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Picosecond semiconductor lasers with an external fibre resonator

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Abstract. The passive mode-locking regime of multisection GaAlAs heterostructure laser diodes has been studied. Pieces of single-mode optical fibres with an edge nonselective mirror or a fibre Bragg grating have been used as an external cavity. Regular trains of optical pulses a few picosecond long and with a peak power of a few watts have been obtained under dc current injection. Spectral characteristics of the pulses are crucially dependent on the parameters and adjustment of the external cavity.

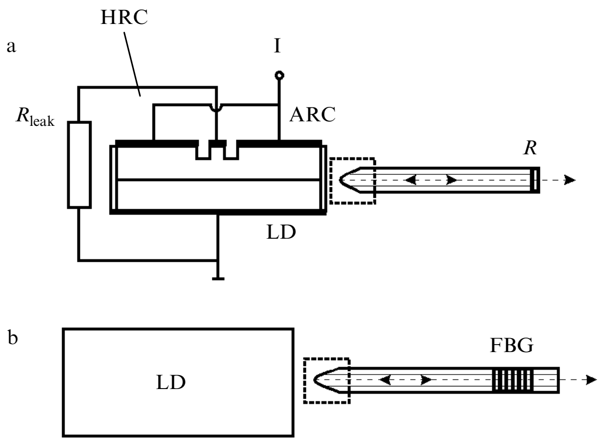

Figure 1. Three-section LD with an external optical fibre cavity with an edge dielectric mirror (a) and a fibre Bragg grating (b).

The use of single-mode optical fibres as external cavities of mode-locked laser diodes (LDs) allows for the fabrication of compact sources of ultrashort light pulses. Dielectric mirrors placed at a fibre edge [1] as well as fibre Bragg gratings (FBGs) written at their core [2] can serve as mirrors of the external cavity. LDs worked in the active mode-locking regime as reported in Refs [1, 2]. The present paper is a continuation of previous work [3, 4]. Here, passive mode locking in similar devices has been studied. This was achieved with the use of a multisection LD with a nonlinear saturable absorber as the active element.

Triple-section double heterostructure GaAlAs LDs similar to those described elsewhere [5] have been used in our investigation. The leakage resistance between the central absorbing section and the amplifying sections located at the LD facets were about 3 kΩ. High-reflection coatings (HRCs) and antireflection coatings (ARCs) coatings with the reflection coefficients of over 95% and less than 0.5%, respectively, were placed on the LD facets. The absorber was grounded down with a leakage resistor of $R_{\text{leak}} = 100\ \Omega$.

External fibre cavities of different configurations have been studied (Fig. 1). Pieces of a single-mode fibre Lucom SM/800 were used to form the cavities. A multilayer dielectric $\text{ZrO}_2/\text{Al}_2\text{O}_3$ coating was placed on the cleaved edges of the fibres. The coating ensured a reflection coefficient of $R = 22\%$ at the boundary with air, and $R = 12\%$ for coupling to a similar fibre. These mirrors were virtually nonselective within the spectral bandwidth of the optical gain of the lasers under study. Moreover, pieces of Ge/Si single-mode optical fibres made by QPS Technology with FBGs written at their core were also utilised. In contrast to the FBGs reported in Ref. [4], these gratings were written through a special slit diaphragm which restricted the area of the fibre irradiated by the interfering beams of the UV emission. The grating length was around 0.3 mm. The FBGs with the resonant reflection in a spectral range of 850 nm – 860 nm corresponding to the saturation region of a LD absorber were both ‘narrow-band’ with a FWHM of $\Delta\lambda = 0.2$ nm – 0.4 nm and ‘broad-band’ with a FWHM of $\Delta\lambda = 2.0$ nm – 4.0 nm (Fig. 2b). Their transmission at the resonant wavelength was 70 – 85%.

Edge microlenses were used for the optical connection of the emitting area of the LD with the fibre core. Microlenses of two types were used, namely, spherical ones formed by a controlled melting of the fibre edge in the fire of an electrical discharge and aspherical ones which were optimised in accordance with a far-field pattern of emission of the LDs under study. The latter were fabricated by a precise mechanical treatment of the fibre edge. The spherical microlenses, which were more simple during fabrication and adjustment, ensure a coupling coefficient into the fibre of about 35%. The aspherical microlenses provide the coupling efficiency of over 70%. The lengths of the fibres from the edge lens to the edge mirror or the FBG were 10 cm. This corresponded to a repetition frequency of ultrashort pulses under passive mode locking of the external cavity (the first harmonic) of about 1.0 GHz.

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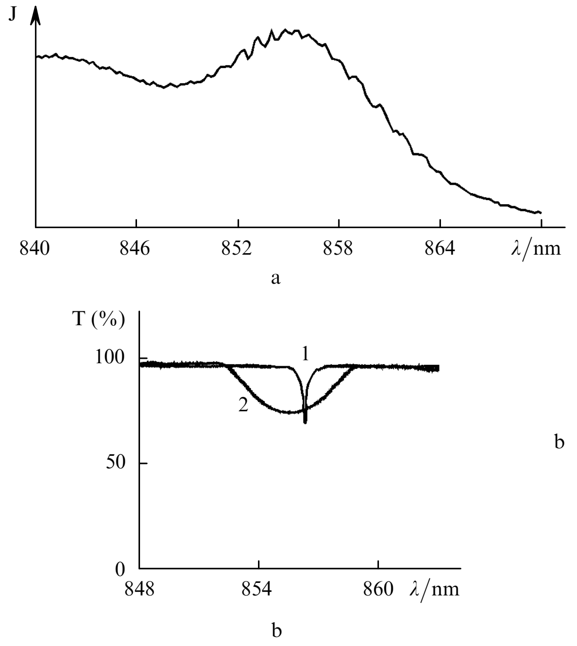

Figure 2. Long-wavelength wing of the luminescent spectrum of a LD without the external cavity ($I = 140$ mA) (a) and the transmission spectra of the narrow-band (1) and broad-band (2) fibre Bragg gratings (b).

