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Multichannel extremely broadband near-IR radiation sources for optical coherence tomography

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***Abstract*. The construction and output parameters of two experimental samples of near-IR radiation sources based on the superposition of radiation from several superluminescent diodes are described. The first, three-channel sample emitting 18 mW of cw output power in a spectral band of width 105 nm through a single-mode fibre, is optimised for ophthalmology coherence tomography. The second, four-channel sample emits the 870-nm band of width more than 200 nm, which corresponds to the record coherence length smaller than 4 μm.**

Keywords: *superluminescent diode, broadband fibre coupler, optical coherence tomography*.

1. Introduction

The advantages of semiconductor radiation sources are well known. Optimal radiation sources for optical coherence tomography (OCT) [1, 2] are light-emitting modules based on superluminescent diodes (SLDs), which combine a high brightness of semiconductor lasers and a broad emission spectrum of semiconductor light-emitting diodes and, therefore, have a small coherence length $L_c = \lambda^2/\Delta\lambda$, where λ is the central wavelength of laser emission and $\Delta\lambda$ is the laser linewidth.

The superposition of radiation from two or more SLD modules with fibre pigtails and shifted but overlapped emission spectra, which is realised by using broadband fibre couplers, is a simple and comparatively cheap method for the development of extremely broadband radiation sources for OCT and other practical applications, in particular, in fibreoptic sensors.

A two-channel Broad-Lighter-890 radiation source with the 150-nm spectral half-width based on quantum-well SLDs was tested in OCT systems in 2004 [3, 4]. Quite encouraging results were obtained: the axial resolution of 3.3 μm was achieved in tomography of the human eye retina and 2.3 μm in analysis of skin layers. This light source is not optimal for ophthalmology because the long-wavelength wing of its emission spectrum (about 30 % of the output power) is absorbed by the eye liquid.

In this paper, we consider the experimental samples of new broadband radiation sources which were manufactured due to the development of two new types of quantum-well SLDs: the three-channel source with a fibre pigtail emitting 18 mW of cw output power in a spectral band of width 105 nm corresponding to the transparency band of the eye liquid, and the four-channel source emitting 6.0 mW in a record broad band of width 200 nm.

2. Output parameters of SLD modules

We used six types of SLD modules. They were made of separate-confinement double heterostructures (SCDHs) grown by the metal-organic chemical vapour deposition (MOCVD) method. The active channels of SLDs represented ridge optical waveguides of width 4 μm produced by the method of ion etching through a photolithographic mask. To suppress positive optical feedback, the active channels were arranged at an angle with respect to crystal end-faces, which were covered with dielectric AR coatings. SLDs were mounted in the DIL or Butterfly housings together with thermoelectric microcoolers and thermoresistors providing thermal stabilisation. The output radiation of SLDs was coupled through end microlenses to Corning Pure Mode HI 780 single-mode fibres. The method of optimisation of the design and operating regimes of SLDs in the development of combined broadband radiation sources is described in [4]. The emission spectra of SLDs used in our study are presented in Fig. 1.

In the short-wavelength wing of the spectrum, serial SLD-381-HP modules based on 'bulk' SCDHs with the quasi-Gaussian emission bands at 775 nm (type I) and 795 nm (type II) were used.

Modules of types IV and VI based on single-layer quantum-well heterostructures (QWSs) used in a Broad-Lighter-890 source are described in detail in [5 – 7].

A new SLD of type III developed in this paper was manufactured from a single-layer QWS with a step optical fibre, which is similar to that used in the SLD of type IV [5, 6]. The emission spectrum of the SLD of type III exhibits two maxima at 790 and 820 nm, which can be made equal under certain conditions. In this case, the SLD module will have the following output parameters: $P = 3.0 - 5.5$ mW

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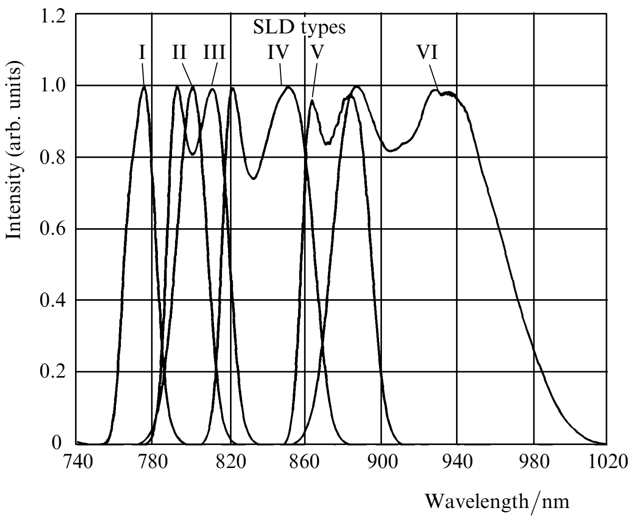

Figure 1. Spectra of SLDs used in multichannel radiation sources.

