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1.6 W hybrid master oscillator power amplifier with α-DFB-laser as master oscillator at 1057 nm

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A hybrid master oscillator power amplifier is realised on a small area less than 100 mm^2 combining an α-DFB-laser as master oscillator and a broad area laser as power amplifier. A quasi-cw output power of $P = 1.6$ W at the wavelength $\lambda = 1057$ nm is achieved with a beam quality factor M^2 less than 2 and a spectral width less than 6 pm.

Introduction: High-power continuous-wave (CW) sources with a high quality beam are required for many applications including printing, spectroscopy, and fibre-laser pumping. The best results for diode lasers with respect to high output power and a high brightness have been obtained using monolithic and hybrid master oscillator power amplifiers (MOPA). Monolithically integrated MOPAs with flared amplifier section have the disadvantage of a considerable astigmatism connected with a low stability of the longitudinal mode [1, 2]. Up to now, hybrid MOPAs achieved the highest output power but they require a sophisticated mounting scheme including optical isolators [3]. In this Letter we present the properties of a hybrid MOPA combining an α-DFB-laser fabricated by two-step epitaxy [4] and a broad area power amplifier. The mounted MOPA requires an area smaller than 100 mm^2 (Fig. 1).

Setup and properties: The α-DFB-laser is a distributed feedback semiconductor laser with a tilted Bragg-grating in the resonator [5] ensuring longitudinal and lateral singlemode emission. It has a length of $L = 2000$ μm, a stripe width of $w = 80$ μm, a slant angle of 10° and a grating period of 0.885 μm. The reflectivity of the uncoated facets is 0.32. The maximum singlemode output power is $P = 295$ mW (CW) per facet at a wavelength of $\lambda = 1057$ nm. The threshold current is $I_{th} = 750$ mA and the differential efficiency $\eta_d = 0.17$ W/A per facet. The output from the MO is a single longitudinal mode with a linewidth smaller than 6 pm and a sidemode suppression (SMS) higher than 22 dB. The linewidth is at the resolution limit of the measurement equipment. The far field pattern in the slow axis is diffraction limited with $M^2 \leq 1.1$. The main advantage is the low lateral divergence angle of 0.7°–1.0°.

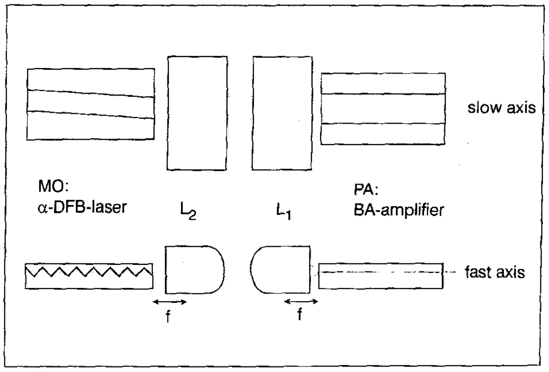

Fig. 1 *Schematic diagram of hybrid MOPA*
Optical design for fast and slow axes shown

The BA power amplifier (PA) has a LOC AlGaAs-waveguide structure with an InGaAs quantum well. The length is $L = 2000$ μm and the stripe width $w = 100$ μm. Both facets of the PA are antireflection (AR)-coated with reflectivity less than 1%. The MO and the PA are mounted on one copper heatsink *p*-side up and *p*-side down, respectively. They are operated at a temperature of 20°C.

The coupling between MO and PA requires the mode matching for the lateral (slow axis) and vertical (fast axis) plane. The considerable divergence in the vertical plane requires beam collimation and focusing, realised by two cylindrical aspherical FAC-micro-lenses of LIMO with a focal length of 0.9 mm as shown in Fig. 1. No collimation and focusing is needed in the lateral plane because of the small lateral divergence of the radiation by the MO. The beam width of the MO emitted light matches nearly the stripe width of the PA. The complete MOPA is realised on a small area $F < 100$ mm^2.

