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CONTROL OF LASER RADIATION PARAMETERS

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Phase locking of a diode bar using a phase diffraction mirror

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Abstract. **A method for synchronising the emission of a laser diode bar using a phase diffraction mirror is proposed. It is confirmed experimentally that this method makes it possible to phase the bar emission, but its selective properties are insufficient to ensure stable single-mode lasing.**

Keywords: *laser diodes, phase locking.*

Phase locking of diode lasers (i. e., coherent addition of their beams) is a promising direction in the development of high-power semiconductor lasers with high beam quality (in particular, with low beam divergence). To date, many various phase-locking methods and schemes have been proposed and investigated; the best results were obtained with the schemes using an external cavity [1]. The latter provides an optical coupling between the diodes from a set placed in the cavity by transferring some part of radiation of each diode to others, thus implementing their locked lasing. However, a drawback of the scheme with application of external cavity is the excitation of collective modes (supermodes) of total radiation in it; the number of these modes is determined by the number of the diodes involved in collective lasing. Therefore, to obtain a single-mode total output beam of radiation phased by an external cavity, it is additionally necessary to select a single supermode. Specifically this problem is the main one at the modern stage of research on phase locking of diode lasers. It is rather difficult to solve because of the proximity of lasing thresholds for different supermodes. This circumstance explains rather poor efficiency of many previously proposed mode selection techniques and calls for developing new ones.

In this paper, we report the results of experimental studies of the method for phase-locking laser diode bar radiation with a phase diffraction (grating) mirror (Fig. 1), which was theoretically proposed in [2]. According to this method, a diode bar is placed in an external cavity, formed by a Fourier lens (*6*) and a phase diffraction mirror (*7*), which serves as an output mirror and is located in the lens focal plane. The laser diode bar (*2*) has a highly reflecting rear mirror (*1*) and an antireflection coating on an output aperture (*4*). The radiation emitted by the diode bar is focused by the Fourier lens directly on the mirror surface. This lens performs a direct Fourier transform of the incident radiation and inverse Fourier transform of the radiation reflected from the phase mirror. As a result, the reflected and transformed image of the emitting bar end face (*4*) is superimposed on itself in a position specularly rotated with respect to the optical axis of the scheme. Thus, the radiation from one half of the diodes arrives at the diodes of the opposite half to implement their optical coupling. Simultaneously, the Fourier lens performs the function of a selective element: it filters off high spatial harmonics.

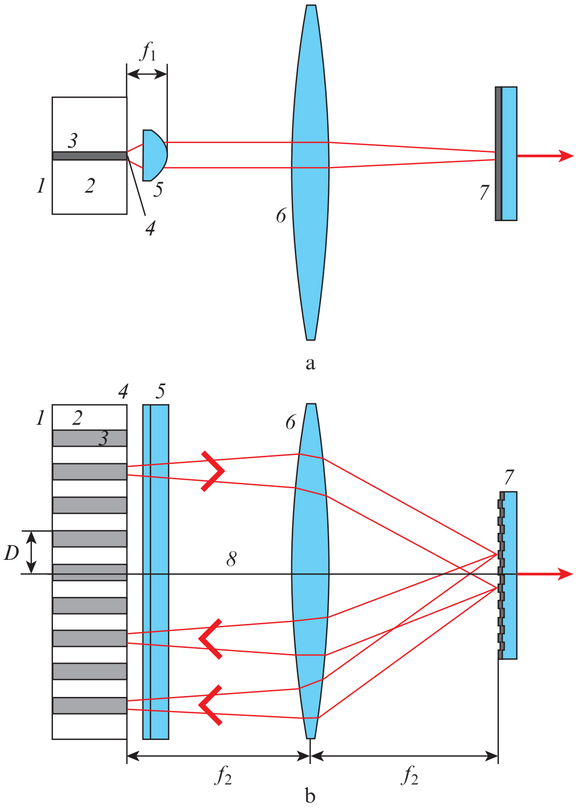

Figure 1. Phase-locking scheme using a phase diffraction mirror and Fourier optics: (a) side and (b) top views;
(*1*) highly reflecting rear mirror of the diode bar; (*2*) laser diode bar; (*3*) individual diode; (*4*) bar output aperture; (*5*) collimating lens with a focal length f_1; (*6*) lens with a focal length f_2; (*7*) reflecting phase diffraction grating; (*8*) optical axis of the system. The lines show the beam boundaries for the ±1st diffraction orders from one laser diode.