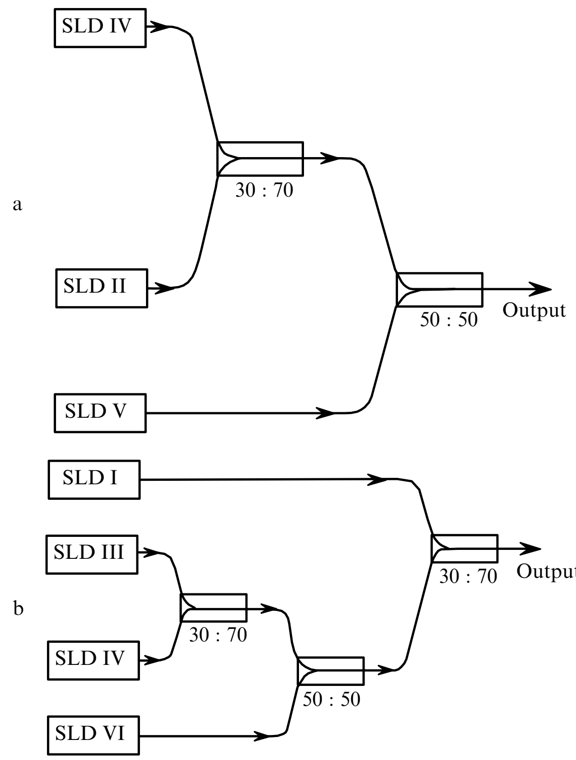

Figure 2. Schemes of three-channel (a) and four-channel (b) radiation sources.

(depending on the temperature and length of the active channel), $\lambda = 803$ nm, and $\Delta\lambda = 35$ nm.

The second new SLD of type V is based on a gradient-waveguide QWS, similar to that used in the SLD of type VI [7]. In the case of equal spectral maxima, it has the following output parameters: $P = 9 - 19$ mW (depending on the temperature and length of the active channel) $\lambda =$ 875 nm, and $\Delta\lambda = 38$ nm.

3. Combined radiation sources

Combined radiation sources were fabricated by using original broadband Corning Pure Mode HI 780 single-mode fibre Y-couplers [4]. Except symmetric 50 : 50 couplers, we also used asymmetric 30 : 70 couplers. This provided an additional degree of freedom in the construction of combined sources.

The scheme of a three-channel source consisting of modules of types II, IV, and V and the 50 : 50 and 30 : 50 couplers is shown in Fig. 2a. After the optimisation of operating regimes of SLDs (injection currents and temperatures), this source had the following output parameters: $P = 18$ mW, $\lambda = 840$ nm and $\Delta\lambda = 105$ nm. The emission spectrum and the autocorrelation intensity function of this combined source are presented in Figs 3a, b.

It is known that the eye liquid mainly consists of water. Figure 3a shows the transmission spectrum of a 5-cm thick water layer. One can see that the radiation of this source can be completely used in ophthalmologic OCT systems. The corresponding tests of a high-resolution OCT system with spectral Fourier detection were performed at the Massachusetts Institute of Technology. Figure 4 shows the image of the human eye retina obtained after 8100 axial scans for 0.3 s. The 3.5-μm axial resolution was achieved, which is close to that obtained with a BroadLighter-890 source, although the emission spectrum of the latter is almost 1.5 times broader. This resolution approaches the record values achieved in OCT systems by using broadband mode-locked femtosecond solid-state lasers. However, such sources are rather bulky, expensive, and complicated under operating conditions. In addition, they have a rather high level of the relative intensity noise, which requires the use of complicated schemes for double balance detection of the useful signal. The noise level of SLDs does not exceed, as a rule, – 130 dB Hz^{-1} in the radiofrequency band used in OCT, which allows one to give up these schemes.

Figure 2b shows the schemes of a four-channel source in which SLDs modules of types I, III, IV, and VI and the 30 : 70, 50 : 50, and 30 : 70 couplers were used. After the optimal alignment, this source had the following output parameters: $P = 6$ mW, $\lambda = 870$ nm, and $\Delta\lambda = 201$ nm. The corresponding spectrum and the autocorrelation intensity function are shown in Figs 3c, d. The obtained coherence length $L_c < 4$ μm is, to out knowledge, the record for semiconductor near-IR radiation sources. The use of such a source in OCT systems allows one to count on the achievement of the axial resolution better than 2 μm.

