

Fibre Mode-Locked Lasers at 10GHz and 40GHz Repetition Rate

Le Nguyen Binh, Department of Electrical and Computer Systems Engineering, Monash University, Clayton, Victoria 3168 Australia. E-mail: le.nguyen.binh@eng.monash.edu.au

Summary

Mode-locked fibre lasers offer a number of advantages as compared with their integrated semiconductor counterparts such as high average optical output power, adjustable repetition rate, flexibility of control of pulse width etc. As ML fibre lasers are constructed from discrete optical components, it is therefore possible to integrate an optical-RF self-adaptive feedback for self-locking that would provide long-term stability and minimise amplitude and phase noises of the generated optical pulse train.

This paper gives a detailed account, for the first time, of the design, construction and characterisation of an ultra-stable mode-locked mode locked fibre ring laser proven to be practically feasible for ultra-high speed optical communications systems and networks.

The implemented ML laser structure employs in-line optical fibre amplifiers, a guided wave optical intensity Mach-Zehnder interferometric (MZI) modulator and associate optics to form a ring resonator for generating optical pulse trains of several GHz repetition rate with pulse duration whose pulse width is in order of a few pico-seconds.

Long term stability of amplitude and phase noise obtained indicates that the optical pulse source can be error-free in a self-locking mode for more than 20 hours. This would be suitable for laboratory use. Further evaluation of the stability of the mode-locked laser is needed for field deployment such as stabilisation and control of DC drift of the bias voltage of the MZI modulator. A mode-locked laser operating at 10 GHz repetition rate has been designed, constructed and packaged. The laser generates optical pulse train of 4.5 ps pulse width when the modulator is biased just below the phase-quadrature quiescent point. Preliminary experiment of a 40 GHz repetition rate mode-locked laser has also been conducted, although still unstable in long term, without an opto-electronic feedback loop, optical pulse trains have been observed.

1 Background and Motivation

Generation of ultra-short optical pulses with multiple Gb/s repetition rate is critical for ultra-high bit rate optical communications, particularly for the next generation of terabits/sec. optical fibre systems. Mode locked fibre laser offer a potential source generator of such pulse train. Although the generation of ultra-short pulses by mode locking of a multi-modal ring laser is well known, the applications of such short pulse trains in multi-Gb/s optical communications challenges its designers on its stability and spectral properties. Recent reports on the generation of short pulse trains at repetition rates in order of 40 Gb/s, possibly higher in the near future[1], motivates us to design and experiment with these sources in order to evaluate whether they can be employed in practical optical communications systems. Further the interest of multiplexed transmission at 160 Gb/s and higher in the foreseeable future, requires us to experiment with optical pulse source having a short pulse duration and high repetition rates.

This paper describes laboratory experiments of a mode-locked fibre ring laser (MLFRL), initially with a repetition rate of 10 GHz and that of a proposed system of higher multiple repetition rates up to 40 GHz. The mode locked ring lasers reported hereunder adopt an active mode-locking scheme whereby partial optical power of the output optical waves is detected, filtered and a clock signal is regenerated for optical ring feedback at the desired repetition rate. This regenerative clock is then used as a RF drive signal to the MZI modulator incorporated in the feedback loop of the ring laser. A brief description on the principle of operation of the MLFRLs is given in the next section followed by a description of the mode-locked laser experimental set up and their characterisation.

2 Mode-locking techniques and conditions for generation of transform limited pulses from a mode locked laser

2.1 Schematic structure of MLRL

Figures 1(a) and (b) shows the composition of the MLFRL without and with feedback loop, ie. free running and regenerative feedback controlled configurations, used in this study respectively. It consists principally, for a non-feedback laser ring, an optical close loop with an optical gain medium (the EDF amplifiers), an optical modulator (intensity or phase type), an optical fibre (OF) coupler and associated optics. An opto-electronic feedback loop detecting and repetition-rate signal and generating RF sinusoidal waves to electro-optically drive the intensity modulator is necessary for the regenerative configuration as shown in Figure 1(b).

