Mode locking and frequency tuning of a laser diode array in an extended cavity with a photorefractive phase conjugate mirror

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We demonstrate active mode locking and a tunable narrow spectrum under cw conditions in an extended cavity laser which uses an AlGaAs/GaAs array gain medium and an external feedback from a self-pumped photorefractive phase conjugate mirror. The mirror ensures self-aligned, spatially matched feedback. The mode-locked pulses are 92 ps wide. The tuning, obtained by an intracavity grating, has a range of 70 Å under cw conditions.

Extended cavity lasers which utilize semiconductor gain elements and many different types of cavities have long been used for both tunable, single-frequency operation[1] and for short-pulse generation by mode locking.[2] Proper operation of an extended cavity laser requires a semiconductor gain element (which is achieved by antireflection coating semiconductor laser facets) and a high overall feedback (which requires a high-coupling efficiency between the gain medium and the extended cavity, a low loss in that cavity, and a high reflection at the cavity end). A major limitation of extended cavity lasers is the limited power levels at which they operate, determined by the relatively low powers of conventional semiconductor lasers. High powers are readily available from diode laser arrays (LDAs), but incorporating a laser array in an extended cavity is difficult, because the complex radiation pattern does not lend itself to efficient coupling. Several types of extended cavities have previously been used in conjunction with array gain elements. These include a simple mirror in a mode-locked laser,[3] a Fabry–Perot étalon[4] in a laser which oscillates in a single longitudinal mode, and a diffraction grating[5] for control over the radiation pattern.

Here, we demonstrate active mode locking and frequency tuning under cw conditions in a new type of an extended cavity laser. The new laser has an AlGaAs/GaAs array gain element and it makes use of a self-aligned, spatially matched feedback from a photorefractive passive phase conjugate mirror (PCM). The laser uses the advantages offered by the almost completely reciprocal imaging and distortion correction properties of PCM, which ensure efficient coupling to the array and the possibility of incorporating intracavity elements. Active mode locking with resultant pulses of 92 ps duration, a narrow spectrum under cw conditions, and incorporation of an intracavity grating, which enables frequency tuning over a range of 70 Å, have been obtained. The use of a PCM in conjunction with an extended cavity laser has been previously modeled and experimentally demonstrated for a conventional single-emitter gain element[6] and for arrays.[7,8] Such compound lasers (which may have rather complicated cavities) may open the possibility of obtaining a significant increase in the intensities of short pulses generated from compact diode lasers.

One of the extended cavity lasers we constructed is shown schematically in Fig. 1. The gain medium consisted of a ten gain guided emitters array, operating at a wavelength near 0.8 μm with a double-lobed far field. The gain medium was obtained by antireflection coating (using silicon monoxide) a commercial LDA. The back facet was high-reflectivity coated and the maximum power before coating was 100 mW. The intracavity grating had 1200 lines/mm. The grating is located in such a manner as to keep the feedback level from the PCM constant over the entire tuning range.

The PCM was a ring photorefractive oscillator[6–8] with a $BaTiO_3$ crystal. It is a passive (self-pumped) device which can operate at very low-power densities and does not eliminate the longitudinal modes of the extended cavity as other types of PCMs do.[8,9] The PCM provided a reflectivity of about 15% (not corrected for Fresnel reflections) which was not dependent on the light intensity. The buildup time of the phase conjugate beam depends on the light intensity and for the power levels in the present laser, it was one to several minutes. A gradual change of the laser parameters, following the achievement of a steady-state feedback level, such as sinusoidally modulating the gain or rotating the intracavity grating, does not deteriorate the reflectivity. The photorefractive crystal had dimensions of $7\times6\times3$ mm^3 (with the c axis along the 6 mm side). It was held in a cuvette and immersed in an index matching oil. As an output coupling port we used a 4% intracavity beamsplitter (a flat glass) since the highly reflecting back facet could not serve as an output port.

