18GHz Fabry-Pérot integrated extended cavity passively modelocked lasers

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Abstract: *Integrated modelocked lasers producing pulses down to 2.1 ps were fabricated in bulk InGaAsP using butt-joint active-passive integration. It is demonstrated that good modelocked operation can be obtained in devices using this integration technology. Pulses obtained are close to transform limited and the dynamics outside the control parameter range for modelocked operating are reduced through the use of an extended cavity.*

Introduction

Modelocked lasers (MLL) are useful devices in optical telecommunications as transmitter sources and all-optical clock recovery devices [1]. When MMLs are realised in active-passive integration technology, they can be located anywhere on a larger chip containing other devices connected to the MLL. Also integrated extended cavity MLLs can have long cavities and therefor relatively low repetition rates which is usefull for many applications outside optical telecommunications. In this paper results from linear integrated extended cavity passively modelocked lasers (EC-MLL) are presented and comparisons are made with results obtained with all-active Fabry Perot MLLs (FPMLL). The active-passive wafer on which the EC-MLLs here were realized, is the one that showed very low butt-joint loss and reflections as presented in [2]. A number of 18 GHz self-colliding pulse modelocked lasers have been demonstrated. Pulses with a length of 2.1 ps and with a small pedestal have been observed. The linear lasers presented here demonstrate that butt-joint active-passive integration with sufficiently low junction reflectivity, as developed at COBRA can be utilized for integrated modelocked lasers. Moreover, the pulses obtained are close to transform limited [3,4] and the intensity modulations of the laser output in the range of the relaxation oscillation are significantly lower than the values observed in all-active FPMLLs [5].

Design and fabrication of the EC-MLL

A photograph of four fabricated 18 GHz EC-MLLs is presented in Fig. 1. The devices have been realized starting from extended cavity Fabry-Perot lasers that have been fabricated in active-passive integration technology at COBRA. A chip containing 12 lasers was cleaved at a length of 2.2 mm and no coating has been applied. One of the cleaves was made through the amplifier (active section). The other cleave went through the passive waveguides. The ridge waveguides are 2 µm wide. These are visible as dark

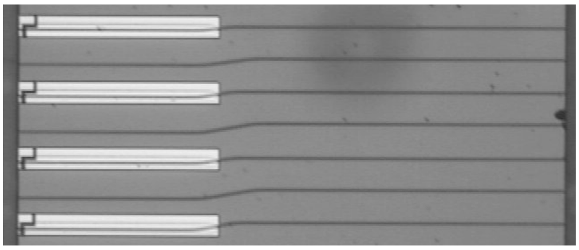


Fig. 1: Top view of four realized 18 GHz integrated extended cavity modelocked lasers. The active regions are covered by the bright metal pads. The short SAs at the left hand side of the FP cavity have been fabricated using a Focused Ion Beam (FIB) machine. One can see that the butt-joints are crossed at different angles.

lines in Fig. 1. The active regions are 30 µm wide, 750 µm long and are fully covered by the bright metal pads. The short SAs at the side of the FP cavity have been realized by electrically isolating a short section of the contact on the amplifier. This was done by using a Focused Ion Beam (FIB) machine at Bristol University within the COST 288 frame work to etch away the metal layer and highly doped top waveguide layers between two parts of the amplifier. By realizing the SA in this way, no extra mask was required and the SA lengths could be accurately controlled to vary from 5 to 17.5 µm. The electrical isolation sections that separate the SAs from the amplifiers are 15 µm long. With this method also part of