2.2 Mode-locking conditions

The basic conditions for MLFRL to operate in pulse oscillation can be stated for free running MLFRL and regenerative MLFRL as follows.

2.2.1 Non-feedback “free running” optical mode-locking

Condition 1: The total optical loop gain must be greater than unity when the modulator is ON-state, i.e. when the optical waves transmitting through the MZI modulator is propagating in phase[2];

Condition 2: The optical lightwaves must be depleted when the optical modulator is in the OFF-state, i.e. when the lightwaves of the two branches of the MZI modulator is out of phase or in destructive interference mode [3];

Condition 3: The frequency repetition rate at a locking state must be a multiple number of the fundamental ring resonant frequency[4].

2.2.2 Optical-RF feedback mode locking - Regenerative mode-locking

Condition 4: Under an optical-RF feedback to control modulation of the MZI modulator the optical noise at the output of the laser must be significantly greater than that of the electronic noise for the start-up of the mode locking and lasing processes. In other words the loop gain of the optical-electronic feedback loop must be greater than unity.

Thus it is necessary that the erbium doped fibre (EDF) amplifiers are operated in saturation mode and the total average optical power of the lightwaves circulating in the loop must be sufficiently adequate for the opto-electronic detection at the photodetector and electronic pre-amplifier. Under this condition the optical quantum shot noise dominates the electronic shot noise.

2.3 Factors influencing the design and performance of mode-locking and generation of optical pulse train

The locking frequency is a multiple of the fundamental resonance frequency of the laser ring defined as the inverse of the travelling time around the loop and is given by

$$f_{RF} = \frac{N_c}{n_{eff} L} \quad (1)$$

where f_{RF} is the RF frequency required for locking and the required generation rate, N is an integer and indicates longitudinal mode number order, c is the velocity of light in vacuum, n_{eff} is effective index of the guided propagating mode and L is loop length including that of the optical amplifiers.

Under the requirement of the OC-192 SONET (SDH-798) standard bit rate the locking frequency must be in the region of 9.95 Giga-pulses per second. That is the laser must be locked to a very high order of the fundamental loop frequency that is in the region of 1 MHz to 10 MHz depending on the total ring length. For an optical ring of length about 30 metres and a pulse repetition rate of 10 GHz, the locking occurs on approximately the 1400th harmonic mode.

It is noted also that the effective refractive index n_{eff} can be varied in different optical sections of the laser ring. Furthermore the two polarised states of propagating lightwaves in the ring, if the fibre were not a polarisation maintaining type, would form two simultaneously propagating rings, and they could interfere or hop between these dual polarised rings.

The pulse width, denoted as $\Delta\tau$ of the generated optical pulse trains can be found to be given by[5]

$$\Delta\tau = 0.45 \left(\frac{\alpha_t G_t}{\Delta_m} \right)^{1/4} \frac{1}{(f_{RF} \Delta\nu)^{1/2}} \quad (2)$$

with $\alpha_t G_t$ is the round trip gain coefficient as a product of all the loss and gain coefficients of all optical components including their corresponding fluctuation factor, Δ_m is the modulation index and $\Delta\nu$ is the overall optical bandwidth (in units of Hz) of the laser.

Hence the modulation index and the bandwidth of the optical filter influence the generated pulse width of the pulse train. However the optical characteristics of the optical filters and optical gain must be flattened over the optical bandwidth of the transform limit for which a transform limited pulse must satisfy, for a sech^2 pulse intensity profile, the relationship

$$\Delta\tau\Delta\nu = 0.315 \quad (3)$$

Similarly, for Gaussian pulse shape the constant becomes 0.441. The fluctuation of the gain or loss coefficients over the optical flattened region can also influence the generated optical pulse width and mode locking condition.