The dependence of power against current of the PA for different pump powers of the MO is shown in Fig. 2. Saw tooth pulses with a rise time of 100 ms were used to operate the PA. Without MO the PA has a threshold current of $I_{th} = 0.49$ A. The PA starts amplification at $I_{PA} = 130$ mA, corresponding to a transparency current density of the PA of $j_T = 65$ A/cm^2. These data also agree with measured length dependent efficiencies. With increasing output power of the MO, the differential efficiency of the MOPA grows from $\eta_d = 0.55$ W/A to $\eta_d = 0.77$ W/A. The maximum output power of the MOPA of $P = 1.6$ W is achieved at a current $I_{PA} = 2.37$ A. It is limited by the onset of ring oscillations in the PA which were indicated by light spots on the side facets. The higher the MO is pumped, the later the competitive ring modes occur, and the higher optimum power the MOPA emits.

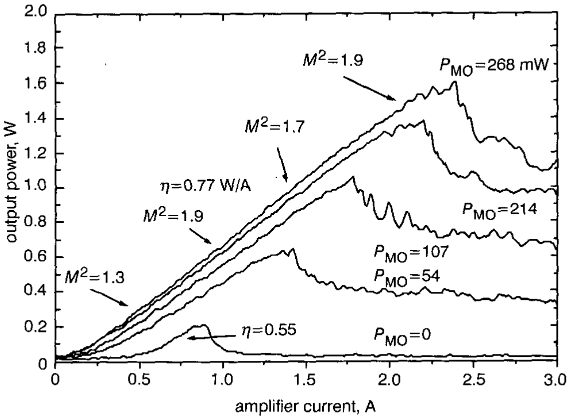

Fig. 2 *Optical power of MOPA against amplifier current at output power of MO for I = 0–268 mA*

The measured near- and far-field patterns at output powers 0.3 and 1.4 W of the MOPA and 268 mW pump power of the MO are shown in

Fig. 3. In both cases the near-field fills the whole output aperture of the PA. The beam waist at the $1/e^2$ level of the maximum intensity has a width of $w_{1/e^2} = 89$ μm at $P = 0.3$ W and $w_{1/e^2} = 91$ μm at $P = 1.4$ W. The lateral angle of the far-field pattern increases from $\Theta_{1/e^2} = 1.2°$ at $P = 0.3$ W to $\Theta_{1/e^2} = 1.6°$ at $P = 1.4$ W. For a current of $I_{PA} = 0.5$ A, the MO saturates the PA so that the far-field pattern has a Gaussian-like shape. If the current of the PA exceeds $I_{PA} = 2$ A then additional lobes appear besides the main lobe. The near- and far-field measurements result in $M^2 = 1.3$ ($P = 0.3$ W) and $M^2 = 1.9$ ($P = 1.4$ W). There is no filamentation.

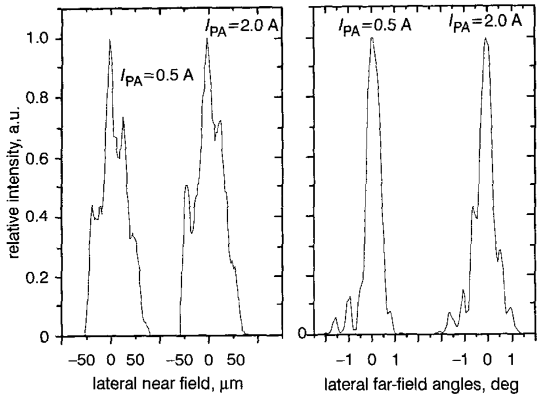

Fig. 3 *Near- and far-field pattern of hybrid MOPA*

Fig. 4 shows the longitudinal spectrum at a PA current of $I_{PA} = 2.3$ A and an output power of the MO of $P_{MO} = 268$ mW. A single longitudinal mode was found with a linewidth less than 6 pm and an SMS higher than 18 dB. No feedback effect from the PA to the MO was detected. This fact demonstrates the stability of the α-DFB-laser as well as the stability of the coupling scheme.

