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Semiconductor lasers with a continuous tuning range above 100 nm in the nearest IR spectral region

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Abstract. **We have developed two new types of lasers based on quantum-confined semiconductor optical amplifiers with an acousto-optic tunable filter in an external fibre ring cavity. The lasers offer continuous wavelength tuning ranges from 780 to 885 and from 880 to 1010 nm, 20 mW of cw output power, and a tuning rate up to 10^4 nm s^{-1} at an instantaneous spectral linewidth less than 0.1 nm.**

Keywords: *semiconductor optical amplifier, tunable and single-frequency lasers.*

1. Introduction

The unconventional interference technique referred to as optical coherence tomography (OCT) [1] has seen an explosive growth between the late 1980s and the early 1990s. At present, more than 50 companies mass-produce various OCT systems, more than a hundred research centres and laboratories are concerned with this scientific area, more than a thousand engineering solutions have been patented, and the number of scientific reports exceeds ten thousand. OCT has found a variety of engineering applications, but it is most widely used in medicine and biology, because it enables real-time, non-contact, *in vivo* imaging of biological tissue. In traditional OCT techniques (time domain OCT and Fourier-domain OCT) [2], use is made of bright, low-coherence light sources that operate, as a rule, in continuous mode [most frequently, these are superluminescent diodes (SLDs)]. The last decade has seen rapidly growing development of a new OCT technique, swept source OCT, which will, in principle, allow one to considerably increase the capabilities of the technique and improve the quality of tomograms. As light sources, this technique employs lasers that are rapidly swept over broad spectral ranges. In a recent review, Drexler et al. [3] described more than a dozen commercial models of such lasers that are used in OCT systems for medical applications.

All these lasers are based on semiconductor gain elements and various rapidly tunable wavelength-selective components in their external cavity. The latter include a tunable Fabry – Perot filter, a KTN deflector based on a Littman configuration, a controlled integrated distributed Bragg reflector, a rotating multifaceted mirror prism in combination with a diffraction grating, a microelectromechanical system (MEMS) controlled external mirror of a vertical cavity laser, a MEMS-controlled scanning mirror in combination with a diffraction grating, and an extended mode-locked external fibre cavity. The wavelength tuning range of rapidly swept lasers is 30 – 220 nm, their sweep rate ranges from several kilohertz to several megahertz, the coherence length of their output is from a few to tens of millimetres, and their average output power is 8 – 50 mW. All the lasers operate in the spectral range 1000 – 1600 nm. The only exception is an EXALOS model, which has the tuning range 810 – 870 nm.

The above list does not include Broadsweeper tunable lasers, which employ acousto-optic tunable filters (AOTFs) as wavelength-selective elements [4, 5]. These lasers contain no moving mechanical components. Their emission wavelength is determined by the frequency of an rf control signal, which ensures extremely high spectral tuning accuracy and reproducibility and a strictly linear emission frequency sweep in time. Unfortunately, the sweep frequency does not exceed 2 kHz, which is insufficient for most medical applications of OCT. At the same time, these lasers proved to be optimal for some applications of OCT, including medical ones (see e.g. Refs [6, 7]). Moreover, they are of practical interest for spectroscopy and optical metrology.

It is important to note that, on the whole, the Broadsweeper lasers span the optical range 750 – 1000 nm, where essentially no rapidly tunable lasers are commercially available. Specially designed broadband travelling wave semiconductor optical amplifiers (SOAs) based on nanoheterostructures are used as gain elements in such devices. Until recently, the tuning range of an individual device in this series did not exceed 80 nm. The advent of new types of SOAs, based on nanoheterostructures with ultrathin active layers [8], which have a broadened optical gain spectrum and rather high reliability, has made it possible to create prototypes of new laser designs with a tuning range near 100 nm. Andreeva et al. [8] described a laser tunable in the spectral range 1010 – 1110 nm.

In this paper, we report two new lasers of this kind, tunable in the ranges 780 – 885 and 880 – 1010 nm.

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2. Experimental results

Marked broadening of the tuning range was achieved by producing two new types of travelling wave SOAs based on laser nanoheterostructures with ultrathin active layers. The growth of such structures by metal-organic vapour phase epitaxy was described briefly in a previous report [9]. They had the form of symmetric separate-confinement double heterostructures (SCDHS's). The type I structure had a 0.23-μm-thick step-index waveguide and a 7.0-μm-thick $In_{0.03}Ga_{0.97}As$ active layer. The type II structure had a 0.4-μm-thick graded-index waveguide and an $In_{0.18}Ga_{0.82}As$ active layer less than 6.0 μm in thickness. The SOA design was identical to that described by Andreeva et al. [8].