The laser was first operated under cw conditions. Plots of the output power versus the injection current in the

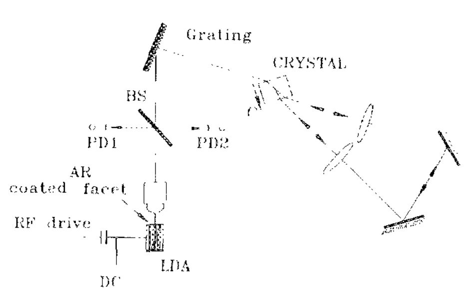

FIG. 1. Schematic diagram of the extended cavity laser with the intracavity grating. (LDA) laser diode array, (PD) photodiode, (BS) beamsplitter, (C) denotes the direction of the crystal c axis.

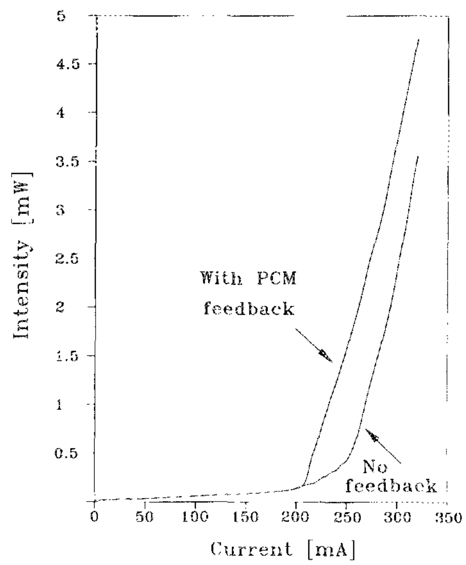

FIG. 2. Output power vs the injection current in the antireflection-coated laser with and without the feedback from the PCM.

antireflection-coated laser array are given in Fig. 2 with and without the feedback from the PCM. The spectra of the output are shown in Fig. 3. The laser had a threshold current of 255 mA without feedback and a broad spectrum, shown in Fig. 3(a) for a drive current of 280 mA. With feedback, the threshold current was reduced to 215 mA. At 230 mA and without feedback, the output was

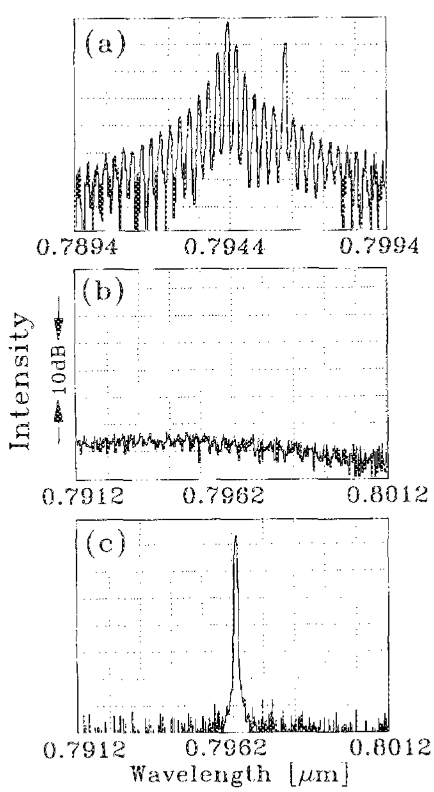

FIG. 3. Spectra of the laser output measured with a resolution of 0.1 nm. (a) cw operation at 280 mA without external feedback, (b) cw operation at 230 mA without external feedback, (c) cw operation at 230 mA with external feedback. The vertical scale in all cases is 5 dB/div.

