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Semiconductor disk laser-pumped subpicosecond holmium fibre laser

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Abstract. **The first passively mode-locked holmium fibre laser has been demonstrated, with a semiconductor saturable absorber mirror (SESAM) as a mode locker. Semiconductor disk lasers have been used for the first time to pump holmium fibre lasers. We obtained 830-fs pulses at a repetition rate of 34 MHz with an average output power of 6.6 mW.**

Keywords: *fibre lasers, holmium-doped optical fibre, semiconductor saturable absorber mirror, semiconductor disk laser, short pulse generation.*

1. Introduction

Holmium-doped fibre lasers have the longest emission wavelength among silica fibre lasers. They operate in the spectral range 2 – 2.15 μm [1], i.e. within one of the atmospheric windows, which makes them potentially attractive for use in laser ranging systems, open-air communications and other applications. Recent advances in this area include all-fibre holmium lasers with an output power of up to 10 W [2] and quantum efficiency of 0.81 [3], and a 83-W laser with bulk cavity elements [4]. The lasers either operate in continuous mode or show self-*Q*-switching behaviour with a pulse duration of hundreds of nanoseconds [5]. At the same time, a number of applications require a considerably shorter pulse duration, which can be achieved through mode-locked operation. The main purpose of this work was to demonstrate mode-locked operation of a holmium fibre laser and determine its parameters. Note also that, in previous studies [1 – 3], holmium fibre lasers were pumped by high-power ytterbium fibre lasers operating in the range 1.12 – 1.15 μm. In this study, a semiconductor disk laser [6] was used for the first time as a pump source, which enabled a more compact laser design. In addition, core pumping ensured a high population inversion, in contrast to the diode-cladding-pumped holmium fibre laser reported by Jackson et al. [7].

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2. Experimental

The experimental configuration is shown in Fig. 1. The active medium of the laser was Ho^{3+}-doped optical fibre with an active-ion concentration of 5.4×10^{19} cm^{-3}. The fibre was produced by MCVD and was solution-doped with holmium oxides. In addition, it was doped with alumina. The core – cladding index difference was 6×10^{-3}, and the cutoff wavelength was about 2 μm. The group velocity dispersion in the lasing range was determined largely by the material dispersion and was near –50 ps nm^{-1} km^{-1}. The fibre length in the cavity was 0.8 m.

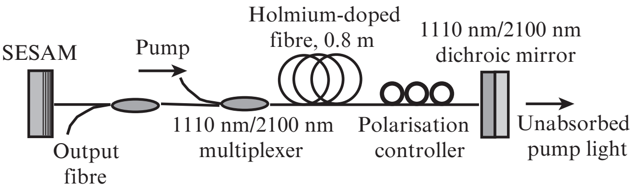

Figure 1. Experimental configuration.

The cavity of the laser was formed by a semiconductor saturable absorber mirror (SESAM) and dichroic dielectric mirror. The SESAM, containing 15 GaInSb quantum wells, was grown by molecular beam epitaxy together with a distributed Bragg reflector consisting of 18 AlAsSb/GaSb pairs. The saturation energy density of the SESAM was 46 J cm^{-2}, and the modulation depth was 10%. At room temperature, the photoluminescence of the quantum wells had a peak at 2035 nm. The reflectivity of the distributed Bragg reflector in the range 1850 – 2150 nm was 99.8%. The recovery time of the SESAM was reduced to several picoseconds by ion irradiation. It is worth noting that similar SESAMs were used to mode-lock thulium fibre lasers emitting in the range 1.9 – 2 μm [8 – 10].

The dichroic dielectric mirror had high reflectivity at the laser wavelength and high transmittance at the pump wavelength. That the pump beam was not reflected prevented saturation and optical damage of the SESAM. The radiation was coupled into and outcoupled from the fibre using a fibre multiplexer. A fibre coupler tapped 1% of the intracavity power.

The pump sources used were two semiconductor disk lasers, operating at 1104 and 1160 nm. Their emission spectra are presented in Fig. 2. Owing to the high output beam quality of the semiconductor disk lasers (Fig. 2a, inset), the pump coupling efficiency exceeded 70% for both lasers. The pump

