1.5 μm GaInNAs semiconductor saturable absorber for passively modelocked solid-state lasers

A. Rutz, R. Grange, V. Liverini, M. Haiml, S. Schön and U. Keller

Fully self-starting and passively modelocking of a 1.5 μm solid-state laser with a GaInNAs semiconductor saturable absorber mirror (SESAM) has been demonstrated for the first time. A saturation fluence of 20 μJ/cm^2, a modulation depth of 0.39% and a fast temporal decay of 18 ps were measured. These well-suited nonlinear optical SESAM parameters allowed for self-starting and passive modelocking of a diode-pumped Er:Yb:glass laser at 1.534 μm with a pulse duration of 5 ps at 61 MHz.

Introduction: Passive semiconductor devices such as saturable absorbers are still a great challenge for the wavelength range around 1.5 μm owing to a lack of a proper absorber material lattice-matched to a high-contrast mirror. InGaAs can provide a bandgap in the requested wavelength range and can be grown lattice-matched to InP. However, InP-based distributed Bragg reflectors (DBRs) suffer from a small refractive index contrast and poor thermal properties. 1.5 μm InGaAs grown on high-contrast AlAs/GaAs DBRs, however, is so strongly lattice-mismatched that mostly 3-D growth occurs. In general, this can cause surface roughness and increases the number of defects. One recent solution to the absorber material problem is the quaternary compound GaInNAs [1]. Here, only a small amount of nitrogen is alloyed to InGaAs addressing two problems: (i) the nitrogen drastically decreases the bandgap of InGaAs to meet 1.5 μm with much less indium and (ii) the incorporation of nitrogen additionally shifts the lattice constant towards the one of GaAs and, thereby, strongly decreases the lattice mismatch. GaInNAs is known to contain a high number of non-radiative defects, which make this material attractive for the application as saturable absorbers [2].

So far, GaInNAs SESAMs were only demonstrated to modelock solid-state lasers at 1.3 μm [3, 4]. Low saturation fluences and low nonsaturable losses proved well their suitability for passive modelocking in this wavelength range. At 1.5 μm, however, two problems were encountered: (i) fast temporal response and (ii) increased nonsaturable losses. The temporal response was decreased by ion implantation but at the expense of very high nonsaturable losses preventing the SESAM from modelocking [5]. Up to now, only a fibre laser at 1.5 μm could be successfully modelocked using a GaInNAs saturable absorber since fibre lasers are much more tolerant against nonsaturable losses [6]. Fibre lasers require SESAMs with a high modulation depth, which was obtained with multiple quantum wells (MQWs) for the absorber region. A complicated absorber structure with barrier layers and even strain relaxation layers was reported [6]. No information about nonsaturable losses was provided. However, solid-state lasers at 1.5 μm have a need for very small modulation depths and low nonsaturable losses [7, 8]. We demonstrate here for the first time self-starting stable passive modelocking of a 1.5 μm solid-state laser by a GaInNAs SESAM.

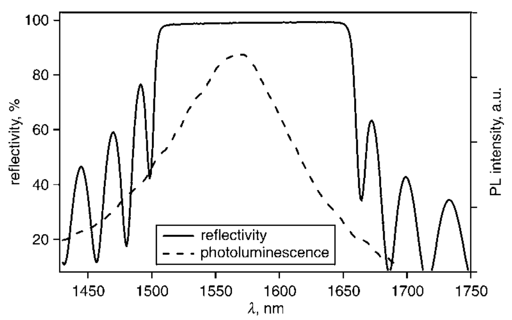

Fig. 1 *Measured reflectivity and photoluminescence spectra of GaInNAs SESAM*

Design and fabrication: The GaInNAs SESAM was designed to be antiresonant [2] and grown by molecular beam epitaxy (MBE). Growth details are reported elsewhere [9]. The absorber region of this SESAM only consisted of a 10 nm GaInNAs single quantum well (SQW), which was sandwiched by a 134 nm GaAs cap layer and an 80 nm GaAs spacer layer. The GaInNAs SESAM was based on a 40-pair AlAs/GaAs distributed Bragg reflector (DBR) centred at about 1590 nm (Fig. 1). The GaInNAs SQW absorber contained 35% indium and 2.6% nitrogen and showed an as-grown photoluminescence (PL) emission at 1563 nm. The broad PL spectrum indicates the increase in the defect concentration obtained by the incorporation of nitrogen.

