Stabilized Mode-Locked Tapered Semiconductor Laser Diodes with 100-200pJ Pulse Energies for Space Metrology Applications

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***Abstract*— We demonstrate the first mode-locked laser diode producing picosecond pulses of 200 pJ energy without amplifier. It operates at low pulse repetition frequency (PRF) of 2.9 GHz in a very-long (13.5 mm) monolithic tapered cavity. The output pulses can be compressed to 2.4 ps width. The chip consumes 8.2 W of electric power. The PRF can be continuously tuned within a 9.8 MHz band. In a hybrid mode-locking regime with RF current modulation or introducing a PLL loop actuating the DC current, PRF relative stabilities of $9{\cdot}10^{-10}$ and $1{\cdot}10^{-10}$ on 1 s intervals are achieved. We also demonstrate the inverse bow-tie external cavity mode-locked semiconductor laser reaching 70 pJ picosecond pulses without amplifier and at extremely low PRF of 1.65GHz, while consuming only 2.9W of electric power. The compressed pulse width is 0.73 ps. The laser operates in a 80 mm long external cavity. By translation of the output coupling mirror, PRF is continuously tuned over a 9.1 MHz range without additional adjustments. Active stabilization has allowed us to reach PRF relative stability at $3{\cdot}10^{-10}$ level on 1 s intervals. These MLSCL lasers fulfill the requirements of the European Space Agency (ESA) for inter-satellite long distance measurements.**

I. Introduction

European Space Agency (ESA) considers Mode-Locked Semi-Conductor Laser (MLSCL) technology as a promising candidate for space applications in precision optical metrology systems such as High Accuracy Absolute Long Distance Measurement (HAALDM). However very challenging performance requirements need to be met for these applications: pulse duration < 1 ps, pulse repetition frequency (PRF) of 1-3 GHz, PRF stability $< 5{\cdot}10^{-9}$, PRF tunability > 20 MHz, average optical output power > 200 mW, pulse energy > 200 pJ, high spatial beam quality ($M^2 < 2.5$) in addition to the space application requirements on launch vibrations, volume, weight, power consumption and efficiency. We have realized two types of passively mode-locked (ML) multiple section edge emitting lasers to address these challenging targets: (*i*) very long (13.5mm) monolithic tapered (MT) laser [1] (Fig.1), and (*ii*) inverse bow-tie (IBT) external cavity (EC) laser [2] (Fig.8). Both lasers are designed using the model from [3] and operate without an amplifying stages, producing, respectively 70 pJ and 200 pJ pulse energies. In this communication we summarize the design, fabrication and testing of these novel tapered mode-locked semiconductor lasers.

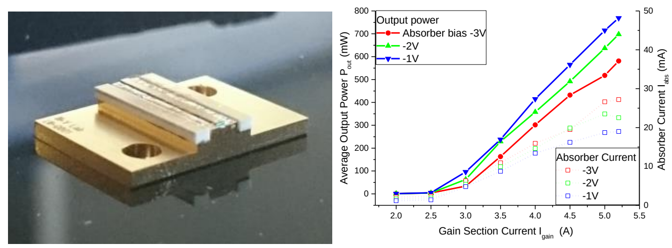

Fig. 1. Left: 13.5 mm long monolithic tapered (MT) laser chip mounted on copper heatsink. Right: Its L-I characteristics

II. Monolithic Tapered (MT) Laser

In order to get high power and wall plug efficiency on a very long laser cavity we have designed a structure with very low internal losses (~ 1 cm^{-1}) together with high quantum efficiency (> 90 %) and low series resistance. The Aluminium free active region laser structure comprising two 5 nm thick compressively strained GaInAs quantum wells (QWs) is grown by Metal Organic Chemical Vapour Epitaxy (MOVPE) on 3'' substrate. The tapered laser structure comprises different sections (Fig. 2): two absorber sections, tuning section and a tapered gain section. The last one consists of the linear and the tapered waveguide parts and comprises beam spoilers located in between the two parts. The monolithic cavity is made 13.5mm long in order to allow for a ML operation with a PRF of 3 GHz. The rear and front facets have received respectively high (>95%) and low (<0.1%) reflectivity dielectric coatings enabling high-power operation regimes with good quality of the output beam. The laser chips have been mounted on specifically designed copper heatsinks (Fig. 1).

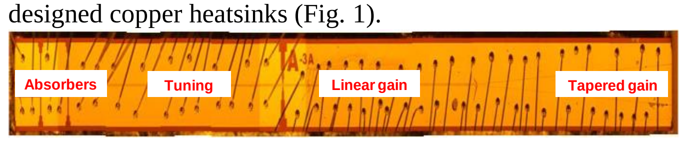

Fig. 2. Photographic image of MT laser chip. The overall length is 13.5 mm.