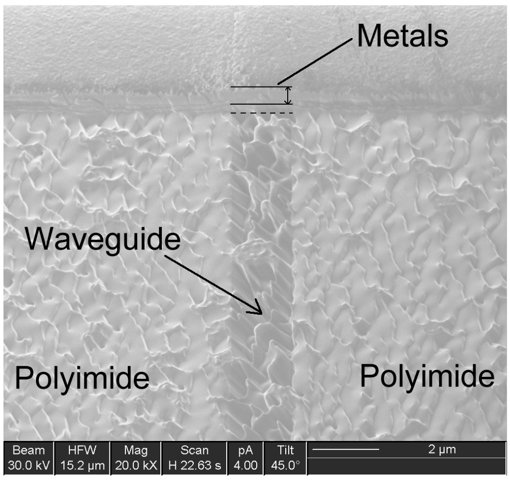


Fig. 2: Picture of a realized isolation between an amplifier and a saturable absorber, recorded with the Focused Ion Beam (FIB) machine. The metal layers of the electrical contact and part of the top cladding are etched away. Isolation obtained is >150 kKΩ.

Table 1: Characteristics of the extended cavity mode-locked lasers

SA length in µm	Butt-joint angle °	Reflectivity butt-joint (dB)	Mode-locked
5.0	15	-53	No
7.5	13	-51	No
10.0	11	-49	Yes
12.5	9	-47	Yes
15.0	7	-45	Limited
17.5	5	-43	No

the cladding (400 nm) has been removed during the etching processing (see Fig. 2). The electrical isolation obtained is 150 kΩ, which is more than sufficient. The waveguide in the EC-MLL contains adiabatic bends to make the crossing of the butt-joint in the cavity at varying angles. The original purpose of these devices was to study the effect of the different crossing angles [2]. The minimum radius of curvature of the bends in the waveguide is 250 µm. No offset between straight and curved waveguides is used.

18 GHz EC-MLL performance

The characteristic parameters of each laser are listed in Table 1. Modelocking has been observed for the devices with a 10 and a 12.5 µm long SA. The device with a 15 µm long SA has a very limited modelocking region. The devices with a 5 and a 7.5 µm long SA did not modelock. The absorption was too low, a higher reverse voltage than 3.0 V could have been applied but work on all-active MLLs has shown that the reverse current density (>20 kA/cm²) damages the SA. For the device with a 17.5 µm long SA no modelocking has been observed; the SA is too long or the laser suffers from internal reflections on the butt-joint which is the highest for this device (Table 1),

The ranges of the optical amplifier current and the saturable absorber voltage where modelocking occures, the modelocking region, have been determined for the 10 µm long SA device. It is modelocked continuously for a range of reverse bias voltages on the SA between 2.1 and 3.0 V and a range of amplifier currents between 144 and 162 mA. This device is discussed in more detail. First the operation outside the modelocked region is discussed. Two RF spectra of the laser output at current values outside the modelocking region are plotted in Fig. 3. Here the reverse bias voltage on the SA is fixed at 2.5V.

Just above threshold the laser is in a quasi-periodic state (Fig. 3.a). The RF peak at the fundamental frequency is 35 dB above the floor, but the laser behavior is dominated by strong amplitude modulation at frequencies below 1 GHz. It is