In the radiation sources described above, as in similar sources fabricated earlier, non-preserving-polarisation fibre were used. Recently, the manufacturing technology of SLD modules with Corning PM-PANDA single-mode fibre pigtails was developed. In this case, the TE mode of the SLD usually propagates along the slow axis of the single-mode fibre. The first experimental samples of broadband couplers based on the same fibre were fabricated. Therefore, all the BroadLighter sources can be manufactured in the modification providing stable polarisation of output radiation, which is a substantial step ahead for a number of practical applications.

Thus, we have developed the prototypes of two new broadband near-IR radiation sources based on SLDs. The emission band of the first source of width 100 nm corresponds to the transparency window of water. The second source features the record coherence length for semiconductor radiation sources, which is smaller then 4 μm.

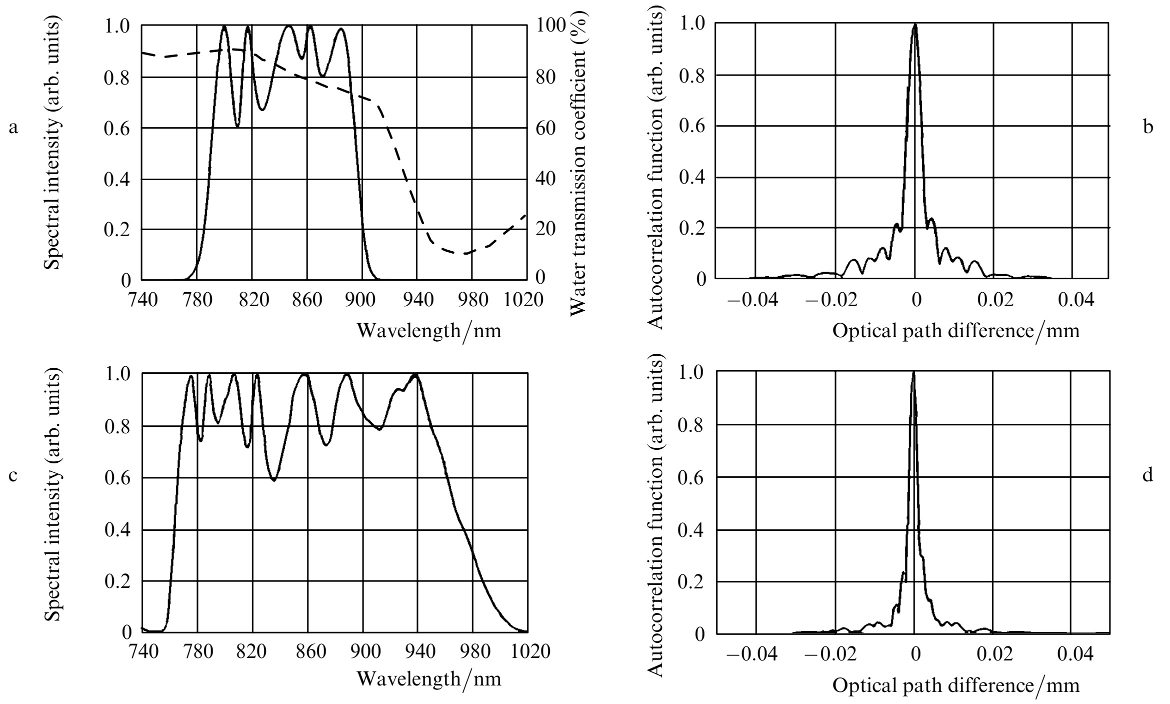

Figure 3. Emission spectra and autocorrelation intensity functions of three-channel (a, b) and four-channel (c, d) radiation sources. The dashed curve in Fig. 3a shows the transmission spectrum of a 5-cm thick water layer.

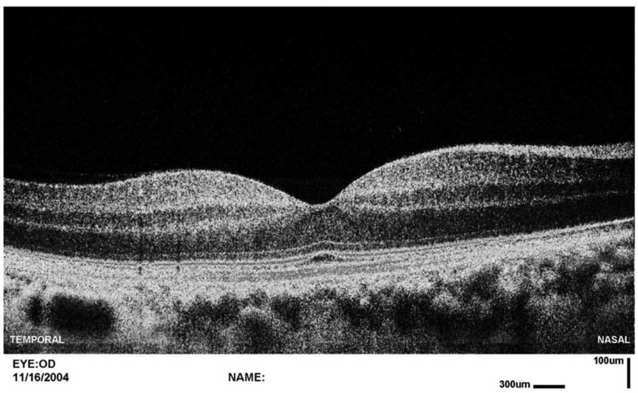

Figure 4. Images of the human eye retina obtained in the OCT system by using a three-channel combined radiation source.

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