra of the hybrid MOPA are completely determined by the spectrum of the DBR laser at any current level and show single longitudinal mode operation at a wavelength of $\lambda = 1061$ nm up to an output power of 3.1 W. The FWHM is 0.2 nm, limited by the spectrometer resolution.

The beam quality of the MOPA was characterized by measuring the near and far-field patterns of the beam waist and comparing it to an equivalent Gaussian beam. The beam widths required to calculate M^2 were identified with the $1/e^2$ widths of the intensity profiles in the beam waist and in the far field. The intensity profiles were calculated by summing up columns obtained from CCD camera. That is equal to the moving slit method according to international standard ISO/DIS 11146. Up to an output power of 1.8 W, the beam quality factor M^2 remained nearly unchanged (Fig. 5) with a lowest value of $M^2 = 1.34$. For higher output powers above 2 W, the beam propagation factor increased up to $M^2 = 11$, caused by broadening of the lateral beam waist. This is possibly caused by a transition of the tapered amplifier to an injection-locked laser. Similar to free-running tapered laser [14], higher-order modes in the backward propagating wave distort the field distribution within the cavity.

IV. Summary

In the end, this letter shows a very simple way to realize a compact hybrid MOPA without a sophisticated mounting scheme. We have realized a high-power hybrid laser light source based on a DBR laser emitting at 1061 nm as MO followed by a tapered amplifier. The low M^2 value of 1.6 up to an output power of 1.8 W shows the near diffraction-limited beam properties and displays the potential of this light source for erbium-doped fiber amplifiers. The small spectral linewidth makes suitable this simple light source for frequency conversion based on nonlinear optics.

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