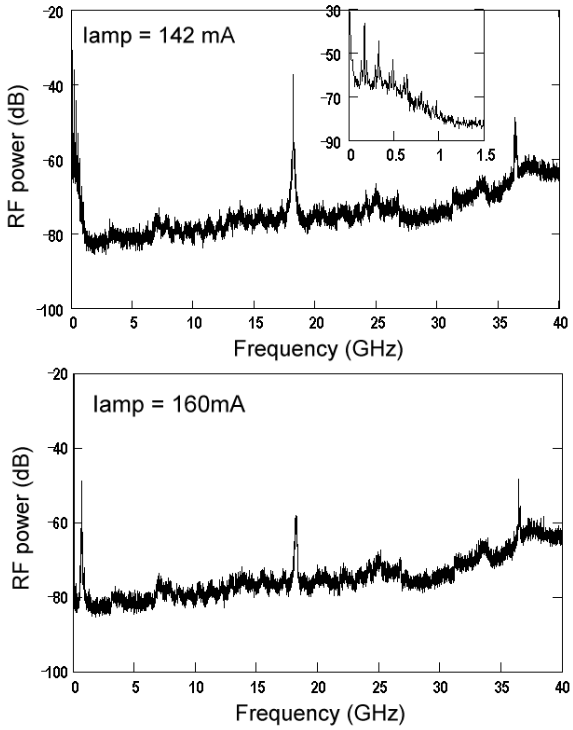


Fig. 3: Measured RF spectra of the passively modelocked laser output (L_{SA} = 10 µm, V_{SA} = – 2.5V) in:
a) a quasi-periodic state and
b) quasi-CW regime with few longitudinal modes beating

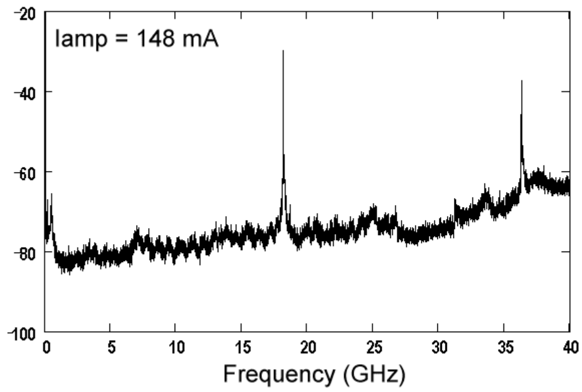
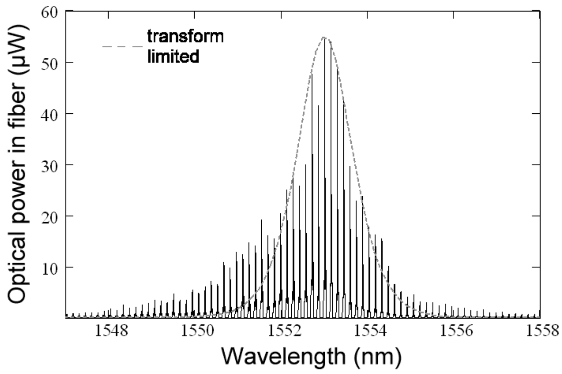


Fig. 4: Measured RF spectra of the passively modelocked laser output in modelocked state.
(L_{SA} = 10 µm, I_{amp} = 148 mA V_{SA} = – 2.5V)

interesting to compare those modulations to those at low frequency recorded from all-active FPMLL devices which have been realized by us in the same active layer-stack as the EC-MLLs here and have been reported upon earlier [5]. Just above threshold the EC-MLL shows pulsed modulation of the output at a frequency of ~150 MHz which is considerably lower than the 1 GHz pulsation observed for the all-active FPMLL output [5]. Another difference is that The intensity of the peak at the fundamental frequency of the EC-MLL output is already quite high (40 dB over the noise floor), close to the value in the modelocked state.



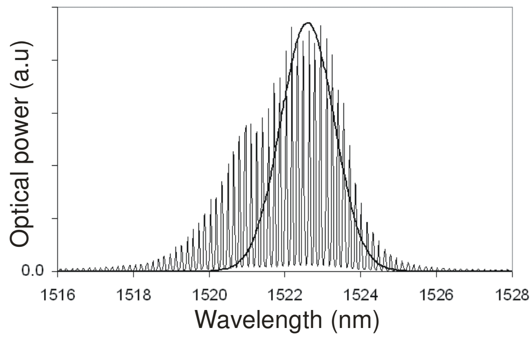


Fig. 5: Optical spectrum in linear scale of **a)** an extended cavity laser in a modelocked state for I_{amp} = 148 mA, L_{SA} = 10 µm, V_{SA} = – 2.5 V. **b)** a Fabry-Perot cavity laser in a modelocked state for I_{amp} = 121.7 mA and V_{SA} = – 1.9 V on the 10 µm long SA [5].

