Antimonide Semiconductor Saturable Absorber for Passive Mode Locking of a 1.5-μm Er : Yb : Glass Laser at 10 GHz

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***Abstract*—We demonstrate the first antimonide (AlGaAsSb) semiconductor saturable absorber mirror (SESAM) for stable passive mode locking of an Er : Yb : glass laser at 10 GHz and a center wavelength of 1535 nm generating 4.7-ps pulses. The nearly resonant SESAM is InP-based, grown by metal–organic vapor phase epitaxy and optimized for high pulse repetition rates. We fully characterized the linear and nonlinear optical parameters: The saturation fluence is 80 μJ/cm^2, the modulation depth is 0.4% and the nonsaturable losses are 0.35%. A 1/e decay time of 95 ps is achieved after wet chemical etching of the 10-nm InP cap on top of the absorber.**

***Index Terms*—High pulse repetition rates, mode-locked lasers, optical materials.**

I. INTRODUCTION

PASSIVELY mode-locked solid-state lasers with high repetition rates are convenient sources for high-speed telecommunications applications at long wavelengths (1.3–1.5 μm) [1], [2]. Such pulsed sources exhibit very low timing jitter because of low intracavity losses and, thus, long photon lifetime [3]. Additionally, they do not require high-speed driving electronics as in actively mode-locked lasers. The key element in these compact sources is the semiconductor saturable absorber mirror (SESAM), which allows for stable, self-starting continuous-wave (CW) mode locking [4]–[6]. However, the growth of SESAMs is still very challenging at long wavelengths and especially for gigahertz (GHz) operation. The nonlinear parameters such as the saturation fluence, the modulation depth, the inverse absorption, the nonsaturable losses, and the recovery time have to be accurately adjusted and balanced to overcome the Q-switched mode locking (QML) threshold [7]. Moreover, the Er : Yb : glass gain medium, well suited for telecom applications with its gain bandwidth covering the entire C-band, has a small emission cross section leading to a strong tendency for QML.

Very few semiconductor materials achieved multi-GHz repetition rates at 1.3 or 1.5 μm. The highly strained InGaAs absorbers grown on GaAs substrate by molecular beam epitaxy (MBE) mode-locked an Er : Yb : glass laser at megahertz (MHz) and GHz repetition rates [2], [8]. GaInNAs absorbers, which are almost lattice matched to GaAs by adding nitrogen, achieved MHz operation at 1.5 μm [9], [10]. So far, GHz repetition rates were reported only at 1.3 μm for GaInNAs [1].

In this letter, we demonstrate a novel long-wavelength semiconductor saturable absorber material, AlGaAsSb, with a wide bandgap tunability (0.8–2.3 eV) and intrinsically low modulation depth [11], [12]. Similar to InGaAsP, AlGaAsSb is lattice-matched to InP, but its absorption edge is not as steep as the one of InGaAsP [13]. Therefore, we can operate the absorber in the band tail to achieve a small enough modulation depth (i.e., usually below 0.5%) for stable mode locking at high repetition rates.

The epitaxial growth development for the absorber was based on the recently demonstrated metal–organic vapor phase epitaxy (MOVPE) growth of a 24-pairs AlGaAsSb–InP distributed Bragg reflector (DBR) with 99.5% reflectivity [14]. In contrast to InGaAsP–InP DBRs, AlGaAsSb has a higher refractive index contrast with InP (0.4). Therefore, a lower number of quarter-wave layers is required for highly reflective DBR. We already reported the first antimonide SESAM, which self-started and mode-locked a 61-MHz Er : Yb : glass laser [15]. Further SESAM optimization allowed us to push the repetition rate up to 10 GHz, which confirms that AlGaAsSb is the adequate choice of material. Here, we fully characterized the linear and nonlinear optical parameters and the laser performance of the antimonide SESAM.

II. ANTIMONIDE SESAM DESIGN AND CHARACTERIZATION

Fig. 1 shows the design of the AlGaAsSb SESAM. It consists of 60 Bragg pairs of InP–InGaAsP grown by MOVPE on an (100) InP substrate centered at 1.55 μm. On top of the DBR, a 90-nm InP spacer layer, a 7-nm AlGaAsSb absorber, and a 10-nm InP cap were grown. The absorber is lattice matched to InP for 51% of As and 4% of Al. This composition sets the 300 K material bandgap at 1.47 μm. The as-grown SESAM is resonant with a field enhancement in the absorber of 3.8 [16].

