Single-Mode High-Power Semiconductor Lasers Using Phase Conjugation

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At Risø National Laboratory we have developed a new technique for single-mode operation of laser diode arrays. A gain-guided GaAlAs laser diode array is coupled to an external frequency selective phase conjugate feedback system. The selective feedback forces the array, which has low spatial and spectral coherence when running freely, to oscillate in a single spatial and a single longitudinal mode. In contrast to most other reported techniques for improving the coherence of laser arrays, our technique improves simultaneously the spatial and the spectral coherence. At a laser drive current of two times the threshold current, the far field pattern is reduced to only 1.4 times the diffraction limit, the spectral bandwidth is less than 0.02 nm and the coherence length is increased by a factor of 70. The technique has general validity and can be applied to various other multimode laser systems.

Introduction

High-power semiconductor lasers can produce impressive amounts of optical power and they are attractive due compactness and simplicity of operation. Figure 1 shows an illustration of a typical laser array (or broad-area laser). Laser arrays are commercially available and can emit power up to 4 watts continuously.

In general, semiconductor lasers are power limited because severe damage occurs at the output facet of the device, if the energy density becomes too large. In order to extract several watts of power the width of the emitting area of a laser array is increased by two orders of magnitude as compared to a low-power (milliwatt range) single-mode semiconductor laser. The contact metallization on top of the laser array, see Fig. 1, has been arranged in stripes in order to ensure a uniform current injection across the emitting area. Moreover, proton implantation has been applied to the semiconductor material in between the stripes to obtain an even better current confinement under the metal stripes. Despite the design with multiple metal stripes, the broad emitting area leads to a device that operates in several spatial and longitudinal modes simultaneously. The oscillation of multiple modes results in a non-diffraction limited radiation pattern with low spatial coherence and an optical bandwidth of 1-2 nm, which yields a very low coherence length of a few hundred microns.

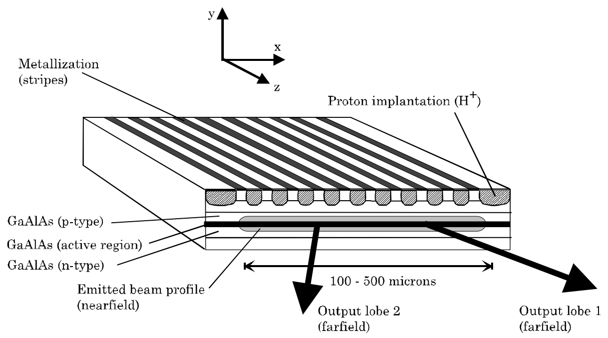

Fig.1. Illustration of a high-power laser diode array.

The poor coherence characteristics limits the usefulness of the high-power sources, since it especially limits the focusability of the output beam, which is essential in many applications such as the launching of light into single-mode waveguides, high precision material processing with lasers, blue light sources based on second harmonic generation and efficient pumping of solid state lasers.

The laser array is the basic unit of many other high-power devices such as laser bars and two-dimensional (2D) laser bars. Figure 2 shows a typical laser bar that can emits up to 20 watts continuously; a number of laser arrays are positioned next to each other on the same substrate. The radiation from a laser bar is almost similar to the radiation from an array; however, it is partly incoherent due to the fact that no coupling takes place between the individual laser arrays in the bar. A two-dimensional laser bar is a number of laser bars placed on top of each other. Due to thermal effects 2D laser bars are not operated continuously, but in a pulsed mode with peak powers up to several kilowatts.

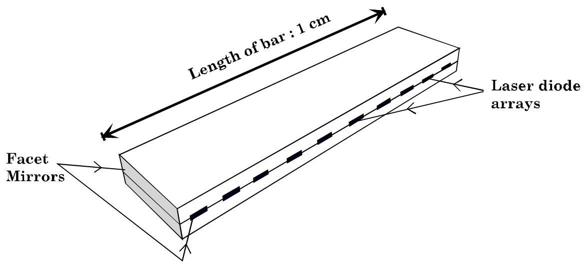

Fig. 2. Illustration of a laser bar. It consists of ten laser arrays placed next to each other on the same substrate.