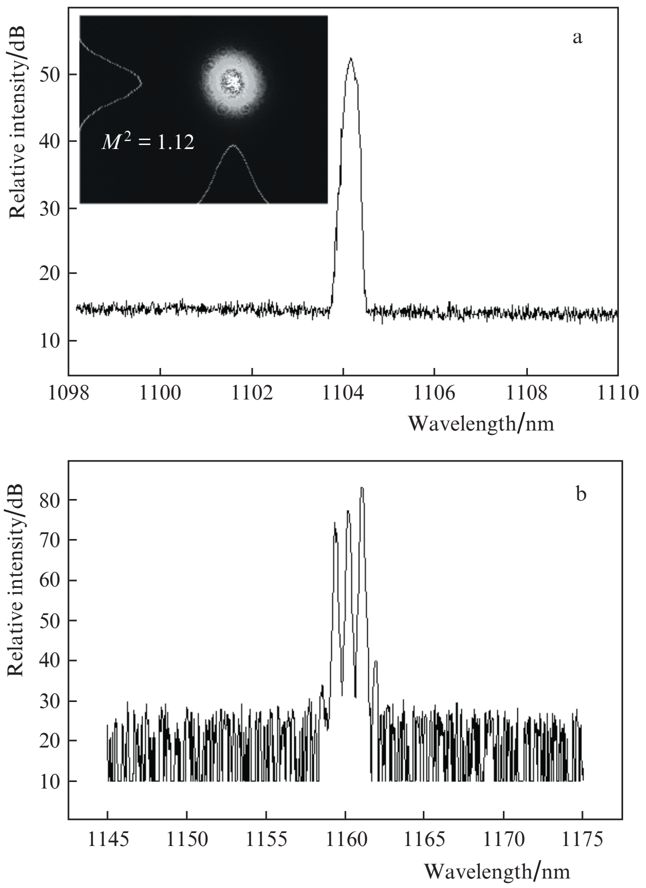

Figure 2. Emission spectra of the semiconductor disk lasers. Inset in Fig. 2a: beam profile and beam quality factor.

efficiency is determined by the absorption spectrum of the active fibre. Figure 3 shows the spectrum of the absorption band used for pumping. The emission wavelength of one pump laser is seen to lie at the short-wavelength edge of the absorption band, and that of the other, at the centre of the band. The highest pump power coupled into the fibre was 1.3 W.

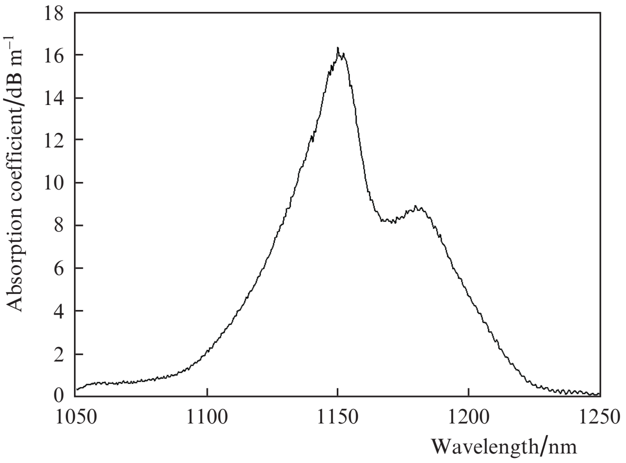

Figure 3. Absorption spectrum of the holmium-doped fibre in the pump region.

3. Experimental results

First, we examined cw operation of the holmium fibre laser. The laser configuration was similar to that represented in Fig. 1, but the SESAM was replaced by a high-reflectivity mirror, and the coupling ratio of the output multiplexer was 30 : 70. The output power of the holmium fibre laser was 50 mW at a pump wavelength of 1104 nm (pump power, 1 W) and 130 mW at a pump wavelength of 1160 nm (pump power, 0.9 W). In both cases, the laser operated in continuous mode at 2.1 μm (Fig. 4).

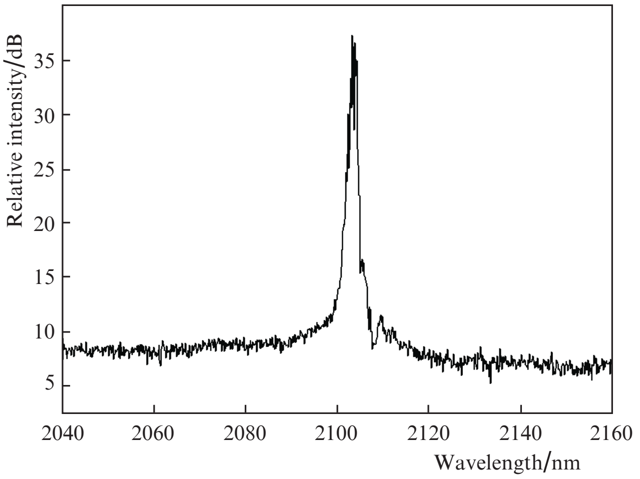

Figure 4. CW output spectrum of the holmium fibre laser.

With the SESAM in place and pumping at 1104 nm, we obtained mode-locked laser operation. The pulse train generation is illustrated in Fig. 5. The pulse repetition rate, 34 MHz, was determined by the overall cavity length, and the average output power was 6.6 mW. Figure 6 shows an oscilloscope trace of a single pulse, obtained using a photodetector with a 0.4-ns time resolution. The actual pulse duration was determined using the autocorrelation method. Figure 7 shows the autocorrelation function of a pulse and a fit to the data. Assuming that the pulse shape can be represented by the func-

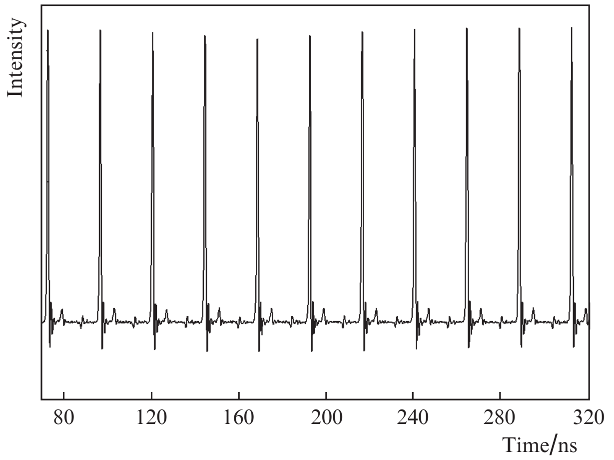

Figure 5. Pulse train generated in the mode-locking regime.