The phase diffraction mirror is a reflecting diffraction grating deposited on a transparent substrate (*1*) with corrugated surface (*2*) (Fig. 2). The rectangular corrugation period $\Lambda = \lambda D/f_2$, where D is the distance between neighbouring bar diodes, f_2 is the focal length of the Fourier lens, and the groove

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depth is a quarter of the operating wavelength λ in vacuum. A multilayer dielectric mirror coating, whose reflectance is calculated from the working value λ, is deposited on this substrate.

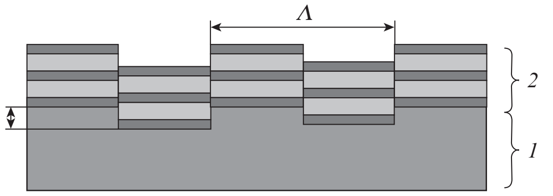

Figure 2. Structure of the phase diffraction mirror: (*1*) substrate and (*2*) multilayer coating.

With the aforementioned corrugation parameters, this phase diffraction mirror provides suppression of the reflection in the zero diffraction order of incident plane wave and equality of the ±1st diffraction order amplitudes. The equality of phases of the ±1st diffraction orders is provided if the grating is located symmetrically with respect to the optical axis of the entire system. Estimates show that these orders may contain up to 80% of total reflected radiation power.

Note that we have already used a multilayer diffraction structure for phasing the radiation of a diode array in our previously studied method with a resonant waveguide mirror [3, 4]; this method has demonstrated good efficiency. Note that the resonant waveguide mirror had a more complex structure than the phase mirror.

Laser diode bar synchronisation mechanism using a phase diffraction mirror is as follows. The radiation of each laser diode, being reflected from the mirror, is split into two beams (the ±1st reflected diffraction orders); hence, it arrives not only at its mirror partner in the bar, as it would be in the case of conventional plane mirror, but also at two laser diodes neighbouring this partner (see Fig. 1b). As a result, each bar diode receives radiation from two other diodes (the only exception is the diodes located on the bar edges). Figure 3 shows a schematic of optical coupling (bidirectional energy exchange) of laser diodes for bars containing odd and even numbers of diodes. In the case of odd number of laser diodes and general symmetry of the optical scheme, all bar diodes form a unified combined emitter in a common external cavity.

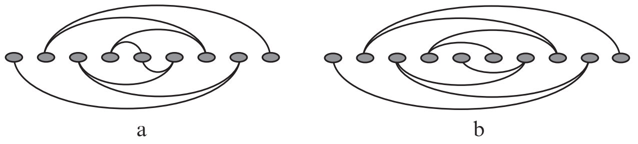

Figure 3. Schematic of optical couplings between laser bar diodes, settled by phase diffraction mirror, for (a) odd and (b) even numbers of diodes.

To provide constructive interference and maximal amplification of arriving radiation by a laser diode, the light beam incident on each diode from two other diodes should be coherent, and their phases should coincide. Specifically the aforementioned condition of phase equality for the ±1st diffraction orders provides fulfillment of this requirement. In the case of phase-locked lasing of all laser diodes, the power distribution in the plane of phase mirror is a typical diffraction pattern from an amplitude grating, where all main maxima are located on either ridges or grooves of the grating. Under these conditions, the phase ratio of the main maxima in the output radiation (transmitted through the mirror) remains the same, thus indicating a minimum influence of the phase grating mirror on the spatial distribution of output radiation, which is determined by only the geometric parameters of laser diode bar.