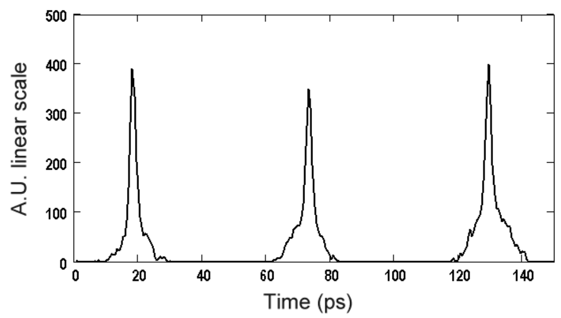


Fig. 6: Autocorrelator trace of an extended cavity modelocked laser for I_{amp} = 148 mA, L_{SA} = 10 µm, VSA = – 2.5 V.

For the EC-MLL, at current values higher than those for the modelocked state (Fig. 3.b), the main feature is a single low frequency component in the spectrum and two peaks separated by 150 MHz around the fundamental frequency. It corresponds to a quasi-CW regime with few longitudinal modes beating. Increasing the current further, the laser becomes more quiet. It demonstrates that the dynamics around the modelocking regime of the EC-MLL are reduced comparing to the all-active FPMLL [5] where at high current strong pulsations are observed at around 1.6 GHz. This reduction in oscillatory behavior is due to the smaller reservoir of carriers in the EC-MLL compared to the FPMLL. Fig. 4 shows the RF spectrum of an EC-MLL in a modelocked state. The peak at the fundamental frequency is 50 dB above the noise floor and 35 dB above the relaxation oscillation peak at ~800 MHz. The fundamental peak is 10 MHz wide (at -20 dB). The modelocked RF spectra are very similar to the ones of the all-active FPMLL [5].

In the modelocked state, differences between the output pulses and the optical spectra of the EC-MLL and the FPMLL are clearly visible. An optical spectrum of the EC-MLL output is plotted in Fig. 5a) for I_{amp} = 148 mA and V_{SA} = -2.5V; and in Fig 5b) for an FPMLL spectrum. Plotted in a linear scale, it reveals extra components at the blue side of the central longitudinal modes. The EC-MLL spectrum is approximately 1.6 nm wide (FWHM) but the shape of the wings of the spectrum is obviously not Gaussian or sech² like. The corresponding observed autocorrelation trace is plotted in Fig. 6. The autocorrelation shows pulses that are short with a considerable pedestal, but with a zero floor level between the pulses. In this condition, because of the pedestal, it is difficult to quantify with accuracy the length of the pulses from an autocorrelation. The estimated pulse length from the peak is ~2.1 ps FWHM. The time-bandwidth product for a transform limited pulse depends on the shape of the pulse (0.441 for a Gaussian pulse and 0.315 for sech² pulse). If it is assumed that the pulses from the laser are transform limited a pulse length and time-bandwidth product can be calculated from the observed optical spectrum. This time-bandwidth product is found to be ~0.33. Using the measured pulse width and spectral width leads to a time-bandwidth product of 0.39. Since these two values are close to each other the observed pulses are not far from being transform limited.

Conclusions

Experimental results from these EC-MLLs show that modelocked lasers can be realized using butt-joint active-passive integration. The intra-cavity reflections can be kept sufficiently low using a waveguide that crosses the butt-joint under an angle. The fabrication of SAs using a FIB did not create problems for the device. It allows for accurate control of the SA length and in the case of self-colliding pulse mode-locked lasers the position of the SA in a cavity with cleaved mirrors. Comparing the experimental results of the EC-MLL with the all-active FPMLL devices [5], a smaller time-bandwidth product is observed from the EC-MLL [3,4]. Furthermore the dynamics outside the modelocking operating region are reduced. In fact, due to the shorter amplifier of the EC-MLL, it operates at one and a half to two times higher carrier density compared to the all-active FPMLL. Therefore, the effective differential gain [6] will be smaller and this leads to reduced Self-Phase Modulation (SPM).

Acknowledgments

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