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# High-Power and Low-Noise 10-GHz All-Active Monolithic Mode-Locked Lasers with Surface Etched Bragg Grating

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**Abstract:** We have fabricated 4.4 mm long monolithic InAlGaAsP/InP mode-locked lasers with integrated deeply surface etched DBR-mirrors. The lasers produce 3.7 ps transform-limited Gaussian pulses with 10 mW average power and 250 fs timing jitter.

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## 1. Introduction

Monolithic mode-locked lasers (MMLs) are attractive as compact pulse sources in high-speed optical communication systems [1], in microwave photonics [1] and in analogue-to-digital converters (ADCs) [2]. Distributed Bragg reflectors (DBR) or other types of filters are needed in these lasers to control the spectral bandwidth, the centre wavelength and to obtain repetition rate tuning of the pulses [3]. There are only a few reports on long ( $\sim 10$  GHz) MMLs with integrated wavelength selective filters at a wavelength of  $1.55 \mu\text{m}$ . The ones reported suffer from low output power ( $\leq 1$  mW) [3,4], and long pulses (6.1 ps) [3], ( $\geq 9$  ps) [4,5]. We present a laser that combines an active material design for short pulses with high power and low noise [6], with a deeply surface etched DBR. To our knowledge, this is the first time a MML is integrated with a surface etched DBR. The potential advantages of deep surface etching are large index contrasts and the possibility of omitting a difficult and expensive regrowth on a corrugated surface.

## 2. Device structure and fabrication

The epitaxial structure is very similar to [6], with one  $7 \text{ nm In}_{0.29}\text{Ga}_{0.71}\text{As}_{0.90}\text{P}_{0.10}$  quantum well as the gain material and  $\text{Al}_{0.16}\text{Ga}_{0.31}\text{In}_{0.53}\text{As}$  barriers, grown in one single epitaxial step. The integration of the DBR is performed by surface etching the grating and the ridge simultaneously. A combined grating and ridge mask in  $200 \text{ nm SiO}_2$  is defined by first e-beam lithography and then UV-lithography. The  $2.2 \mu\text{m}$  wide ridge and the  $364 \text{ nm}$  grating trenches (third order) are then etched to  $2125 \text{ nm}$  depth with a cyclic  $\text{CH}_4/\text{H}_2$  and  $\text{O}_2$  dry etch, see Fig. 1a. Cyclotene 3022-35 (Dow Chemicals) is used for passivation and for support of the  $364 \text{ nm}$  pillars. The chips are cleaved to a length of  $\sim 4.4 \text{ mm}$ , soldered junction side up to an AlN microwave substrate and the  $\sim 100 \mu\text{m}$  absorber section is bonded to a co-planar transmission line that is contacted with a high-frequency probe for hybrid mode-locking. No  $50 \Omega$  termination is employed. After mounting, a 98% HR coating is applied to the absorber facet. Furthermore, a  $\sim 10^{-4}$  AR coating is applied to the DBR facet to ensure low facet reflections.

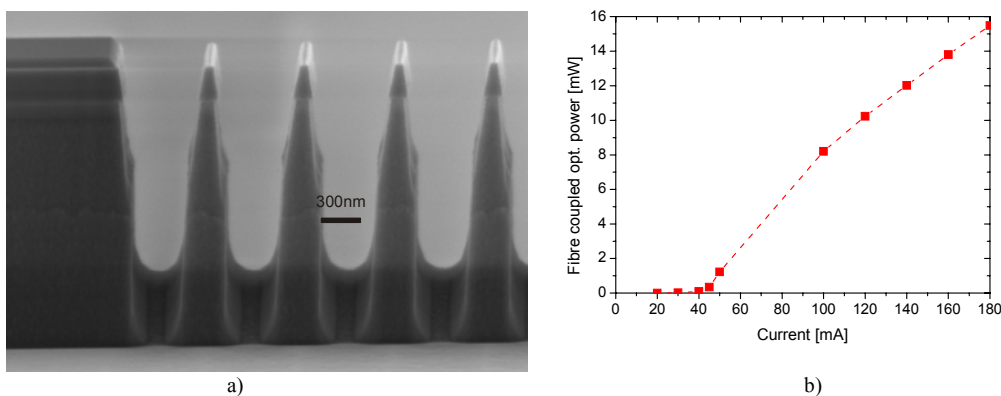


Fig. 1. a) SEM micrograph of laser ridge and grating after dry etch. b) Fibre-coupled power vs. forward current in CW-mode for the same DBR-MMLL that produced the data in Fig. 2.