Another advantage of the above-described method is the suppression of lasing of individual diodes under individual feedback conditions: it in principle allows for only collective lasing of successively coupled diodes. In addition, theoretically , this method should not be sensitive to the diode bar fill factor. In order to check this feature of the method and obtain simultaneously higher powers, we performed studies using a bar of wide-aperture diodes. However, diodes of this type are characterised by fragmentation (filamentation) of radiation in the active medium, which leads to generation of additional modes [5]. In this context, our other purpose was to analyse the potential of this method for suppressing the influence of filamentation.

We carried out experiments using a diode bar with an average operating wavelength of 947 nm at room temperature (a bar characterised by the most uniform radiation distribution along its long side was chosen from a set of identical bars); the nominal radiation power was 20 W. The bar was a set of submesostructures 200 μm wide, spaced by a distance of 200 μm; the total bar width was 10 mm. The rear face of the bar had a 100% reflecting coating, while its front (emitting) face had an antireflection coating and a transmittance of 99.5%. The total number of single diode lasers in the bar was 25, the cavity length for each laser was 1 mm. These bar parameters were chosen, in particular, because they allow one to use a standard photographic lens (we applied a GELIOS 44M photographic lens with a focal length of 58.6 mm) as a Fourier lens. To reduce the diode arrangement period in the bar, it would be necessary (taking into account the aberrations caused by the phase-locking scheme peculiarities) to develop and prepare a special objective with a short (less than 10 mm) focal length.

The nesessary wavelength correction in the experiments was carried out by changing the bar operating temperature. For effective cooling, the bar was mounted with indium solder on a massive gilded copper base, mounted on a Peltier heat exchanger, which was capable of removing up to 50 W thermal power. This excess heat exchanger power made it possible to minimise the influence of temperature fluctuations and maintain reliably the required value of the bar radiation wavelength. A microthermistor, mounted in close proximity to the bar, made it possible to stabilise the bar temperature with an accuracy of 0.1 °C that corresponds to fixing the laser diode wavelength with an accuracy of 0.3 nm.

The phase diffraction mirror was fabricated on a glass (K8) substrate. A reflecting phase diffraction grating with a rectangular profile was formed on the glass surface using etching and deposition techniques. The groove width and depth were equal to the ridge width: 0.202 mm (with an average error of ±5 nm).

To reduce the radiation energy loss, the bar beam was collimated in the direction perpendicular to the p–n junction plane. To this end, we applied an aspherical quartz cylindrical microlens [(*5*) in Fig. 1] with a numerical aperture of 0.8 and a transmittance above 99%. This lens was rigidly fixed (using UV-hardened glue) in front of the bar emitting face.

In some experiments we tried to improve the selection of collective phase-locked modes by installing an optical slit (oriented perpendicular to the direction of the diode bar long side) in front of the phase diffraction mirror. The slit was also used to suppress the formation of filaments and obtain a smooth radiation distribution for each diode in the bar.

The field distributions and the spectral composition of laser diode bar radiation in the external cavity formed by the phase diffraction mirror were experimentally investigated for different pump regimes and parameters. Figure 4 shows a characteristic profile of the experimentally observed distribution of phase-locked radiation power at the output (in relative units).

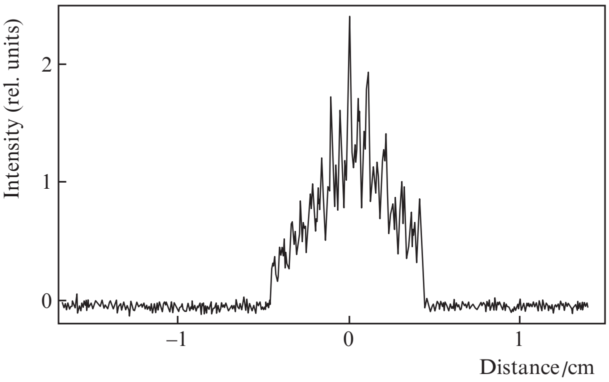

Figure 4. Distribution of the output radiation power in the plane of the phase diffraction mirror; the pump current is 15 A, the pulse duration is 40 μs, and the pulse repetition rate is 250 Hz.