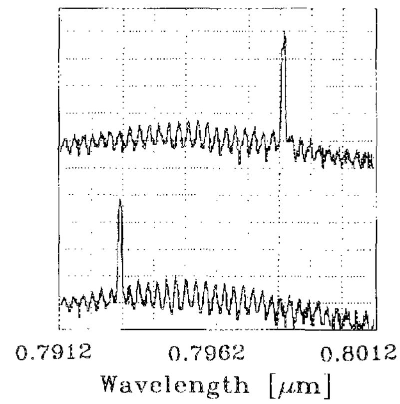

FIG. 4. Operation of the laser with the intracavity grating for two wavelengths, separated by 55 Å. These two points represent part of the 70 Å tuning range. Vertical scale is 5 dB/div. Horizontal scale is 1 nm/div.

essentially white noise [Fig. 3(b)]. When the external feedback was applied (with the drive current held at 230 mA), the spectrum narrowed to a stable single mode as seen in Fig. 3(c). The spectra shown in Fig. 3 were measured with a resolution of 0.1 nm. Therefore, the spectrum shown in Fig. 3(c) may represent a cluster of modes of the long cavity (which are separated by 218 MHz), all centered around a single mode of the short cavity. The wavelength of the laser could be tuned by rotation of the grating over a range of 70 Å. Figure 4 shows two points separated by 55 Å out of that 70 Å range.

The mode-locking experiments were performed before inserting the intracavity grating. Active mode locking was obtained by sinusoidally modulating the gain at the extended cavity resonance frequency (218 MHz) or at the second harmonic of this frequency (436 MHz). The dc bias of the injected current was slightly below the threshold of the laser with the feedback (180–190 mA). The overall time-dependent current, however, is higher (and lower) due to the added ac modulating current. Pulses of 92 ps duration were obtained in both cases. A typical pusle train, detected by a Si *p-i-n* photodetector and a sampling oscilloscope (with a combined impulse response of 65 ps) is shown in Fig. 5. The peak pulse power inside the cavity was on the order of hundreds of mW, for average drive currents around the threshold current of the extended cavity laser. That power could be increased significantly by using higher dc drive currents, resulting also in slightly wider pulses.

In conclusion, we have demonstrated 92 ps active mode-locked pulses and a narrow spectrum under cw conditions with a tunability range of 70 Å in an extended

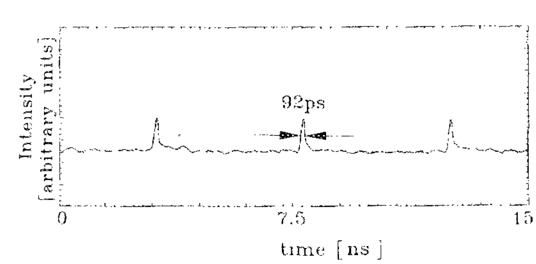

FIG. 5. Detected mode-locked pulse train.

cavity laser with an array gain element and a passive phase conjugate mirror as the feedback element.

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[1] R. Wyatt, K. H. Cameron, and M. R. Matthews, Brit. Telecom. Technol. J. **3**, 5 (1985).
[2] P. T. Ho, L. A. Glasser, E. P. Ippen, and H. A. Haus, Appl. Phys. Lett. **33**, 241 (1978).
[3] J. P. van der Ziel, H. Temkin, R. D. Dupuis, and R. M. Mikulyak, Appl. Phys. Lett. **44**, 357 (1984).
[4] H. Hemmati, Appl. Phys. Lett. **51**, 224 (1987).
[5] J. E. Epler, N. Holonyak, R. D. Burnham, T. L. Paoli, and W. Streifer, J. Appl. Phys. **57**, 1489 (1985).
[6] K. Vahala, K. Kyuma, A. Yariv, S-K. Kwong, M. Cronin-Golomb, and K. Lau, Appl. Phys. Lett. **49**, 1563 (1986).
[7] S. Weiss, M. Segev, and B. Fischer, IEEE J. Quantum. Electron. QE-**24**, 706 (1988).
[8] M. Segev and B. Fischer, J. Quantum Electron. (to be published, 1990).
[9] B. Fischer and S. Sternklar, Appl. Phys. Lett. **46**, 113 (1985).