Over the last 15 years there has been intensive research in the development of high-power monolithic coherent sources. This has proven to be a particularly challenging task. As a result, virtually all the high-power lasers commercially available today are based on the laser array and they emit the radiation into two broad far field lobes, as seen in Fig. 1, in directions that are symmetric around the normal to the output facet, instead of the desired single diffraction-limited lobe. Alternative products such as the master oscillator power amplifier, which deliver several watts with good coherence properties, are commercially available, but are relatively expensive due to the more complicated chip design as compared with the very simple design of a traditional laser array.

In parallel with the research on monolithic coherent sources there have been investigations in the area of external-cavity controlled devices. These investigations have resulted in several techniques for the enhancement of the coherence properties of especially laser diode arrays[1-4]. In the following a new technique using phase conjugate feedback, developed at Risø National Laboratory, for the improvement of the temporal and the spatial coherence of laser arrays will be discussed.

Radiation properties of the laser array

As mentioned above, the laser array has two predominant directions for radiating its energy. The two directions, which are known as the radiation lobes arise from the shape of the spatial modes supported by the cavity of the array. In Fig. 3 the far field profiles of three of the spatial modes are shown schematically. The profiles are displayed along the x-axis (see Fig. 1). Each spatial mode radiates its energy in two lobes but the directions of each mode are slightly different. The different radiation angles allow an efficient mode selection using spatial filtering. The profiles of the spatial modes along the y-axis are identical and have a diffraction-limited Gaussian-like shape.

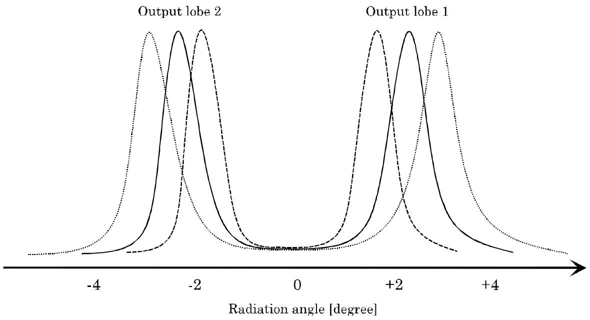

Fig. 3. Illustration of the intensity profiles (along the x-axis) corresponding to three of the spatial modes of a laser array. Radiation angle is with respect to the z-axis.

The laser array has no build-in mode discrimination and, as a result, 10-15 longitudinal modes usually oscillate simultaneously. The longitudinal mode spacing is approximately 0.1 nm for a typical laser array and, consequently, the coherence length of these lasers is very short.

Phase conjugate feedback

Optical feedback has a very strong influence on the characteristics of lasers. In order to improve the coherence properties of the radiation the number of oscillating modes must be reduced. This can be accomplished using external feedback. We have demonstrated that a phase conjugate mirror (PCM) is a very effective device to ensure an efficient feedback to a laser since such a mirror is capable of redirecting the incoming light regardless of its angle of incidence. The large field of view of a PCM is especially important if the laser source has a broad emitter area, as is the case for a laser array.

A photorefractive barium titanate crystal can be used as a phase conjugating mirror[5]. Using different dopants this crystal has a response in the wavelength range of 500-1100 nm. It is self-starting, i.e., a laser beam can be directed to the crystal and the phase conjugate replica of the incident beam will within a few tens of seconds be generated through a self-organized grating structure formed by four-wave mixing. This process requires only a few milliwatts of power in order to initiate and, therefore, barium titanate is suitable for phase conjugating the radiation from even low-power semiconductor lasers.