Each distribution profile, recorded at the same values of system and pump parameters, differed significantly from the previously measured ones, a fact indicative of very high sensitivity of the phase locking scheme to radiation field fluctuations (generated by natural and unremovable temperature and pump current fluctuations). These fluctuations caused weak phase shifts, violating the phase equality for the ±1st diffraction orders; this violation turned out to be sufficient for distorting the distribution profile.

The character of the distribution presented in Fig. 4 confirms that the scheme with a phase diffraction mirror provides phase-locked lasing of the laser diode bar. Moreover, an increase in the pump current led to an increase in the number of laser diodes involved in phase-locked lasing. This was evidenced by both a decrease in the width of spikes in the radiation distribution profile and the transition to a flatter distribution profile with an increase in the pump current. At the same time, the field distribution profile in Fig. 4 shows that the character of radiation is essentially multimode. No changes in the diode bar pump parameters and no variations in the parameters of optical elements of the scheme made it possible to implement stable selection of collective lasing modes. The introduction of an additional selecting element (optical slit located practically in the focus of Fourier lens) into the cavity led only to feedback range cutoff and a decrease in the number of diodes involved in lasing. Note also that the strong indentation of peak profiles in Fig. 4 is due to the effect of filamentation.

An example of an experimentally measured radiation spectrum of the diode array phase-locked using a phase diffraction mirror is presented in Fig. 5. This spectrum is an unambiguous evidence of multimode composition of radiation. The experiments revealed a weak dependence of the shape of the phase-locked bar output spectrum on the pump current, which suggests a small difference between the lasing thresholds for different supermodes. Thus, our expectations to reduce the lasing threshold in the phase-locked regime via constructive addition of beams with zero phase difference did not hold true.

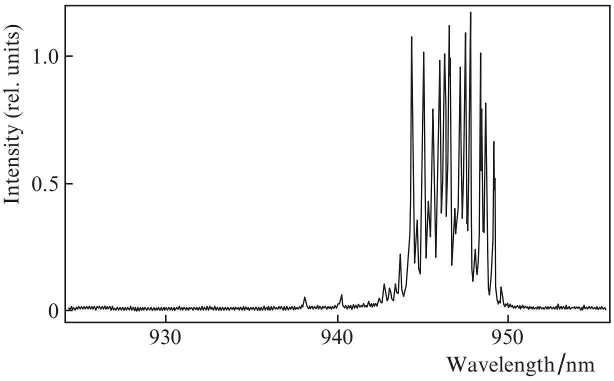

Figure 5. Emission spectrum of a phase-locked diode bar; the pump current is 15 A, the pulse duration is 40 μs, and the pulse repetition rate is 250 Hz.

The maximum values of bar radiation peak power in the phase-locked regime were about 1.2 W.

The experimental studies were supplemented with a numerical simulation of the distribution of phase-locked bar radiation power in the phase mirror plane. Its purpose was to found out which of the obtained results were due to the intrinsic features of the phase locking technique under study and which were caused by experimental errors. To this end, we set different characteristic distributions of the initial radiation field on the end face of laser diode bar: single-mode distribution; distribution with imitation of random filaments; and distribution that was phase-locked over the entire bar but had phase dispersion on individual structural elements of the emitting field. The fast Fourier transform was calculated for the model field distribution; the calculation result yielded a field distribution over the phase mirror. The simulation was performed using the same values of parameters of phase-locking scheme elements as in the experiments. A typical form of the calculated radiation power distributions (in relative units) in the normal beam section is presented in Fig. 6.

The numerical simulation showed that, in the case of phase locking of the entire bar, regardless of whether individual diodes operate in single-mode or filamentation regimes, the radiation distribution in the phase mirror plane should contain sharp narrow peaks, corresponding to the diffraction from the entire laser diode bar aperture (Fig. 6b). Since these peaks were fairly weak in the measured distributions (see Fig. 4), one can conclude that the experimentally observed phasing of diode bar radiation was only partial: the phase-locked mode of the entire bar was generated against a background of rather intense non-phase-locked radiation. The calculations showed also that the directional pattern of output radiation is multilobe.

