Monolithically integrated variable repetition rate mode-locked laser diode

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***Abstract*—A monolithically integrated mode-locked laser diode system is presented. Pairs of 7.6 ps pulses are generated at 1550 nm. An integrated Mach-Zehnder modulator pulse-picker allows electronically tunable repetition rates from 14 GHz to 219 MHz.**

Keywords – mode-locked lasers; tunable repetition rate; monolithic integration; foundry approach

I. INTRODUCTION

Thanks to their advantageous combination of versatility, cost and size, continuous wave diode lasers have come to replace the more traditional solid-state and gas lasers for a wide range of both commercial and scientific applications. Mode-locked laser diodes (MLLDs), however, are yet to meet with the same level of widespread success despite sharing many of their advantages. While MLLDs are not expected to compete with mode-locked solid state or fibre lasers in terms of pulse duration or average power, their simplicity, compactness and low cost does make them highly desirable as a potential source for applications in areas such as biophotonics [1] and optical sampling [2].

One disadvantage of MLLDs for these applications is that due to their inherently short cavities it is difficult to achieve repetition rates below 10 GHz, with 1 GHz being the record to date [3]. This in turn places a limit on pulse energy for a given average power, and thus limits their use for nonlinear applications. It also means that it is difficult to use these pulse trains to probe biological processes when using markers with characteristic lifetimes of 100s of picoseconds or longer. External cavity semiconductor lasers can bypass this problem, but only at the cost of increased complexity [4].

The solution proposed in this paper is the monolithic integration of a MLLD with a Mach-Zehnder modulator (MZM), which is used as a pulse picker. In addition to the achievement of sub-GHz repetition rates, this approach also allows the repetition rate to be tuned electronically over a wide range, a property which may itself have interesting applications, for example in asynchronous optical sampling (ASOPS) [2]. This approach allows us to demonstrate 7.6 ps pulse trains at 1550 nm over a range of repetition rates from 14 GHz to 219 MHz. The fabrication of this device makes use of the advantages offered by a foundry approach in a manner analogous to CMOS electronics [5]. Thus the device is assembled purely from generic building blocks, reducing development costs and further simplifying the device design.

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II. DEVICE DESCRIPTION

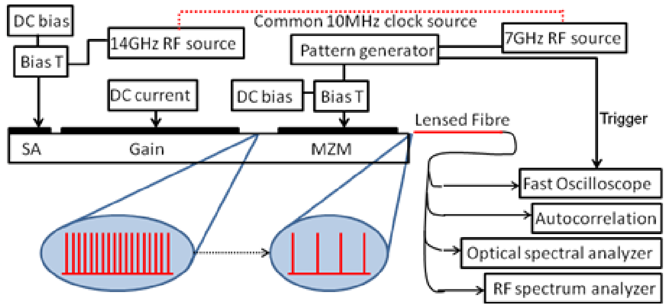

Figure 1. A schematic diagram of the integrated device and of the drive electronics used for hybrid modelocking and modulation of the pulse train, along with the associated characterization equipment.

Fig. 1 shows a schematic of the device and the associated electronics. The active components of the laser diode are a 2.1 mm long gain section and a 50 µm long saturable absorber section. A length of passive waveguide brings the total cavity length to 3.0 mm, resulting in a fundamental repetition rate of 14 GHz. The laser output passes through a MZM with arms containing two 1090 µm long electro-optic phase shifter sections. The output facet is AR coated and angled at 7 degrees to prevent feedback. Pulses are collected by a lensed fibre and then passed into instruments used to measure the laser performance. The whole device is mounted on a copper heaksink whose temperature is maintained at 20^{o}C.

The master oscillator is hybrid mode-locked by applying a DC current of 129.6 mA to the gain section, and a DC reverse bias of 1.67 V with an RF modulation of 18 dBm at a frequency close to the fundamental repetition rate to the absorber section via a bias tee. Modulation of the pulse train is achieved by applying a square wave between 4.15 V and 2.15 V at the desired frequency to one arm of the MZM. A programmable pattern generator, synchronized to the hybrid modelocking frequency, is used to prepare the desired drive waveform. By varying the frequency and duty cycle of the waveform pulse trains with variable repetition rates can be prepared, with the achievable repetition rates only limited by the fundamental repetition rate of the laser at the upper limit, and by the maximum data length of the pattern generator at the lower limit.

