

Demonstration of a Monolithic, Grating-Surface-Emitting Laser Master Oscillator-Cascaded Power Amplifier Array

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Abstract—The design, fabrication, and performance characteristics of a monolithic grating-surface-emitting master oscillator-cascaded power amplifier laser array are reported. Light output from the amplifier chain is obtained using grating output couplers after each amplifier section. Power outputs of 80–100 mW per amplifier were measured, while the spectral purity of the master oscillator was maintained.

WHILE single-element semiconductor diode lasers are limited to about 200 mW of coherent power, there has been much effort devoted to developing coherent high-power (~ 1 W) arrays [1]. Many array approaches under consideration have not yet demonstrated adequate mode discrimination to produce highly coherent output at high power levels. One approach for obtaining high-power single-mode lasers is to use a low power single-mode laser to inject a chain of amplifiers [2]. This has been well established in pulsed dye laser systems [3] and excimer laser systems [4]. The advantage the laser oscillator-amplifier chain system offers is that the mode control and power output controls are independent of each other.

In this letter, we report on the design and operation of a monolithic grating-surface-emitting master oscillator-cascaded power amplifier (GSE-MOPA) semiconductor laser array [2]. The monolithic array, shown in Fig. 1, consists of a single-mode GSE-distributed-Bragg reflector laser and a chain of cascaded power amplifiers with passive grating-output coupled waveguide sections after each power amplifier section fabricated along a common waveguide structure. The period of the coupling gratings is selected so that the Bragg condition is not satisfied for any wavelength within the gain bandwidth of the amplifier sections. Therefore, the output coupled light is emitted off-normal. To optimize the outcou-

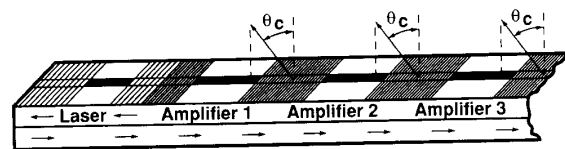


Fig. 1. Schematic diagram of the GSE-MOPA. The emission angle of the out-coupled light is indicated by θ_c for a first-order output coupling grating. A second-order output coupling grating would have emission on the other side of the wafer normal, as well as a second-order beam emitted as a substrate mode.

pled light, it is preferable to select the period of the grating output coupler so that there is only one order and that order is out-coupled into air. The range in first-order grating periods, Λ , that will produce only one out-coupled order is given by

$$\frac{\lambda}{(n_e + 1)} < \Lambda < \frac{\lambda}{n_e} \quad (1)$$

where λ is wavelength of light and n_e is the effective index of the passive waveguide section. To optimize the efficiency and power output from a chain of N identical cascaded power amplifiers and output coupler sections, the coupling strength of each grating coupler must be selected so that the power injected into the next amplifier section is just below the saturation level. Also, the total power coupled out of each passive waveguide section should equal the power generated in each amplifier section. By balancing the power loss of the grating out-coupling with the power gain of the amplifier, the injected power to each successive amplifier in the chain will be the same. In this situation, the total power output of the amplifier chain, P_{out} , is given by $P_{out} = P_{in} CGN$, where P_{in} is the power injected into each amplifier section, C is the fraction of the total power emitted by an output coupler section, G is the gain of an amplifier, and N is the total number of amplifiers in the chain.

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We fabricated GSE-MOPA laser arrays from organometallic vapor phase epitaxial layers grown on a GaAs substrate. The laser structure consists of an $\text{Al}_x\text{Ga}_{1-x}\text{As}$ ($0.25 \leq x \leq 0.75$) graded-index-separate-confinement heterostructure (GRINSCH) with a single 100 Å GaAs quantum well active region [1]. Each GRINSCH layer was 2000 Å thick (4000 Å total) and the p-clad layer in the active sections was 1 μm thick. The gain sections were defined in photoresist and the exposed metal, cap, and a portion of the p-clad was removed by ion-beam etching. The laser oscillator and amplifier sections were 3 μm wide ridge guides with a length of 300 μm. The 3 μm ridge guide was continuous through the passive grating sections. The distributed Bragg reflector (DBR) waveguide sections for the laser oscillator were 200 μm long and the output coupling grating sections for the amplifier sections were also 200 μm long. These DBR waveguide sections were fabricated by etching away the cap and most of the p-clad layer, leaving about 600 Å of the p-clad layer remaining. More details of the fabrication of this structure can be found in [1]. The different period gratings for the single-mode oscillators and the output couplers for the three amplifier sections were exposed using direct write e-beam lithography [5] and ion-beam etched into the remaining 600 Å thick p-clad layer to a depth of about 500 Å. For the single-mode oscillator, a first-order grating (1300 Å period) was used for the rear Bragg reflector and a second-order grating (2600 Å) was used as the front Bragg reflector that also serves to transmit light to the amplifier chain. For the grating output coupler sections, a period of 2300 Å was used. The corresponding second-order Bragg condition is satisfied at a wavelength of 7600 Å, which is outside the gain profile of the amplifier sections, and the out-coupled light (first order) was emitted at an angle of about 23° with respect to the wafer normal.