Optical characterisation: Nonlinear optical characterisation [10] of the as-grown SESAM was carried out and revealed a saturation fluence, F_{sat}, of 20 μJ/cm^2 and nonsaturable losses, ΔR_{ns}, of 0.17% at a linear reflectivity, R_{lin}, of 99.4% (Fig. 2). These losses are higher than those found for the 1.3 μm GaInNAs SESAM reported earlier [3], but still low considering the increase in defect concentration by the rise in nitrogen content. A modulation depth, ΔR, of 0.39% was determined to be in good agreement with the design. Degenerate pump-probe experiments were performed using 61 MHz, 5 ps pulses from an Er:Yb:glass laser (ERGO) at 1534 nm to evaluate the temporal recovery from absorption bleaching (Fig. 3). We obtained a fast temporal response of 18 ps. It is interesting to note that the temporal response of the as-grown GaInNAs absorber layer at 1.5 μm (18 ps) is very similar to the one found for our 1.3 μm GaInNAs absorber (30 ps) reported earlier [3]. This is surprising since the nitrogen content increased from 1.6 to 2.6% while all other growth parameters were kept constant. Usually, the increase in nitrogen content of GaInNAs is accompanied by a strong decrease in the PL intensity suggesting a higher incorporation of non-radiative defects. We observed this too. In addition, we expected a clear decrease in the temporal response. However, there was only a negligible decrease in the temporal decay for the 1.5 μm GaInNAs SESAM, which suggests that the defect concentration relevant for recovery from absorption bleaching stayed nearly constant. Applying annealing at 650°C for 1 min leads to the expected increase in PL intensity but, again, the temporal response did not change accordingly as generally observed for other material systems upon annealing (e.g. low-temperature GaAs [11]). The only change we observed after annealing is a reduction in the nonsaturable losses from $0.17 \pm 0.04\%$ to about $0.08 \pm 0.04\%$ for the benefit of a higher linear reflectivity. Consequently, we conclude that defects generated by an increase in the nitrogen content are not relevant for the recovery from absorption bleaching but contribute to nonsaturable losses, e.g. by additional absorption.

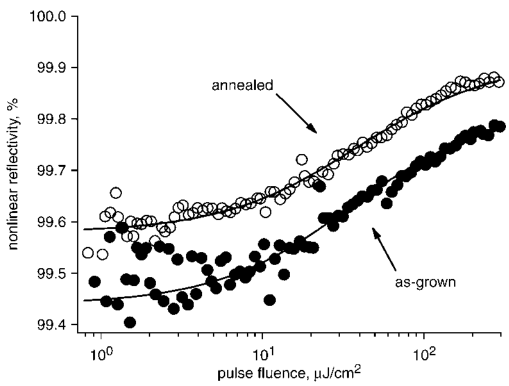

Fig. 2 *Nonlinear reflectivity against pulse energy fluence for as-grown and annealed SESAM*

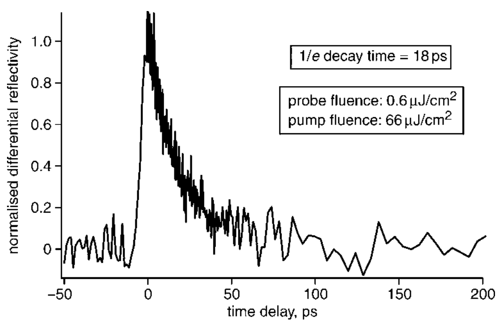

Fig. 3 *Pump-probe experiment: temporal response of 1.5 μm GaInNAs SESAM*

Laser performance: Laser testing was carried out using a 61 MHz Er:Yb:glass laser at 1534 nm. For the first time, a GaInNAs SESAM successfully demonstrated self-starting and stable modelocking of a 1.5 µm solid-state laser. The microwave spectrum (Fig. 4) shows clean CW modelocking without any Q-switching instabilities. Sidebands owing to Q-switch modelocking would be observed at around 25 kHz offset. Pulses as short as 5 ps were measured and fitted with a sech^2 function (inset of Fig. 4). An average output power of 70 mW with 690 mW incident pump power was obtained using a 3% output coupler. We observed no degradation of the SESAM over several hours.

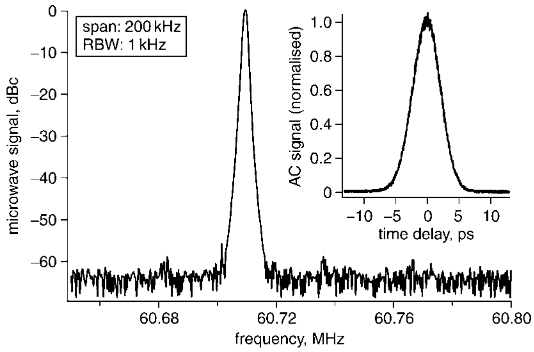

Fig. 4 *Laser performance data: microwave spectrum showing clear and stable modelocking with 200 kHz span*

Inset: Autocorrelation (AC) signal gives a 5 ps pulse duration, fitted with a sech^2 function

Conclusion: We have fabricated and characterised a GaInNAs SESAM, which for the first time self-started and passively mode-locked a 1.5 µm solid-state laser. Laser pulses as short as 5 ps were generated from this Er:Yb:glass laser at 1534 nm. Our GaInNAs SESAM demonstrated low saturation fluence and low nonsaturable losses which make it well suited for passive modelocking in the 1.5 µm wavelength range.

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