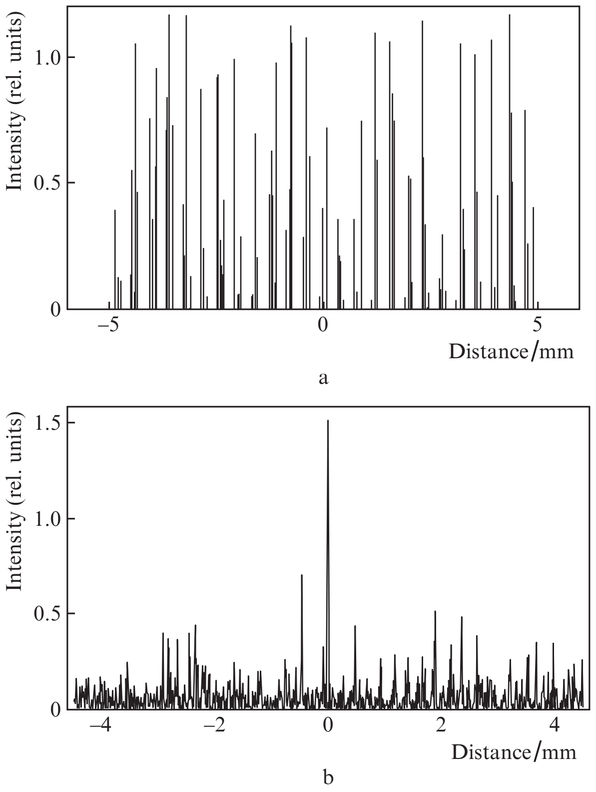

Figure 6. Radiation distribution of filamented laser diodes at a random phase variation in the range of 0–π on (a) the emitting bar end face and (b) phase mirror.

Based on the results obtained, we can conclude that the scheme of phase locking of the laser diode bar in an external cavity formed by a phase diffraction mirror provides optical coupling of bar diodes, which gives rise to collective (phase-locked) lasing of all diodes in the bar. At the same time, the phase locking of diode bar radiation using this scheme is accompanied by unremovable generation of a large number of supermodes. Selection of collective modes in the scheme of phase-mirror-based phase locking was expected to provide a significant decrease in the lasing threshold of the phase-locked supermode due to the constructive addition of radiation beams from individual diodes, emitting with zero phase difference. However, we did not observe any significant difference in the supermode lasing thresholds in the scheme based on a phase diffraction mirror.

Different variations in the working regimes of the diode bar and/or parameters of the cavity and its optical elements could not ensure stable selection of a single supermode, which is explained by the high sensitivity of the method to radiation field fluctuations. The incorporation of an optical slit in the immediate vicinity of the phase diffraction mirror did not facilitate the mode selection but only reduced the number of laser diodes involved in collective lasing. The emission spectrum of a laser diode bar, phase-locked in the scheme with a phase diffraction mirror, is non-monochromatic, which indicates the presence of a large number of supermodes in the phase-locked bar radiation. Thus, the scheme of phase locking of a laser diode bar using a phase diffraction mirror did not allow us to implement the phase-locked lasing regime for a diode bar with stable selection of a single supermode.

The observed low efficiency of phase locking with application of a phase mirror could partly be due to the use of wide-aperture diodes. The comparison of the results obtained with this method and the method using a resonance waveguide mirror [3, 4] indicates unambiguously that the latter is much superior in all main characteristics: number of phase-locked diodes, quality and stability of radiation, radiation power, and beam divergence. However, the phase locking with a resonance waveguide mirror was experimentally investigated using a bar of narrow-aperture single-mode diodes. Therefore, it seems appropriate to use precisely this type of laser diodes in further phasing studies.

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