Frequency selective feedback

Using a spatial filter and a frequency selective filter in the external cavity formed between the laser array and the phase conjugate mirror we have developed a new technique that improves the coherence of laser arrays dramatically. This new technique is referred to as *frequency selective phase conjugate feedback* (FSPCF)[6]. To illustrate the concept we consider the experimental setup shown in Fig. 4. A laser array is coupled to a phase conjugate mirror (PCM).

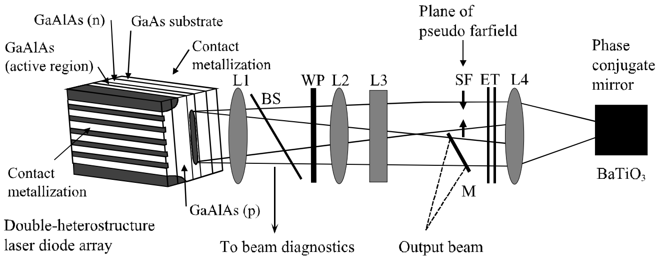

Fig. 4. Experimental setup. The radiation from a laser array is directed towards a photorefractive phase conjugate mirror. The phase conjugate feedback improves the coherence characteristics of the laser array. L1-4: lenses, WP: half-wave plate, BS: beamsplitter, SF: spatial filter, M: mirror, ET: etalon.

The laser is a 0.5 Watt GaAlAs 10-stripe 100 microns array lasing at 814 nm (model SDL-2432). The PCM is made up of a rhodium doped $BaTiO_3$ crystal that is arranged in a self-pumped configuration[5]. A beamsplitter directs a part of the laser emission to a spectrometer so the spectrum can be monitored. The wave plate is used to ensure a polarization state that gives a high phase conjugate reflectivity in the barium titanate crystal.

To discriminate the longitudinal modes of the array a Fabry-Perot etalon (frequency selective filter) is included in the external cavity. Thereby only a limited number of modes are allowed to interact with the adaptive PCM. Moreover, a spatial filter formed by two razorblades is positioned in the external cavity and only the energy radiated in between the razorblades is allowed to reach the PCM. The filters cause the feedback to become very selective, i.e. the phase conjugate feedback can only enhance certain selected modes and will suppress all others.

We consider two different feedback configurations: (i) the single-lobe and (ii) the twin-lobe. In the single-lobe configuration a removable mirror (M) is inserted halfway through the beam line, at the position where a lens has generated a pseudo-far field, and couples out one half of the radiated far field pattern. The reflected beam is the output beam of the system. In the twin-lobe configuration the mirror and the spatial filter (SF) are removed and all the energy of the array is directed towards the PCM.

Twin-lobe configuration

First we will consider the twin-lobe configura-tion. Figures 5(a) and 5(b) display the spectrum of the array when it is exposed to feedback and when it runs freely, respectively. The drive current is two times the threshold current. In Fig. 5(a) it is seen that the cooperative interaction between the PCM, the etalon and the array forces the spectrum to narrow down significantly.

The bandwidth is measured to be reduced from a full width at half-maximum (FWHM) of 0.7 nm to less than 0.02 nm (resolution limited). The etalon has a free spectral range of 350 GHz, a finesse of 17 and a bandwidth of 0.04 nm. The mode spacing for two spatial modes of the array is approximately 0.02 nm, the longitudinal mode spacing is 0.11 nm and, as a result, even the most closely spaced modes have sufficiently different transmission losses when they pass the etalon and, consequently, single-mode operation (a single spatial mode is selected from one longitudinal mode) can be obtained.

Figure 6 shows the far field (along the x-axis) of the array (a) without any feedback, (b) in the twin-lobe feedback configuration and (c) in the single-lobe feedback configuration. When the array runs freely, as seen in Fig. 6(a), the far field is a broad radiation, since it consists of several spatial modes (compare with Fig. 3). However, when the array operates at one single spatial mode, the far field changes to the well-known twin-lobe, as seen in Fig. 6(b) (compare with one spatial mode from Fig. 3).

The number of spatial modes that oscillate have been reduced to one, but still the radiation pattern is non-diffraction limited. In the single-lobe configuration, however, the far field pattern is narrowed down significantly.