Figure 1 shows gain spectra of the SOAs under consideration for a narrow-band continuous small signal gain. Their gain bandwidth markedly exceeds that of the previously described type II and IV SOAs [8], operating in the same spectral ranges. According to preliminary life tests in the double-pass amplification regime at a cw output power of 20 mW, the devices are sufficiently reliable. Their median lifetime, defined as the operation time after which the output power drops by 50%, is about 15 000 and 50 000 h, respectively.

Figure 2 shows a schematic of the devices under consideration. It is topologically identical to that of the S1 tunable laser described previously [8], but all their components – SOAs, AOTFs, optical isolators, broadband fibre-optic couplers, monitor photodiodes, and polarisation-maintaining fibre (PANDA 850 instead of PANDA 980 in Ref. [8]) – differ from those described by Andreeva et al. [8]. The key features of the SOAs used in this study were mentioned above. The other components were optimised or specially designed for use in particular spectral ranges.

The electronic controllers of the Broadsweeper devices ensure three operation modes:

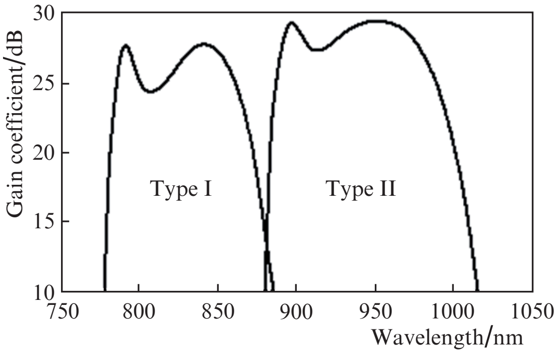


Figure 1. Small signal gain spectra of the type I and II SOAs at injection currents of 250 and 220 mA, respectively.

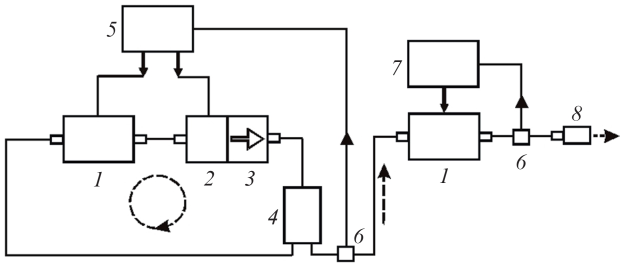


Figure 2. Schematic of a tunable laser with an output power amplifier: (*1*) SOA; (*2*) AOTF; (*3*) optical isolator; (*4*) fibre-optic coupler; (*5*) controller of the laser; (*6*) monitor photodiode of the APC system; (*7*) controller of the output amplifier; (*8*) output fibre-optic connector. Solid arrows mark electrical connections.