### 3. Device performance

The average threshold current is 40 mA ( $J_{th}$ : 0.45 kA/cm<sup>2</sup>) after both coatings have been applied, and the fibre-coupled output power in CW-mode is more than 15 mW. An example of an LI-curve is shown in Fig. 1b. The 60-145  $\mu$ m Bragg gratings are designed to have a centre wavelength of 1550 nm. The spectral widths of the gratings are  $\sim$ 2 nm and the measured reflection is  $\sim$ 1 %. Under uniform injection, the lasers are single-mode, while a negative absorber bias of more than -2.2 V results in passive mode-locking with a Gaussian spectrum Fig. 2a. The background of the spectrum is set by the sidepeaks of the DBR-filter, which are suppressed by 35-40 dB. Pulses with pulsewidths between 3.7 and 6 ps, depending on bias conditions, and a time-bandwidth product of 0.4-0.5 (with 6.3 ps/nm added linear dispersion in SMF) were measured by frequency-resolved optical gating (FROG), Fig. 2b.

Hybrid mode-locking is performed by modulating the absorber bias with a  $\sim$ 9.9 GHz sinusoid from a synthesizer (R&S SMR40), amplified to 26 dBm. The absorber bias needs to be increased to  $\sim$ -5V to obtain good hybrid mode-locking. No major change in pulse width or spectral width could be observed with the addition of the RF-signal, indicating that the filter limits the pulse shortening. By further process optimisation it's possible to achieve a wider filter and thereby shorter pulses [9]. The RF-spectrum becomes much narrower in hybrid operation, indicating a good lock to the modulating synthesizer signal. The timing jitter is measured with an RF spectrum analyzer from the phase-noise in the fundamental RF-line as outlined in [7]. Integrating the phase-noise from 20 kHz to 80 MHz, according to the specifications of jitter generation for telecommunications by ITU-T [8], results in an absolute RMS timing jitter of 250 fs. The jitter from the synthesizer is 161 fs evaluated in the same range and contributes to most of the noise below 1 MHz. To our knowledge, the obtained pulses are shorter, much more powerful and have lower noise than the best earlier 10-GHz DBR-MMLs [3, 4].

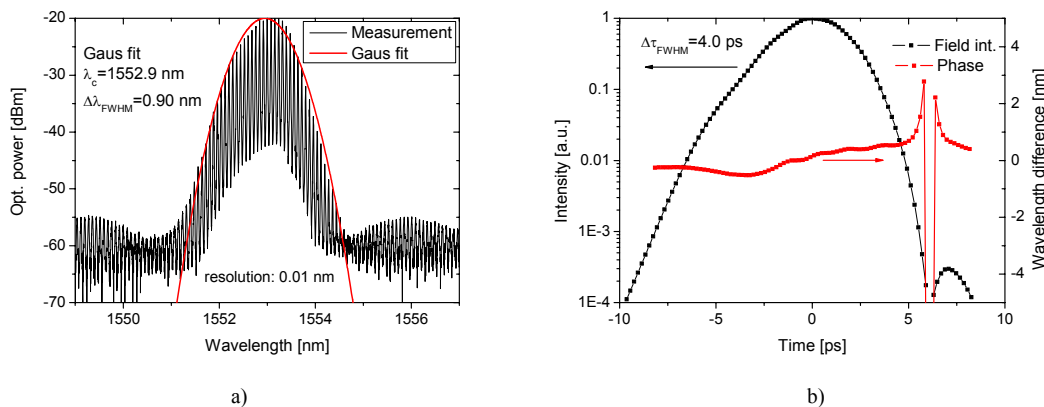


Fig. 2. a) Spectrum of a passive mode-locked laser (after attenuation) measured with an Optical Spectrum Analyzer, and its Gaussian fit. b) Field intensity retrieved from FROG-data (128x128 points; FROG error 0.008) from the same passive mode-locked laser. Operating conditions: gain current 81 mA, grating voltage 1.0 V, absorber voltage -2.53 V.  $(\Delta t \Delta \nu)_{FWHM} = 0.48$  obtained from the FROG-data.

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