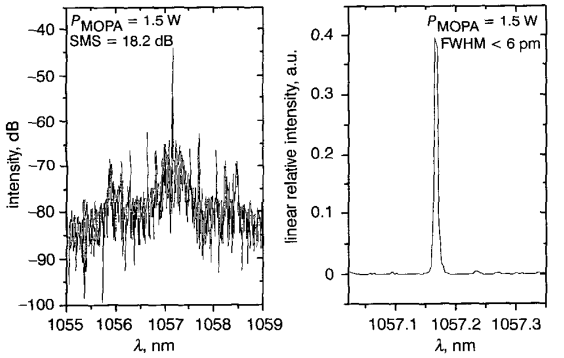

Fig. 4 *Longitudinal optical emission spectrum of hybrid MOPA*

Conclusion: A hybrid MOPA with an α-DFB-laser as MO and a broad area PA has been demonstrated. It was realised on a small area by a quite simple optical scheme. The hybrid MOPA works in a stable manner in the emission spectrum as well as in the near- and far-field as long as the MO saturates the PA. At an output power of $P = 1.4$ W the beam quality factor was better than 2 and the SMSR higher than 18 dB. For higher output power a better suppression of the ring oscillation in the PA is necessary.

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Electrically pumped 10 Gbit/s MOVPE-grown monolithic 1.3 μm VCSEL with GaInNAs active region

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The authors report an electrically pumped MOVPE-grown VCSEL on GaAs substrate with a GaInNAs active region emitting singlemode at 1293 nm with record characteristics. Continuous wave output power at room temperature with 1.4 mW, a threshold current of 1.25 mA and a data transmission rate of 10 Gbit/s has been realised.

Introduction: 1.3 μm vertical-cavity surface-emitting lasers (VCSEL) are promising transmitter devices for short and mid-range optical networks since they can be used for standard monomode and multimode silica-fibres. Regarding eye safety, the maximum transmitted power at 1.3 μm may even be about one order of magnitude higher than at 850 nm. An electrically pumped GaInNAs VCSEL emitting more than 1 mW continuous wave (CW) at 1.3 μm which was grown monolithically by molecular beam epitaxy (MBE) has been presented by Steinle *et al.* [1]. Conversely, metal organic vapour-phase epitaxy (MOVPE) growth is commonly used in the production of VCSELs emitting at 850 nm and is a well established technology [2]. Although reports of MOVPE grown edge emitters on GaAs substrates emitting at 1.3 μm were published [3], the realisation of an electrically pumped VCSEL at 1.3 μm with high optical output power is still difficult to achieve [4]. In this Letter we present the laser characteristics of a monolithic VCSEL with a GaInNAs active region emitting singlemode at 1293 nm and a CW output power of 1.4 mW at room temperature grown with MOVPE. Furthermore, data transmission rates up to 10 Gbit/s could be realised, which was also shown with MBE-grown VCSELs [5].

Device fabrication: The top emitting VCSEL structures were monolithically grown by low pressure MOVPE on (001) GaAs substrate. Triethylgallium (TEG), trimethylaluminium (TMA), trimethylindium (TMI), tertiary butyl arsine (TBA) and 1,1-dimethyl hydrazine (uDMHy) were used as precursors. The samples for this study were grown in a vertical high-speed rotating disc reactor at temperatures between 500 and 700°C. The active region consists of three 6 nm-thick GaInNAs quantum wells (QW) containing 35% indium and 0.7–1.5% nitrogen, separated by 20 nm barriers. The composition values of the quaternary QW could not be determined precisely, since in MOVPE growth the incorporation of nitrogen decreases with increasing indium content [6] and the determination of the indium and nitrogen composition in such quantum well structures is difficult [7].

We have chosen an intracavity-contacted configuration with undoped AlGaAs mirrors and a conventional *pin* doping sequence inside the cavity (Fig. 1). Carbon and tellurium were used as dopants. The top mirror consists of 26 pairs of $Al_{0.9}Ga_{0.1}As$/GaAs, and in order to maximise the reflectivity of the bottom mirror we have used 32 pairs of AlAs/GaAs. A 5 μm current-confinement oxide aperture in a thin AlAs