In the case of regenerative mode-locking as illustrated in Figure 1(b), the optical output intensity is split and opto-electronically detected, the sensitivity and noises generated at the photo-detector must be considered. The signal as received at this stage is assumed to be weak because it is essential to maintain the strength of the locked pulse train in the ring and thus only a fraction of the pulse energy is coupled to the detector. Hence the generated noise sources must be examined and controlled. Two major sources of noises are generated at the in put of the photodetector. Firstly the optical quantum shot noises generated by the detection of the optical pulse trains and secondly the random thermal electronic noises of the small signal electronic amplifier following the detector. Usually the electronic amplifier would have a 50Ω equivalent input resistance R referred to the input of the optical preamplifier as evaluated at the operating repetition frequency, this gives a thermal noise spectral density of

$$S_R = \frac{4kT}{R} \quad \text{A}^2/\text{Hz} \quad (4)$$

with k the Boltzmann's constant. This equals to $3.312 \times 10^{-22} \text{ A}^2/\text{Hz}$ at $300 \text{ }^\circ\text{K}$. Depending on the electronic bandwidth B_e of the electronic pre-amplifier, i.e. wideband or narrow band type, the total equivalent electronic noise (square of noise 'current') is given by

$$i_{NT}^2 = S_R B_e \quad (5)$$

Under the worst case when a wide-band amplifier of a 3-dB electrical bandwidth of 10 GHz, the equivalent electronic noise at the input of the electronic amplifier is $3.312 \times 10^{-11} \text{ A}^2$, i.e. an equivalent noise current of $5.755 \text{ } \mu\text{A}$ is present at the input of the 'clock' recovery circuit. If a narrow band-pass amplifier of 50 MHz 3-dB bandwidth centred at 10 GHz is employed this equivalent electronic noise current is $0.181 \text{ } \mu\text{A}$.

Now considering the total quantum shot noise generated at the input of the 'clock' recovery circuit, suppose that a 1.0 mW (or 0 dBm) average optical power is generated at the output of the MLFRL, then a quantum shot noise[6] of approximately $2.56 \times 10^{-22} \text{ A}^2/\text{Hz}$ (i.e. an equivalent electronic noise current of 16 nA) is present at the input of the clock recovery circuit. This quantum shot noise current is substantially smaller than that of the electronic noise.

In order for the detected signal at the optical receiver incorporated in the 'clock' recovery circuit to generate a high signal-to-noise ratio the optical average power of the generated pulse trains must be high, at least at a ratio of 10. We estimate that this optical power must be at least 0 dBm at the photodetector in order for the MLFRL to lock efficiently to generate a stable pulse train.

Given that a 10% fibre coupler is used at the optical output and an estimate optical loss of about 12 dB due to coupling, connector loss and attenuation of all optical components employed in the ring, the total optical power generated by the amplifiers must be about 30 dBm . To achieve this we employ two EDF amplifiers of 16.5 dBm output power each positioned before and after the optical coupler, one is used to compensate for the optical losses and the other for generating sufficient optical gain and power to overcome the electronic noise in the regenerative loop as examined above.

3 Experimental set-up and results

The experimental set ups for free running and regenerative MLFRLs are as shown, again, in Figure 1(a) and (b). Associate equipment used for monitoring of the mode locking and measurement of the lasers is also included. We note the followings:

- In order to lock the lasing mode of the MLFRL to a certain repetition rate or multiple harmonic of the fundamental resonance ring frequency, a synthesiser is required to generate the required sinusoidal waves for modulating the optical intensity modulator and tuned to a harmonic of the cavity fundamental frequency.
- A signal must be created for the purpose of triggering the digital oscilloscope to observe the locking of the detected optical pulse train. For the HP-54118A amplitude of this signal must be $> 200 \text{ mV}$. This is also critical for the regenerative MLFRL set up as the RF signal detected and phase locked via the clock recovery circuitry must be spit to generate this triggering signal.

A typical experimental procedure can be as follows: (i) After the connection of all optical components with the ring path broken, ideally at the output of the fibre coupler, a CW optical source can be used to inject optical waves at a specific wavelength to monitor the optical loss of the ring; (ii) Close the optical ring and monitor the average optical power at the output of the 90:10 fibre coupler and hence estimate the optical

power available at the photodetector is about -3 dBm after a 50:50 fibre coupler; (iii) Determine whether an optical amplifier is required for detecting the optical pulse train or whether this optical power is sufficient for opto-electronic RF feedback condition as stated above; (iv) Set the biasing condition and hence the bias voltage of the optical MZI modulator (v) Tune the synthesiser or the electrical phase to synchronise the generation and locking of the optical pulse train.