III. RESULTS AND DISCUSSION

Fig. 2 shows oscilloscope traces of pulse trains at repetition rates of 14 GHz and 219 MHz. At 219 MHz two pulses are seen to be transmitted by the MZM rather than a single pulse. This is because the maximum frequency of the pattern generator used here was 12.5 GHz, which corresponds to a minimum bit length of 80 ps, slightly longer than the spacing between pulses. A higher bandwidth pattern generator would allow single pulses to be selected. Colinear second harmonic autocorrelations of the pulse train allows a pulse duration of 7.6 ps to be measured, assuming a sech-squared fit.

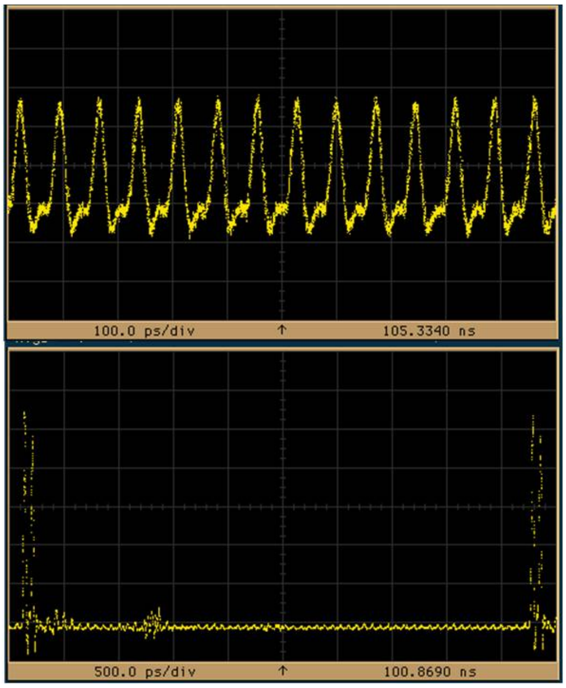

Figure 2. Sampling oscilloscope traces of modulated pulse trains at repetition rates of 14 GHz and 219 MHz. The double pulses at 219 MHz result from the limited bandwidth of the pattern generator.

It is clear that an architecture integrating a MLLD with an MZM can be used to demonstrate a very compact device that is able to achieve repetition rates usually associated with much larger sources. However, a potentially more significant advantage of this device concept is that the MZM allows the repetition rate to be switched electronically in discrete steps, while fine continuous tuning of the repetition rate can be achieved by varying the hybrid modelocking frequency, giving the device a very large degree of repetition rate flexibility.

Figure 3 demonstrates that continuous tuning of the fundamental repetition rate over an 8 MHz range is possible without loss of hybrid modelocking stability, while figure 2 shows switching of the repetition rate by a factor of 64. While lacking the flexibility of a continuously tunable laser [6], the combination of coarse discrete control and fine continuous control of the repetition rate is attractive, both in terms of the simplicity of the device, in terms of the electronic control of the repetition rate, and in term of the very large dynamic range that can be achieved. In fluorescence sampling, for example, the ideal repetition rate is one close to the fluorescence lifetime of the dye used, so as to maximize the data acquisition rate while still allowing the sample to recover between pulses. This device can be tuned simply to achieve optimal conditions for a given dye.

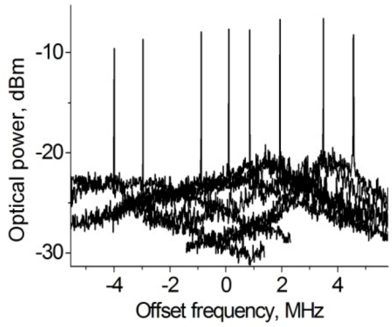

Figure 3. RF spectra of the fundamentally mode-locked laser at eight different hybrid modelocking frequencies, showing a continuous tuning range greater than 8 MHz.

A switchable repetition rate also makes this device potentially suitable as a low cost source for applications such as ASOPS [2], which uses two lasers with slightly different repetition rates to perform delay line free pump-probe experiments. When compared to a classical pump-probe system, ASOPS can provide superior data acquisition times and reduced complexity thanks to the elimination of a mechanical delay stage. Key laser parameters in an ASOPS system are the repetition rate and the frequency offset between the two lasers, which control the effective delay length and the time resolution. In the device presented here both of these parameters are electronically controllable over a large range, enabling much greater freedom than a system based on solid-state or fibre sources. A further advantage of this device is its low cost compared to these sources, particularly in the context of foundry-based design and manufacture.

IV. CONCLUSIONS

We demonstrate a monolithically integrated source consisting of a MLLD and a MZM. For simplicity and low cost the device is designed and fabricated under a foundry approach. The source emits 7.6 ps pulses at 1550 nm, and at repetition rates which can be tuned electronically over a very large range. This cheap and flexible source is expected to be suitable for applications in biophotonics and optical sampling.

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