L-I characteristics at different biases (Fig.1), measured with a large aperture integrating sphere just in front of the laser,

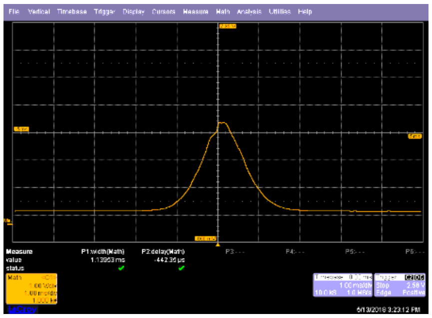

Fig. 3. SHG IAC trace in MT laser.

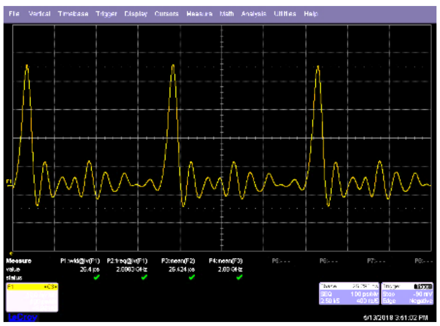

Fig. 4. Sampling scope waveform in MT laser.

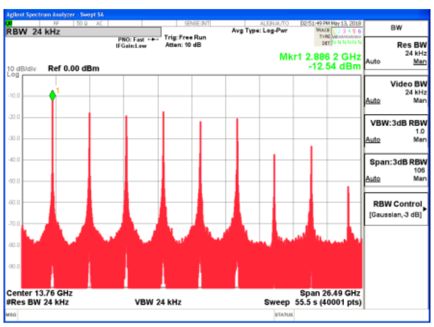

Fig. 5. RF spectrum in MT laser

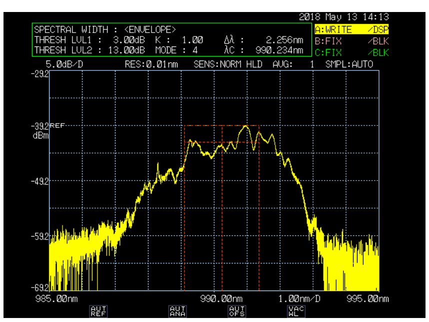

Fig. 6. Optical spectrum in MT laser.

shows high average powers and high efficiencies (0.5 W/A to 0.6 W/A) near threshold currents. The output beam is then collimated using a combination of an aspherical and cylindrical lenses and is fed to the test setup via an optical isolator. After a beam splitter, one portion is used for the pulse width measurements while another one is injected in a single mode fibre for optical (ANDO AQ6317B) and RF (Agilent Signal Analyser) spectral analysis as well as to monitor the pulse train waveform with a sampling scope (LeCroy, WaveExpert 100 H). The pulse width is measured by a non-collinear Second Harmonic Generation Intensity Auto Correlator (background-free SHG IAC) from Femtochrome Research Inc (Fig. 3). Prior to the measurements, the autocorrelator was calibrated using fs laser pulses from a mode-locked laser (Origami-10, Onefive).

Under the driving currents I_{gain}=5.2 A and I_{tune}=50 mA in the gain and tuning sections and the absorber bias U_{abs}= -3 V, an average optical power of 581 mW is measured after the collimation lens assembly. In Fig. 3, the scale factor of SHG trace is 15.2 ps / ms while the marker width of the correlation peak is of 1.14 ms, yielding a FWHM estimate for the ML pulse of $1.14 \cdot 15.2 \cdot 0.648 = 11$ ps (we assume a hyperbolic secant pulse shape). The waveform on the sampling scope (Fig. 4) and the RF spectrum (Fig. 5) indicate a periodic pulse train at the fundamental PRF frequency in the cavity of 2.886 GHz. The ringing in waveform is due to electronics. The pulse peak power and energy are 18.3 W and 201 pJ, respectively. Narrow high order PRF harmonics seen in the RF spectrum attest for a ML regime. The optical spectrum (Fig. 6) is relatively continuous and broad (2.26 nm wide). The time bandwidth product (TBP) is 7.7, indicating possibility to compress the pulse. Indeed, using grating compressor, the pulse width was reduced down to 2.4 ps.

PRF was stabilized by introducing a PLL loop actuating on the gain section current or by injecting RF modulation into the tuning section in order to realize a hybrid mode-locking regime. The Allan variance of $1.15 \cdot 10^{-10}$@ 1s and $9.16 \cdot 10^{-10}$@ 1s respectively was achieved, fulfilling ESA requirements (Fig.7).