The following results have been obtained (i) The optical pulse train generated at the output of the MLFRL or regenerative MLFRL. Experimental set up is shown in Figure 2(a); (ii) Synthesised modulating sinusoidal waveforms can be monitored. Figure 3(a) and 3(b) show the sinusoidal waveforms generating when the MLFRL is operating at the self-mode-locking state for mode-locking at 10 GHz repetition rate (iii) The interference of other supermodes of the MLFRL without RF feedback for self locking is indicated; (iv) Observed optical spectrum (not available in electronic form); (vi) Electrical spectrum of the generated pulse trains was observed showing a -70dB super-mode suppression under the locked state of the regenerative MLFRL;

Figure 3(a) and Figure 4(a) show that the regenerative MLFRL can be operating when the modulator is biased either at the positive or at the negative going slope of the optical transfer characteristics of the MZI modulator. The optical pulse width is measured using an optical autocorrelator (slow or fast scan mode). Typical pulse width obtained with the slow scan auto-correlator is shown in Figure 5. A minimum pulse duration of 4.5 ps has been obtained with a time-bandwidth product of about 3.8 showing that the generated pulse is near transform limited. The observed optical spectrum indicates some chirps of the generated optical pulse train.

BER measurement is used to monitor the stability of the regenerative MLFRL. The bit-error-rate (BER) error detector has been programmed to detect all '1' at the decision level at a tuned amplitude level and phase delay. The clock source used is that produced by the laser itself. An error-free has been achieved for over 20 hours. The opto-electronically detected waveform of the output pulse train for testing the BER shown in Figure 3(b) after 20 hours operation, the recorded waveform is obtained under infinite persistence mode of the digital oscilloscope.

A drift of clock frequency of about 20 kHz over one hour in open laboratory environment is observed. This is acceptable for a 10 GHz repetition rate. The 'clock' recovered waveforms were also monitored at the initial locked state and after the long-term test as shown in Figure 4(a) and Figure 4(b) respectively. Figure 4(b) obtained under the infinite persistence mode of the digital oscilloscope;

We note the following factors related to the above measurements (Figures 3-5): (i) All the above measurements have been conducted with two distributed optical amplifiers (GTi EDF optical amplifiers) driven at 180 mA and a specified output optical power of 16.5 dBm; and (ii) Optical pulse trains are detected with 34 GHz 3dB bandwidth HP p-I-n detector directly coupled to the digital oscilloscope without optical pre-amplifier.

4 40 GHz regenerative mode-locked laser

Following the initial success of the construction and testing of a regenerative MLFRL at 40 GHz repetitions rate regenerative mode locked laser was constructed. The schematic arrangement of the 40G regenerative MLRL is shown in Figure 8. Initial observation of the locking and generation of the laser has been observed and progress of this laser design and experiments will be reported in the near future.

5 Concluding remarks

We have been successfully constructed a mode locked fibre laser operating under an open loop condition and with opto-electronic RF feedback providing regenerative mode locking. The opto-electronic feedback can certainly provide a self-locking mechanism under the condition that the polarisation characteristics of the ring laser are manageable. Ensuring that all fibre paths are under constant operating condition does this. The regenerative MLFRL can self-lock even under the DC drifting effect of the modulator bias voltage (over 20 hours)[7]. The generated pulse trains of 4.5 ps duration can be, without difficulty, compressed further to less than 3 ps for 160 Gb/s optical communication systems.

The pulse trains generated, for the first time according to our knowledge, by the ring laser reported here above are stabilized over a long period that is considered to be most suitable for long haul ultra-broadband optical transport networks.