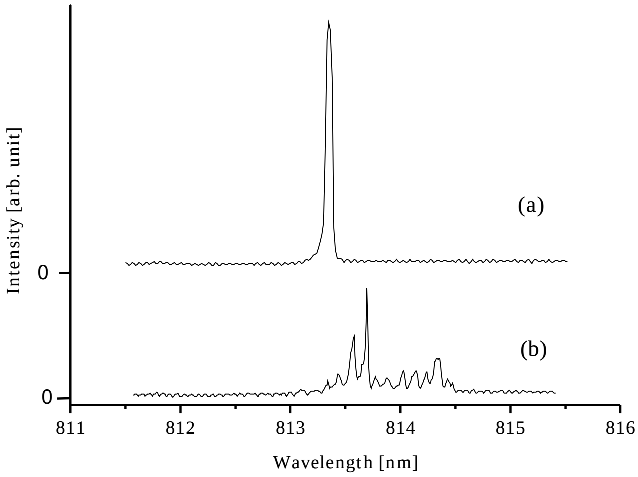

Fig. 5. Optical spectrum at two times the threshold current. (a) Phase conjugate feedback is applied: FWHM = 0.02 nm; (b) Freely running: FWHM = 0.7 nm.

Single-lobe configuration

Next we consider the single-lobe configuration. Feeding back only one of the two lobes is somewhat similar to a previously reported injection locking technique, where a photorefractive PCM is used[4]. Figure 6(c) displays the far field for a drive current of two times the threshold current. It is the negative angle lobe (output lobe 2, see Fig. 3) that is fed back to the array. As the reflectivity of the PCM builds up, the positive far field lobe grows at the expense of the negative lobe, and the radiation pattern becomes asymmetric (compare with Fig. 6(b)). From a technological point of view, this asymmetry is very attractive since a large fraction of the radiated energy can be extracted from the laser system using the mirror (M). The edges of the two razorblades that form the spatial filter are positioned at -1.9 degrees and -2.5 degrees and only allow energy radiated within this range to reach the PCM (one spatial mode is selected).

For a 100 micron wide laser junction lasing at 814 nm, the diffraction limit is 0.55 degree.[3] The FWHM of the far field in Fig. 6(c) is measured to 0.7 degree corresponding to only 1.4 times the diffraction limit.

In the single-lobe experiment 70% of the available energy after lens L3 is carried in the output beam, and 50% of the total amount of radiated energy (before lens L1) is contained in the output beam. However, as seen from the profile in Fig. 6(c), the positive lobe contains more than 80% of the total radiated far field energy; based on this profile it is estimated that 80% of the total amount of radiated energy can be contained in the output beam provided that losses at lenses etc. are eliminated. The measured power of the output beam is 107 mW for a drive current of two times the threshold current. The amount of feedback measured at the beamsplitter is typically in the range of 0.4-1%.

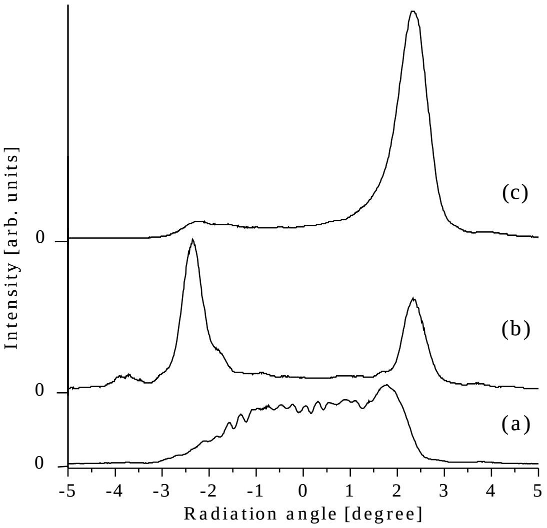

Fig. 6. Measured farfield from the array (all curves on the same scale): (a) Freely running (b) The twin-lobe configuration (the mirror M and the spatial filter SF are removed); (c) The single-lobe configuration.