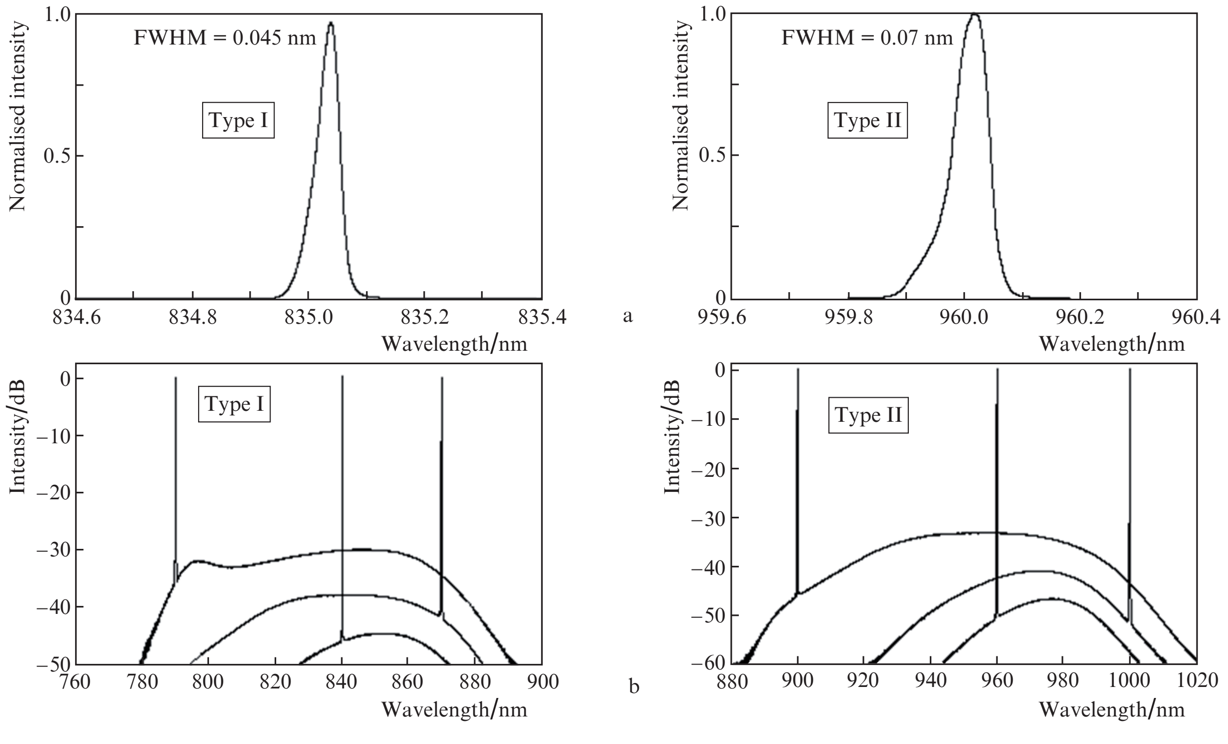


Figure 3. Emission spectra of the type I and II lasers at an output power of 20 mW and various settings: (a) linear axes, 0.002-nm resolution; (b) logarithmic vertical axis.

manual emission wavelength tuning to a 50-pm accuracy, with automatic output optical power control (APC);

wavelength sweep (periodic monotonic variation) between two preset values within the tuning range at a rate of 10^5 nm s^{-1} in the APC regime with internal and external (synchronising pulse) triggering; and

two-frequency mode, i.e. periodic switching at a certain repetition rate between two preset wavelengths from the tuning range.

Figure 3 presents examples of normalised steady-state output spectra of the two types of lasers at various settings. Wavelength tuning in the APC regime changes the injection current of the SOA and the ratio of the spectral density of the wanted signal to the superluminescent 'pedestal' (SMS ratio). In this study, the optical power at the input of the output amplifiers was maintained at a level near 2 mW. As a result, there was a negligible superluminescence background: the SMS ratio exceeded 55 dB. The output power was maintained at a level of 20 mW.

Figure 4 illustrates the effect of wavelength tuning on the injection current of the output SOAs and the SMS ratio. The oscilloscope traces in Figs 5 and 6 illustrate the operation of the lasers in wavelength sweep and two-frequency modes. Strictly speaking, the APC system used ensures precise control (with about 0.2% accuracy) not over the output power but over the photocurrent through the monitor diodes (OZ Optics Model OPM-830-Si and Model OPM-930-Si), to which 2% of the output power is directed. In the course of wavelength tuning, the output power varies slightly according to the spectral sensitivity of the photodiodes (Figs 5a, 6a).

The described lasers can in principle be integrated into one device with a common fibre output, which will ensure a continuous wavelength tuning range from 780 to 1010 nm. To this end, use can be made of ultrabroadband fibre-optic couplers for this spectral range. Unfortunately, these devices have high levels of wavelength-dependent optical losses. For example, a Y-coupler manufactured by AFR Ltd. ensures a coupling ratio of 50 : 50 in the range 750 – 1050 nm. Its optical loss spectrum has a minimum at a wavelength of 840 nm, and the loss reaches 5.5 dB at the boundaries of this spectral range. Thus, the device under consideration is suitable for engineering applications where the width of the wavelength tuning range is a key parameter and output powers around 5 mW are acceptable. This will of course require drastic changes in the electronic controller design.

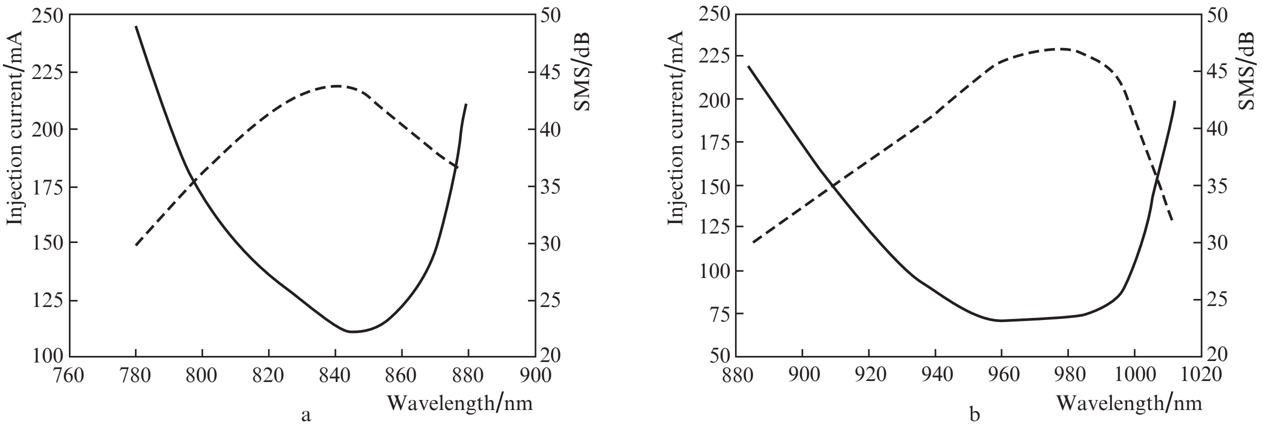


Figure 4. Effect of wavelength tuning on the injection current of the output SOA (solid lines) and the SMS ratio (dashed lines) for the type (a) I and (b) II lasers; APC at a level of 20 mW.