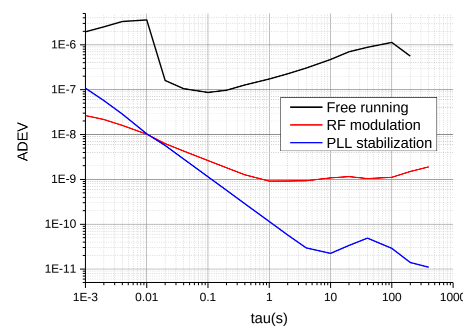

Fig. 7. PRF stability in free-running passively mode-locked MT laser, stabilized with PLL loop or via hybrid modelocking with RF modulation.

III. External Cavity Inverse Bow-Tie Laser

The PRF targeted for passive ML operation in this laser is very close to the frequency of its relaxation oscillations. We established a dedicated cavity design approach in which the cavity losses, gain and absorption are tailored so as to avoid Q-switched mode-locking with low-frequency modulation of the pulse train envelope. The fabricated gain chip comprises several absorber and gain sections. For high wall plug efficiency, it is designed to have low internal losses (~1cm^{-1}) and low series resistance. The Aluminium-free active region with two 5 nm thick compressively strained GaInAs quantum wells (QWs) is grown by MOVPE. The absorber section is placed at one EC cavity edge to avoid harmonic ML and is made of a single-mode waveguide to provide spatial filtering. For reaching high pulse energy, one portion of the gain section is made strongly multimode while for matching with the external cavity mode the entire section has inverse bow-tie geometry [3]. The rear and front facets are HR (>95%) and AR (<0.1%) coated for high-power operation with good beam quality. The external cavity is closed with a flat 5% mirror. The mode matching is achieved by refocusing the laser beam on the output coupling mirror (Fig. 8).

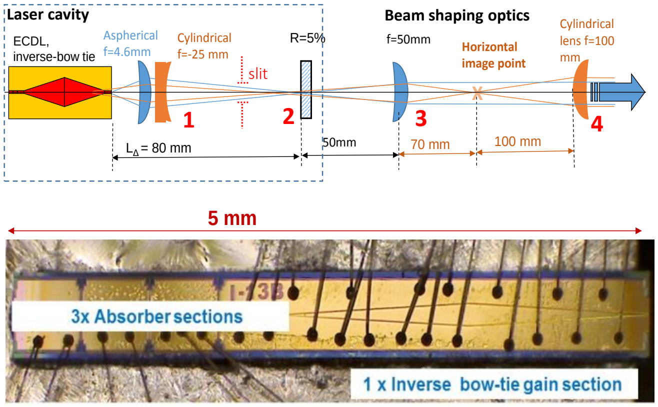

Fig. 8. Top: Schematic diagram of the external-cavity IBT laser. Bottom: photographic image of the IBT laser gain chip.

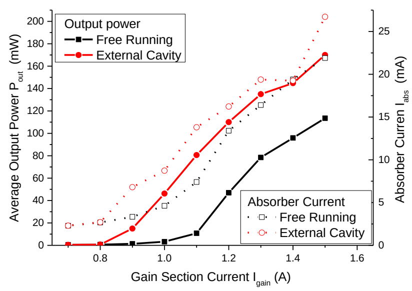

Fig. 9. LI curves (left axis, closed symbols) in free running IBT laser module and in the external cavity configuration.

Good mode coupling with EC is attested by a 20% (0.2A) threshold current reduction in EC configuration as compared to free-running laser chip (Fig.9). The average output power of 170 mW can be reached in EC configuration at 1.5A pump current and -3V absorber bias.

Passive ML at fundamental cavity frequency is achieved at the pump current of 1.7 A (2.9 W of electric power) on the inverse bow-tie gain section and absorber bias of -2.7V. The background-free intensity autocorrelation trace (Fig. 10) reveals a pulse width of 6.0 ps. RF power spectrum (Fig.12) and waveform (Fig.11) affirm ML at fundamental PRF of 1.65GHz. The average power is 116 mW yielding the pulse energy of 70pJ. The time bandwidth product is of 6.2, indicating potential for pulse width reduction down to sub-picosecond scale. Indeed with a grating pulse compressor it was compressed to 0.73 ps

When the laser is operating at fundamental roundtrip frequency of the EC, PRF can be continuously tuned over a 9.1 MHz range by translating the output coupling mirror without any other additional adjustments [Fig.14]. In order to implement an active stabilization loop of the PRF and to measure its Allan variance, we use an architecture with two local oscillators (LOs). The first LO is a reference in the phase locking loop while the second one provides an independent reference for absolute PRF stability measurements. Active stabilization with a phase locking loop actuating on the driving current of the gain sections resulted in PRF relative stability at $2.9{\cdot}10^{-10}$ level on 1s intervals [Fig.3(b)].