The coherence length of the output beam (single-lobe configuration) is measured using a standard Michelson interferometer. It is observed that the coherence length is increased by a factor of 70 when the feedback is applied to the laser array. The phase conjugate feedback increases the coherence length to at least 25 mm.

Once the PCM is turned on and single-mode operation is obtained, the output becomes very stable with respect to wavelength and power. The output characteristics are almost unaffected by even very strong mechanical vibrations of the optical table or by tapping on the optical components of the setup. The measured standard deviation of the detected power and the center wavelength are 0.6% and 0.01 nm (resolution limited), respectively, for continuous operation over more than three hours. The system was tested over five days (hands-off operation) continuously and the wavelength and power varied less than 0.1 nm and 1.5%, respectively.

Tunable wavelength

We have also developed a technique for tunable single-mode operation of a laser array^7. This technique is also based on the concept of frequency selective phase conjugate feedback. The configuration is very similar to the configuration shown in Fig. 4. The only difference is that the etalon is replaced by a diffraction grating; the radiation from the laser array is diffracted in the grating and then enters the phase conjugate mirror. Tilting the diffraction grating controls the wavelength of the laser emission. Figure 7(a) shows the spectrum of the laser array when it runs freely at a drive current of two times the threshold current. Figures 7(b-e) show the single-mode spectrum for different tilts of the grating. The wavelength can be tuned over a range of 5 nm.

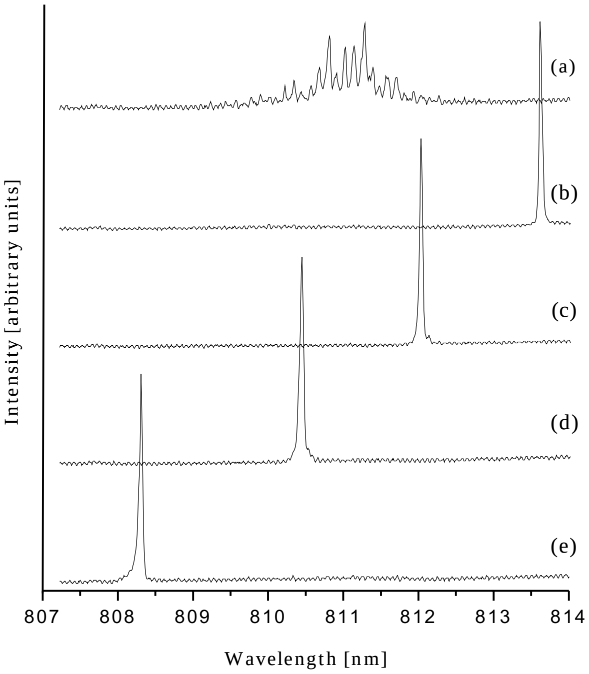

Fig. 7. Optical spectrum. (a) The array runs freely; (b) The feedback is applied. The angle of incidence, θ, at the grating is 19.73 deg. Bandwidth (FWHM) of 0.03nm; (c) Same as (b) but θ = 19.60 deg; (d) Same as (c) but θ = 19.47 deg; (e) Same as (d) but θ = 19.30 deg.

Conclusion

We have presented a new technique using frequency selective phase conjugate feedback that highly improves the spatial and temporal coherence of high-power semiconductor laser arrays. At a drive current of two times the threshold current the far field is narrowed down to 1.4 times the diffraction limit and the coherence length is increased with a factor of 70.

Finally, it should be emphasized that this technique also applies to laser bars and, thereby, it is possible to create a laser source with good coherence characteristics and with an output power of ten watts or even more.

The results presented are obtained in connected with the work performed under a Ph.D. project by M. Løbel. The concept of the frequency selective feedback technique has been patented^8 by Risø National Laboratory and licensed to a Danish company.

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