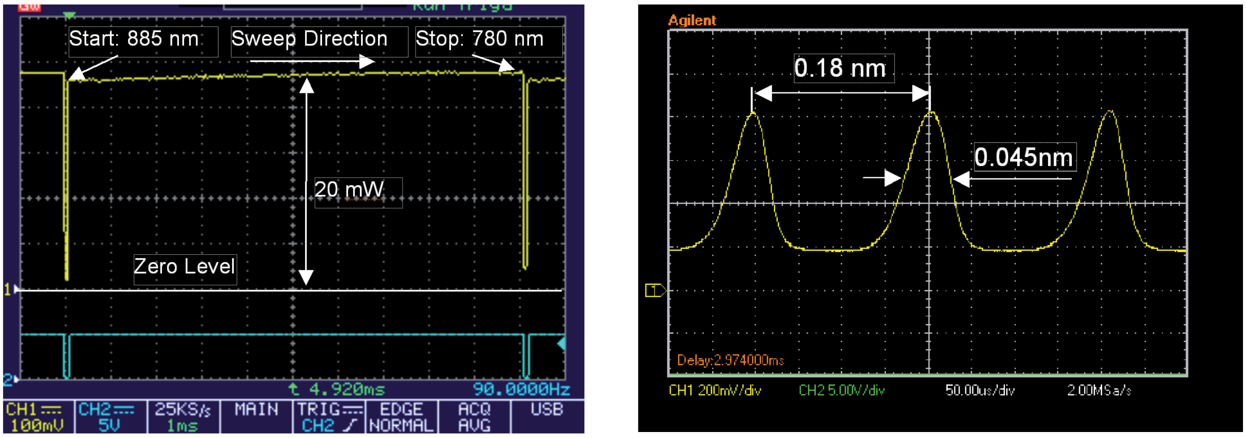
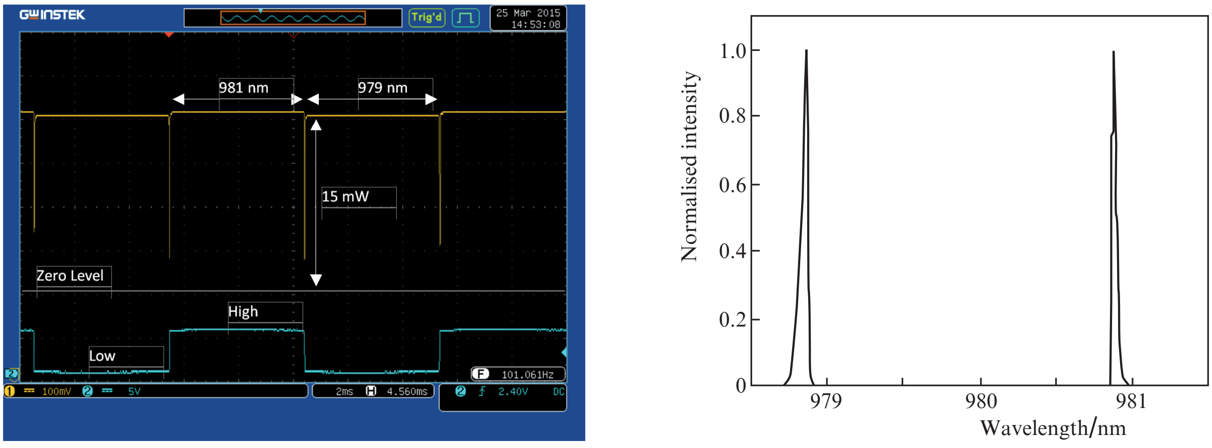


Figure 5. (a) Oscilloscope trace illustrating type I laser operation in wavelength sweep mode between 780 and 885 nm at a repetition frequency of 90 Hz in the APC regime (the lower trace represents the synchronising signal); (b) oscilloscope trace of a signal passed through a Fabry–Perot etalon with a free spectral range of 0.18 nm.



a b

Figure 6. (a) Oscilloscope trace illustrating type II laser operation in two-frequency mode at a switching frequency of 101 Hz (the lower trace represents the synchronising signal); (b) corresponding average output emission spectrum.

3. Conclusions

We have developed two new types of rapidly tunable semiconductor lasers based on quantum-confined SOAs and AOTFs in an external fibre ring cavity. According to the present results, their continuous wavelength tuning ranges (780–885 and 880–1010 nm) markedly exceed those of existing analogues.

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