After the growth, we removed the 10-nm InP cap layer with wet chemical etching to decrease the decay time of the SESAM (Fig. 2). In contrast to low-temperature MBE growth [17],

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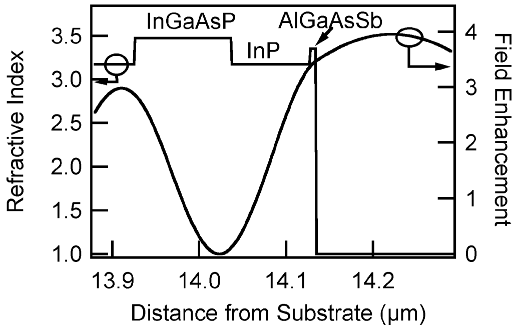

Fig. 1. SESAM design and field enhancement calculation for a laser wavelength of 1535 nm.

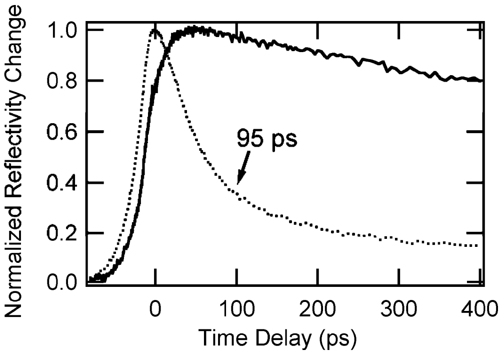

Fig. 2. Normalized time response of the AlGaAsSb SESAM before (solid line) and after (dotted line) wet chemical etching of the InP cap, measured with a SESAM mode-locked Er : Yb : glass laser at 1535 nm, 61 MHz, and with 20-ps pulses. Pump fluence $= 60\ \mu\text{J/cm}^2$ and probe fluence $= 1\ \mu\text{J/cm}^2$.

MOVPE grown absorbers suffer from long relaxation times, which are usually reduced by ion-implantation [18], or by defects close to the surface. In our case, we selectively etched the InP cap layer to obtain fast recombination at the surface states of the AlGaAsSb–air interface. A degenerate pump–probe experiment gives a 1/e decay time of 95 ps without the 10-nm InP cap, which is much faster than with the cap (more than 1 ns) (Fig. 2). Although the decay time is long compared to the pulse duration, this is sufficient to mode-lock multi-GHz lasers [19], [20]. The surface oxidation was not an issue due to the low aluminum content in the absorber. The simulated design gives a field enhancement of 3.4 without the InP cap (Fig. 1). So the SESAM is still close to resonance.

The linear reflectivity of the SESAM is measured with a CARY 5E spectrophotometer and shows a resonance dip close to the laser wavelength of 1535 nm, as expected from the design (Fig. 3). The nonlinear characterization is performed with an Er : Yb : glass laser source at 1535 nm, 61 MHz, and 20-ps pulse duration. From the nonlinear reflectivity measurements, we obtained a saturation fluence of 80 μJ/cm^2, a modulation depth of 0.4%, and nonsaturable losses of 0.35% (Fig. 4) [21]. This is a rather high saturation fluence and unusually low modulation depth for a resonant SESAM design [16]. But it results from the fact that the absorber is operated in the band tail. Both absorber parameters are important and have to be well balanced to achieve stable CW mode locking at multi-GHz repetition rates. The nonsaturable losses are low and originate most probably from transmission losses through the DBR. Finally, inverse absorption (the decrease of the nonlinear reflectivity for pulse fluences higher than 120 μJ/cm^2) plays a key role to stabilize the laser against QML instabilities, even at pulse durations in the picoseconds regime [22].

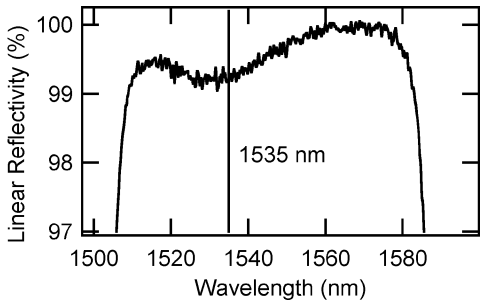

Fig. 3. Measured linear reflectivity of the AlGaAsSb SESAM.