Fig. 2(a)–(d) shows the spectral output of the first amplifier section (similar spectra were observed from the other sections) as the pulsed injection current (50 ns pulse widths at 0.1% duty cycle) to the single-mode DBR laser oscillator section is increased successively and 0 mA, 150 mA, 300 mA, and 600 mA. When the laser oscillator section is not operated, the spectral output of the amplifiers is broad-band. As the laser oscillator current is increased through threshold, the amplifier's power output is predominantly concentrated in the narrow spectral (~ 1 Å) bandwidth of the laser oscillator. Saturation of the amplifier gain was observed to have occurred with an input power of about 1 mW from the laser oscillator. The peak of the spontaneous emission from the amplifiers occurs at about 7900 Å, consistent with the $n = 2$ quantum well transition, and the oscillator operating wavelength was set (by suitable choice of the first- and second-order grating periods) at 8223 Å. This wavelength was selected because the maximum gain for GRINSCH-SQW structure used in the amplifiers occurs at about 200–300 Å to the long wavelength side of the peak wavelength of the spontaneous emission profile [6].

The power-current curves for the oscillator and each of the three amplifier sections is shown in Fig. 3(a). The

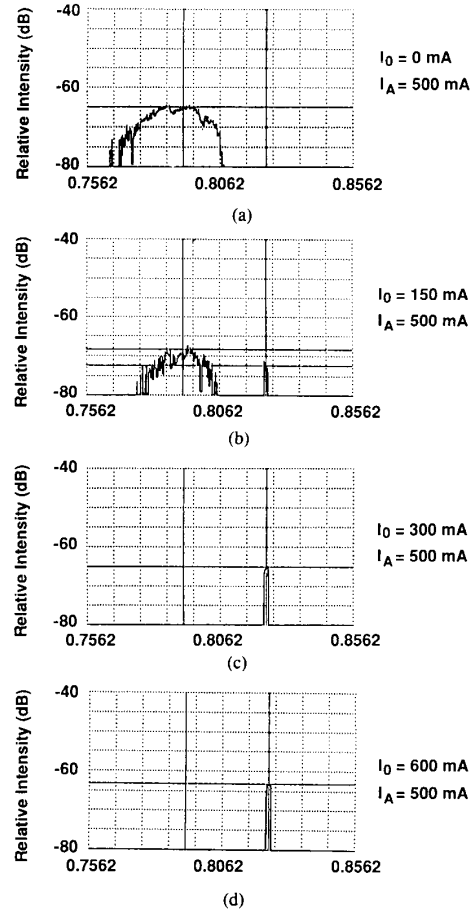


Fig. 2. The spectral output of an amplifier is shown at a constant amplifier current for laser oscillator currents of 0 mA (a), 150 mA (b), 300 mA (c), and 600 mA (d). The current to each amplifier is given by I_A . The spontaneous emission intensity around the laser line is below instrument measurement sensitivity.

threshold of the laser oscillators is about 130 mA and the transparency currents for the amplifiers [obtained from the power-current curves in Fig. 3(a)] are 191 mA, 177 mA, and 176 mA. In Fig. 3(b), the total power output is shown as each amplifier is turned-on and the current is successively increased. The power output of the amplifier chain is seen to increase linearly with the number of amplifiers in the chain, as discussed above. The current to the laser oscillator is adjusted to about twice threshold. When operated at the maximum current value of 600 mA per amplifier section, between 80 and 100 mW is output coupled from each amplifier section. No change in the narrow-band spectral output of the laser oscillator is observed as additional amplifier sections are turned on. Over the operating range, the far-field pattern due to all grating outcouplers had a visibility [7] of 70%. The reason higher values were not observed was probably because of the chirping of the oscillator due to the pulsed operating conditions.

In summary, we have developed a design for a monolithic grating-surface-emitting-master oscillator-cascaded power

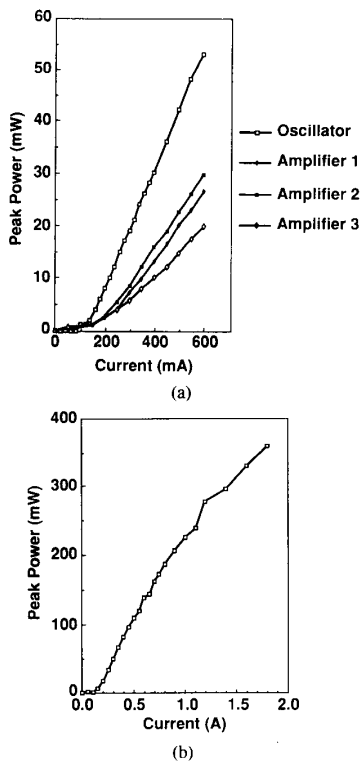


Fig. 3. The power-current curves as shown for the oscillator and the three amplifier sections in (a). The power-current curve is shown in (b) for all three amplifiers as each amplifier is turned-on and the current is successively increased up to a maximum value of 600 mA.

amplifier (GSE-MOPA) semiconductor laser array. These devices have been successfully fabricated using direct write e-beam lithography to write the different grating periods required for the grating output couplers. The operating characteristics of these GSE-MOPA laser arrays reported here demonstrate that the spectral characteristics determined by the laser oscillator and power control provided by the amplifier sections are independent.

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