The regenerative MLRL can be an important source for all-optical switching of an optical packet switching system. The followings are recommended for future works of regenerative MLFRL: (i) Eliminating polarisation drift through the use of Faraday mirror or all polarisation maintaining (PM) optical components, for example polarised Er-doped fibre amplifiers, PM fibres at the input and output ports of the intensity modulator; (ii) Stabilising the ring cavity length with appropriate packaging and via piezo/thermal

control to improve long term frequency drift; (iii) Control and automatic tuning of the DC bias voltage of the intensity modulator; (iv) Developing electronic RF 'clock' recovery circuit for regenerative MLFRL operating at 40 GHz repetition rate together with appropriate polarisation control strategy; (iv) Study of the dependence of the optical power circulating in the ring laser by varying the output average optical power of the optical amplifiers under different pump power conditions; (vi) Incorporating a phase modulator, in lieu of the intensity modulator, to reduce the complexity of polarisation dependence of the optical waves propagating in the ring cavity, thus minimising the bias drift problem of the intensity modulator.

Acknowledgement

The author wishes to acknowledge the financial support of Nortel Networks, Advanced Technology Centre for this research work. The author would like to the two referees, Prof. Paul Edwards of University of Canberra and Dr. DingYuan Tang of Nanyang Technological University for their fruitful comments and suggestions for the improvement of the paper.

References:

- [1] See for examples K. Kuroda and H. Takakura, "Mode-locked ring laser with output pulse width of 0.4 ps", IEEE Trans. Inst. Meas., vol. 48, Dec. 1999, pp. 1018-1022; B. Bakhshi and P.A. Andrekson, "40 GHz actively mode-locked polarisation-maintaining erbium fibre ring laser", Elect. Lett., vol. 36, March 2000.
- [2] D. Jones, H. Haus and E. Ippen, "Subpicosecond solitons in an actively mode locked fibre laser", Opt. Lett., 1996, pp. 1818-1820.
- [3] as [1] D. Jones, H. Haus and E. Ippen, "Subpicosecond solitons in an actively mode locked fibre laser", Opt. Lett., 1996, pp. 1818-1820.
- [4] X. Zhang, M. Karlson and P. Andrekson "Design guideline for actively mode locked fibre ring lasers", IEEE Photonic tech. Lett., 1998, pp. 1103-1105.
- [5] A.E. Siegman, 'Laser', Mill Valley, C.A.: University Press, 1986.
- [6] by using the relationship of the quantum noise spectral density of $2qRP_{av}$ with P_{av} the average optical power, q the electronic charge and R the responsivity of the detector.
- [7] Typically the DC bias voltage in a LiNbO₃ MZI modulator is drifted by 1.5 volts after 15 hours of continuous operation.

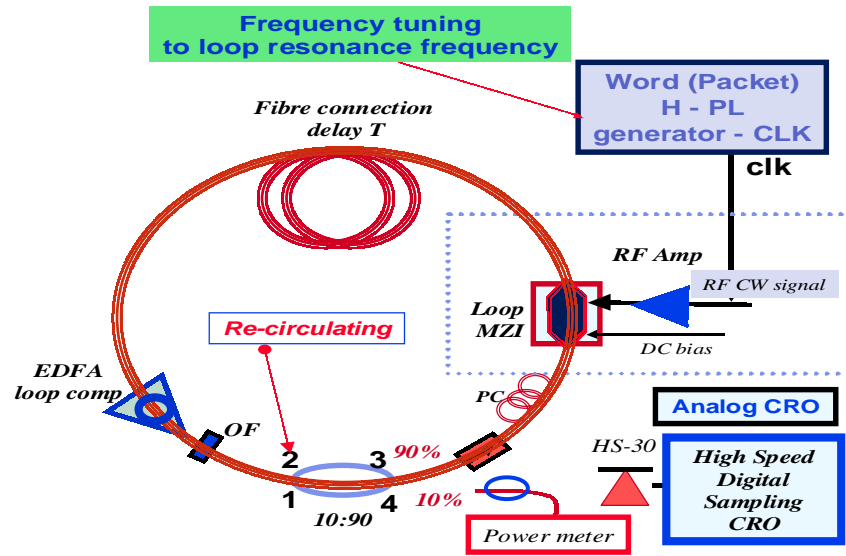


Figure 1(a)