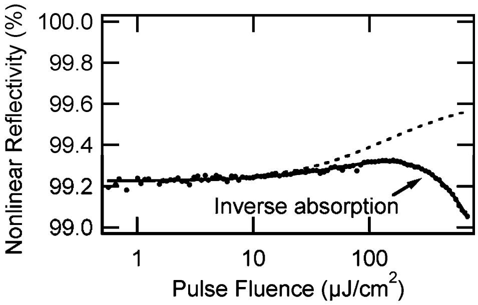

Fig. 4. Nonlinear reflectivity measurement of the AlGaAsSb SESAM without InP cap: measured data (dots), fit with inverse absorption (solid line), and fit without inverse absorption (dashed line).

III. Laser Performance

This AlGaAsSb SESAM was used to successfully mode-lock a 10-GHz Er : Yb : glass laser. In contrast to harmonic mode locking (where stable operation requires sophisticated measures), our approach uses fundamental mode locking, i.e., with a single pulse circulating in the laser cavity. The laser cavity uses strongly curved mirrors in a folded geometry [2]. The usefulness of such a cavity concept in terms of low noise properties has been demonstrated using an optimized packaging in [3]. The laser is pumped with fiber-coupled (single-mode) telecom-grade laser diode emitting 250 mW at 980 nm. We obtained a pulse duration of 4.7 ps (fitted for a sech^2-shaped pulse) with an optical bandwidth of 0.9 nm (Fig. 5). This corresponds to a time-bandwidth-product of 0.53, which is 1.68 times the transform limit. The mode locking was stable and self-starting.

The microwave spectrum shows a clean peak at the cavity repetition rate of 9.788 GHz with no side peaks, as they would occur due to QML operation (Fig. 6). The output power was 9 mW with diffraction limited beam profile, which allows for efficient fiber coupling. No degradation was observed over hours.

IV. Conclusion

We demonstrated the first AlGaAsSb SESAM, which successfully mode-locked an Er : Yb : glass laser at 10-GHz repetition rate and 1535 nm. The antimonide SESAM was grown by

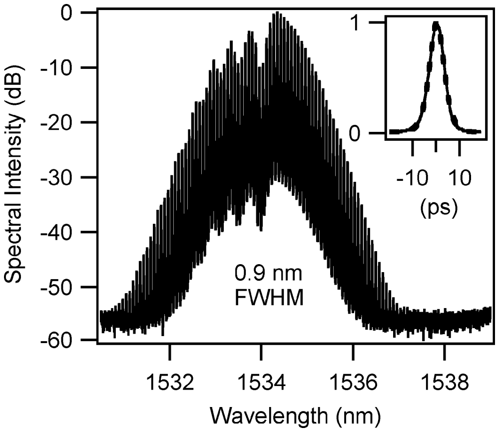

Fig. 5. Optical spectrum, logarithmic scale. Inset: normalized second-harmonic signal versus the time delay (solid line) and its sech^2 fit (broken line) giving a pulse duration of 4.7 ps. The time bandwidth product is 0.53.

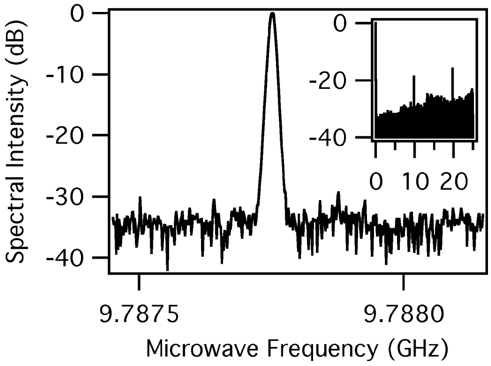

Fig. 6. Microwave spectra showing the absence of Q-switching instabilities, resolution bandwidth (RBW) 10 kHz, and span 0.8 MHz. Inset: RBW 1 MHz and span 25 GHz.

MOVPE on a commercial InP substrate. The nonlinear optical parameters were optimized for high repetition rate operation by using the band tail of the broadened absorption edge of antimonide.

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