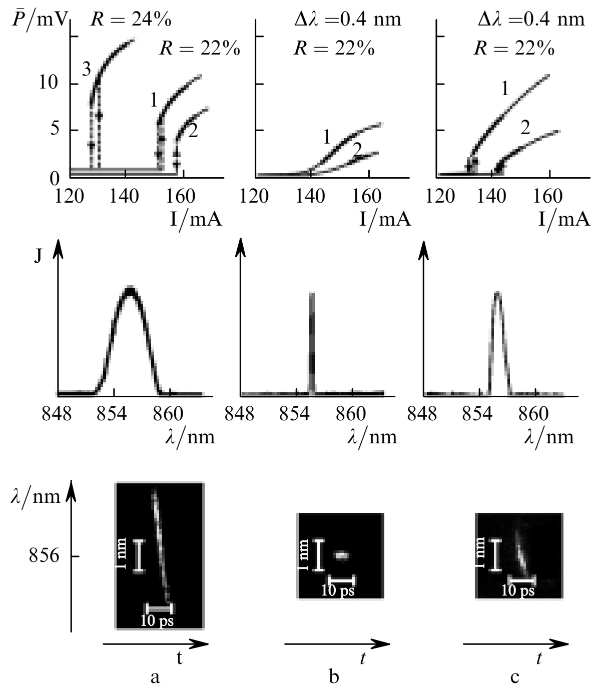

Figure 3. Typical light – current characteristics (upper row), averaged in time emission spectra (middle row), and time-resolved spectra of the generated ultrashort pulses (bottom row) of the lasers with a nonselective external cavity (a), and narrow-band (b) and broad-band (c) fibre Bragg gratings; the external cavity with aspherical (1) and spherical (2) lenses, and the bulk external cavity (3).

The universal measurement installation described in Ref. [4] has been used for the study of output characteristics of the laser. Fig. 3 shows typical light – current characteristics for cw current injection, time-averaged emission spectra, and time-resolved spectra of ultrashort pulses generated from the LD with different fibre external cavities. A corresponding light – current characteristic of a LD with a bulk external cavity formed by a wide-aperture AR-coated micro-objective and a plane nonselective mirror ($R = 24\%$) is shown for comparison in Fig. 3a.

As expected, unavoidable losses during coupling of the emission into the fibre and back into the active region of the LD result in an increase in the generation threshold and in a decrease in the external quantum efficiency compared with the bulk cavity. Nevertheless, a stable passive mode-locking regime (the thicker parts of the curves) of the external cavity has been achieved for both fibre configurations within sufficiently large ranges of the pumping currents. The generated ultrashort pulses represent monopulses of a few picoseconds in duration and a peak power of the order of 1 W. The use of the aspherical fibre microlenses decreases significantly the current thresholds, increases the output power, and broadens the range of stable mode locking (see Figs 3b and 3c).

The ultrashort pulses generated are bandwidth-limited when 'narrow-band' FBGs are used. The pulses acquire a strongly pronounced quasi-linear chirp when 'broad-band' FBGs or nonselective edge mirrors are used. These pulses can be compressed further with the use of external temporal compressors, as well as with the use of pure fibre optics. In order to do this, the fibre output of the laser can be connected to a three-port fibre circulator whose second port is attached to a FBG having 100% reflection and a corresponding linear chirp, i.e. a linear dependence of the grating period on the coordinate along the fibre axis. In addition it is possible to exploit such modulated FBGs in an external cavity directly in order to provide the intracavity chirp correction.

Parameters of ultrashort pulses usually deteriorate with an increase in the injection current and the output power. Their duration increases and the fluctuation level and repetition rate rises, the trend being stronger than in a laser with a bulk external cavity. One reason for this is a competition between mode locking and intensity self-modulation of the emission which is well known in LDs with nonuniform injection [5]. The self-modulation characterised by a strong dependence of the pulsation frequency on the pumping level has also been observed in the lasers used prior to deposition of ARC. It stopped after deposition of a high-quality ARC on the facet because the LD was transformed into a double-pass superluminescent diode (see Fig. 2a). This situation is complicated by a weak reflection from the edge fibre microlenses which are placed at a distance of a few microns from the LD facet with ARC. This reflection results in the creation of a composite cavity which explains the observed phenomenona. We assume that a significant enhancement of the range of stable mode locking and an increase in the output power can be achieved provided the fibre microlenses have ARC.

The decrease in the LD output power with the fibre cavity in comparison with a laser with a bulk external cavity is compensated by the possibility of fabrication of compact monolithic modules which are ultrashort pulse generators. Such devices can find independent applications and can also be used as master oscillators in high-power travelling-wave semiconductor optical amplifier systems (MOPAs) [6, 7]. In this case, it can be relied on to enhance the output power by two orders of magnitude, with the size of the device still being compact.

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