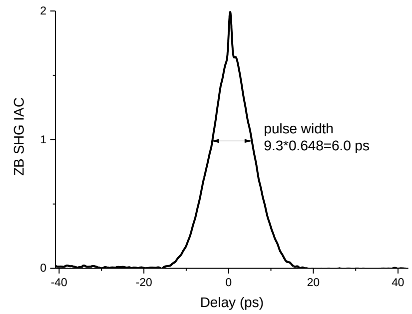

Fig. 10. SHG IAC trace in IBT EC laser.

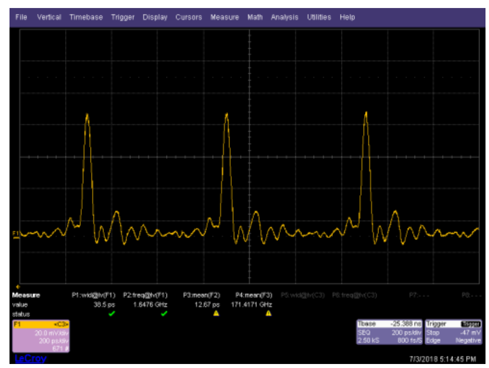

Fig. 11. Sampling scope waveform in IBT EC laser.

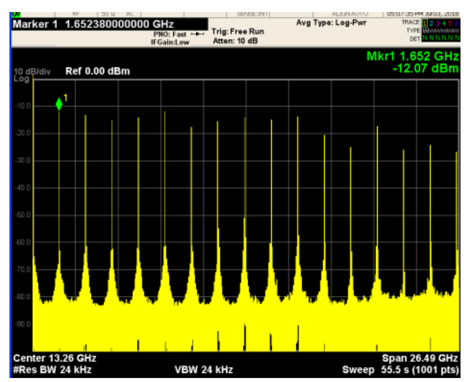

Fig. 12. RF spectrum in IBT EC laser.

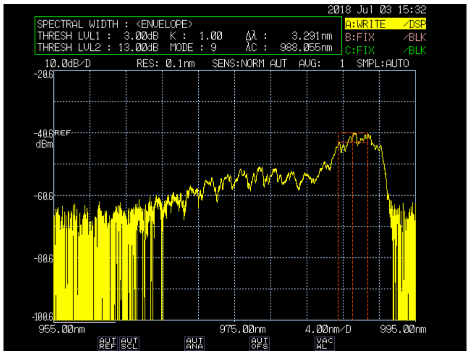

Fig. 13. Optical spectrum in IBT EC laser.

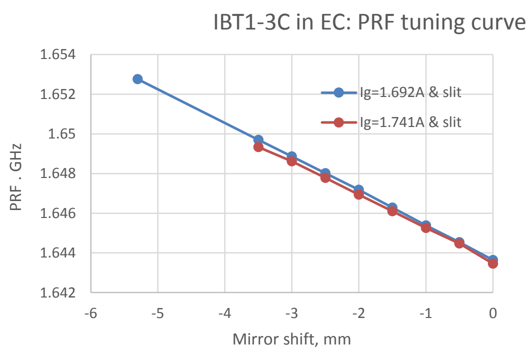

Fig. 14. PRF tuning by output coupling mirror translation in external cavity IBT laser for two operating set points.

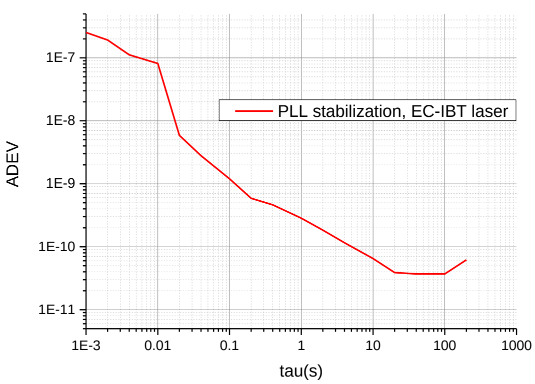

Fig. 15. PRF stability (ADEV) in stabilized external cavity IBT laser.

IV. Conclusions

We have demonstrated two approaches to build mode locked semiconductor lasers capable to fulfill challenging ESA requirements for application in space-borne optical metrology systems. To the best of our knowledge, this is the first time that fundamental cavity ML is reached at such low frequency and with such high pulse energies, without any additional amplification stages.

Acknowledgment

The authors gratefully acknowledge the support of the European Space Agency. The authors are very thankful to Borge Vinter for fruitful discussions and optical gain modelling for QW heterostructures.

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