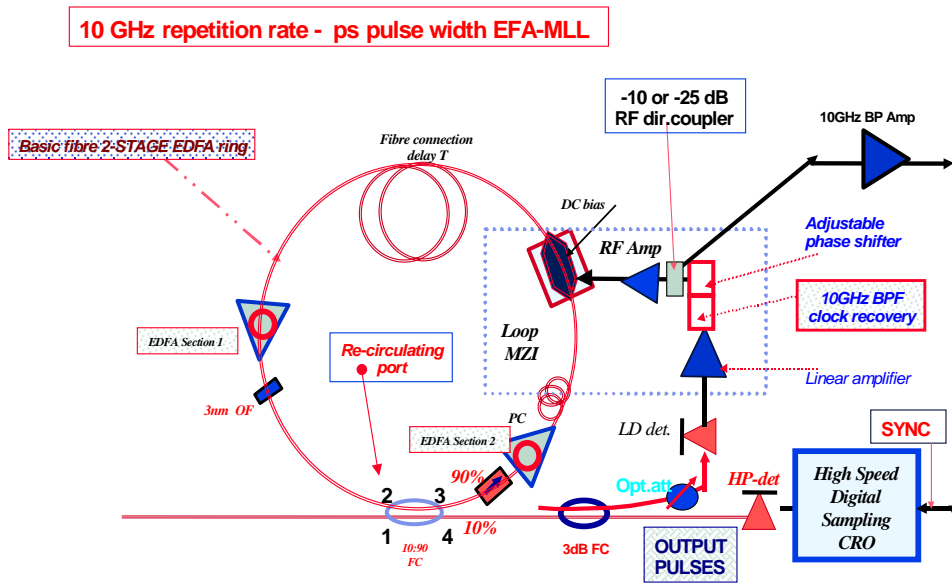


Figure 1(b)

Figure 1 Schematic arrangement of a mode-locked ring laser (a) without active feedback and (b) 2 with opto-RF electronic active feedback loop

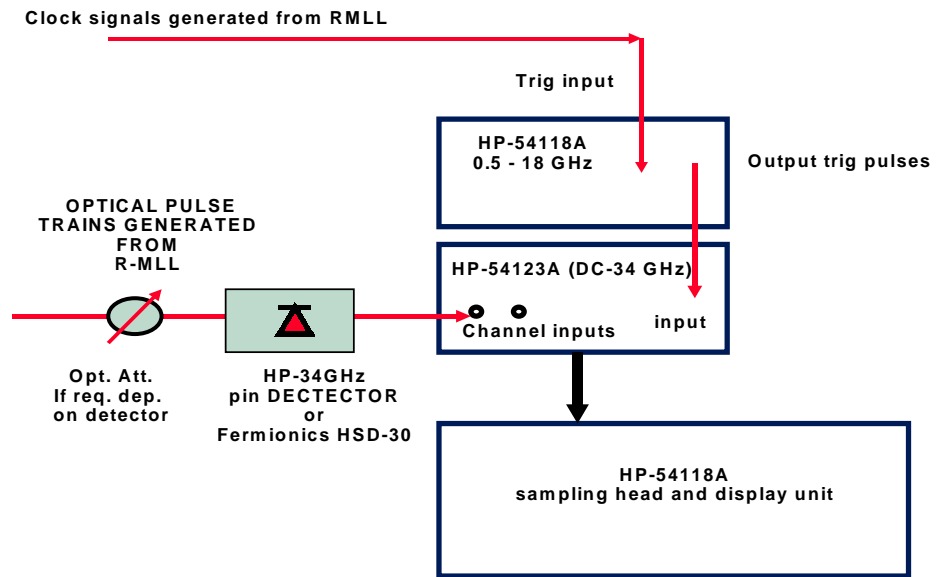


Figure 2(a)