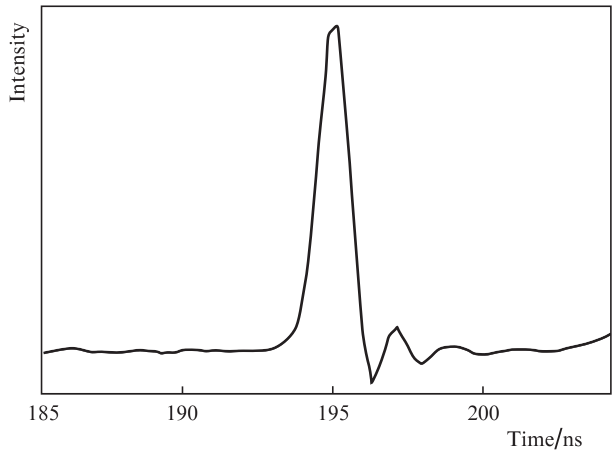

Figure 6. Oscilloscope trace of a single pulse.

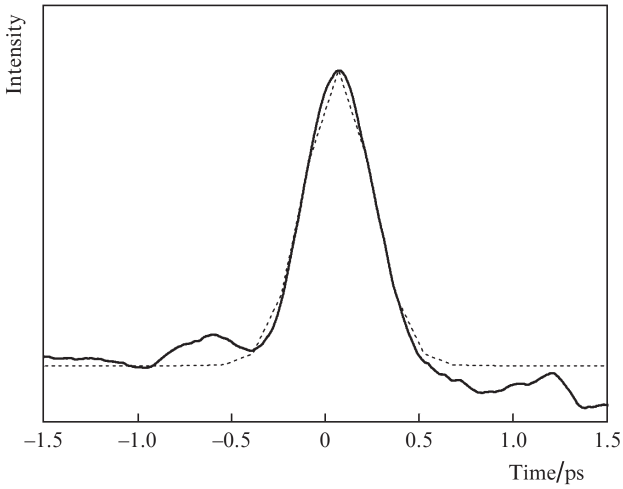

Figure 7. Autocorrelation function of a single pulse.

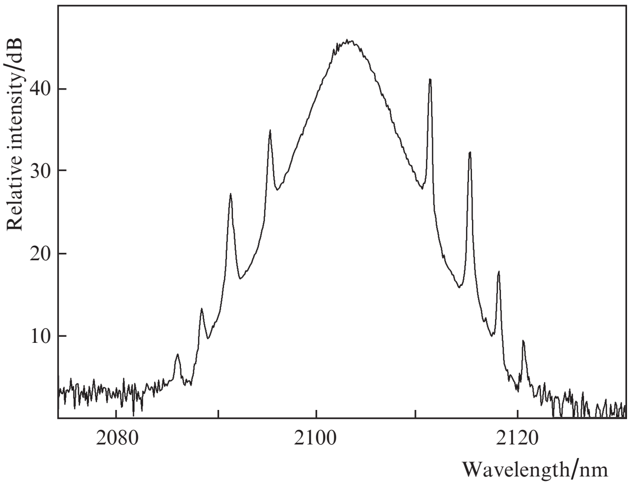

Figure 8. Emission spectrum in the mode-locking regime.

tion sech^2, we obtained a pulse duration of 830 fs. Figure 8 shows the output spectrum of the pulsed laser. The spectrum has well-defined spectral components, which point to a soliton nature of the laser pulses. The time–bandwidth product of the pulses is 0.41.

At a pump wavelength of 1160 nm, corresponding to the maximum in absorption, we obtained high average powers. However, just above the lasing threshold there was a pronounced tendency for the laser to switch to multiple pulse operation. Further increasing the pump power led to Q-switched laser operation. This behaviour suggests that further work is needed to understand in detail the spectral properties of holmium-doped silica fibres.

4. Conclusions

The first passively mode-locked holmium fibre laser has been demonstrated. As a mode locker, we used a semiconductor saturable absorber mirror (SESAM). In addition, semiconductor disk lasers have been used for the first time to pump holmium fibre lasers. Such pump sources make it possible to build high-power, efficient fibre lasers because they offer considerable output power in combination with diffraction-limited beam quality [11]. This offers the possibility of multiwatt power coupling into the core of single-mode fibres with an efficiency above 80%. In this study, we obtained a pulse repetition rate of 34 MHz, pulse duration of 830 fs, and average output power of 6.6 mW.

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