BER MEASUREMENT OF RMLL-EDF

BER circuitry and equipment set-up

FIGURE 4

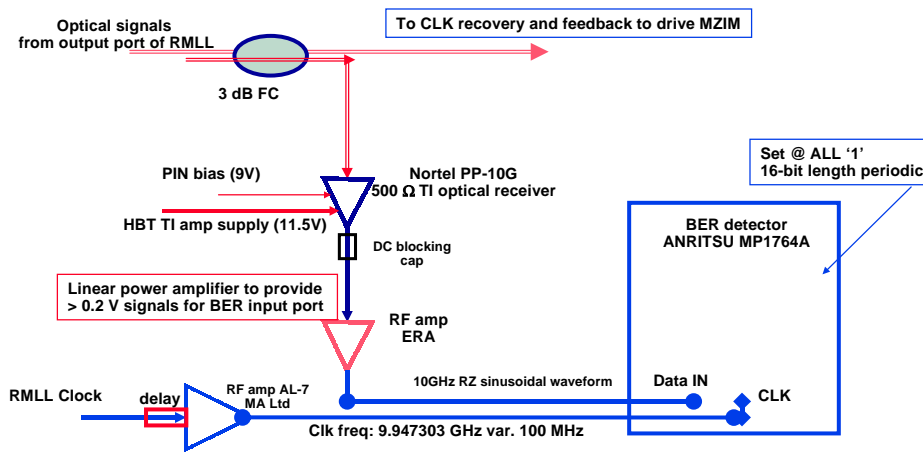


Figure 2(b)

Figure 2(a) Experimental set up for monitoring (a) the locking of the optical pulse train and (b) the BER of the optically locked pulse train.

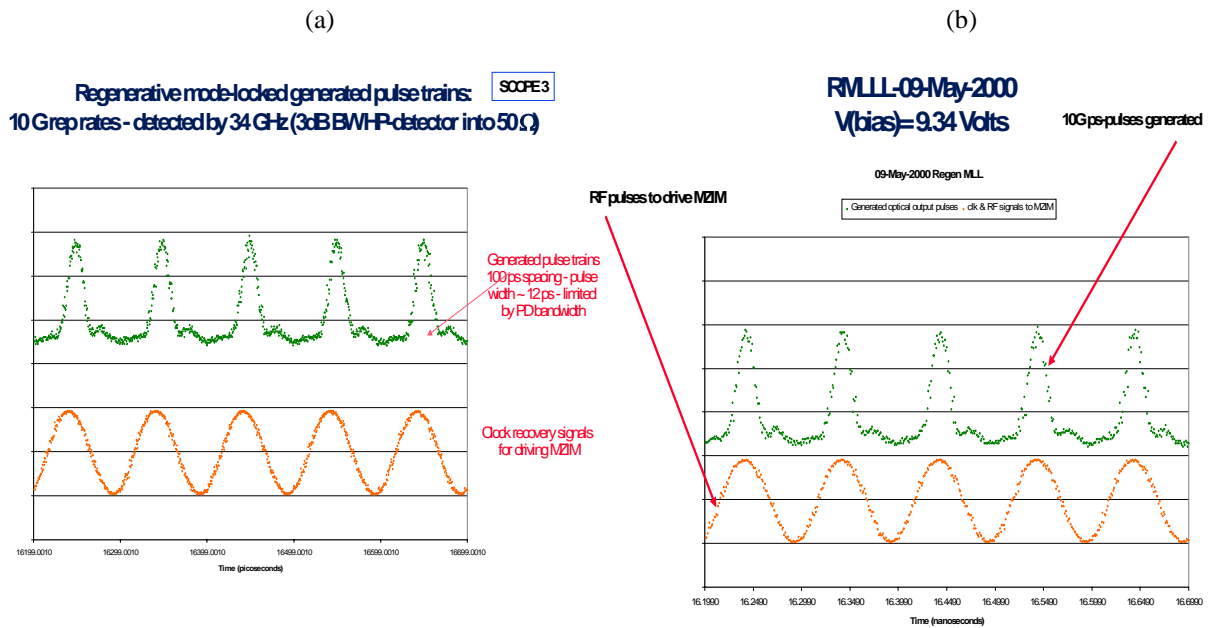


Figure 3(a) Output pulse trains of the regenerative MLFRL and the RF signals as recovered for modulating the intensity modulator for self-locking (b) Detected output pulse trains of the regenerative MLFRL and recovered clock signal when the modulator is biased at a negative going slope of the operating characteristics of the modulator

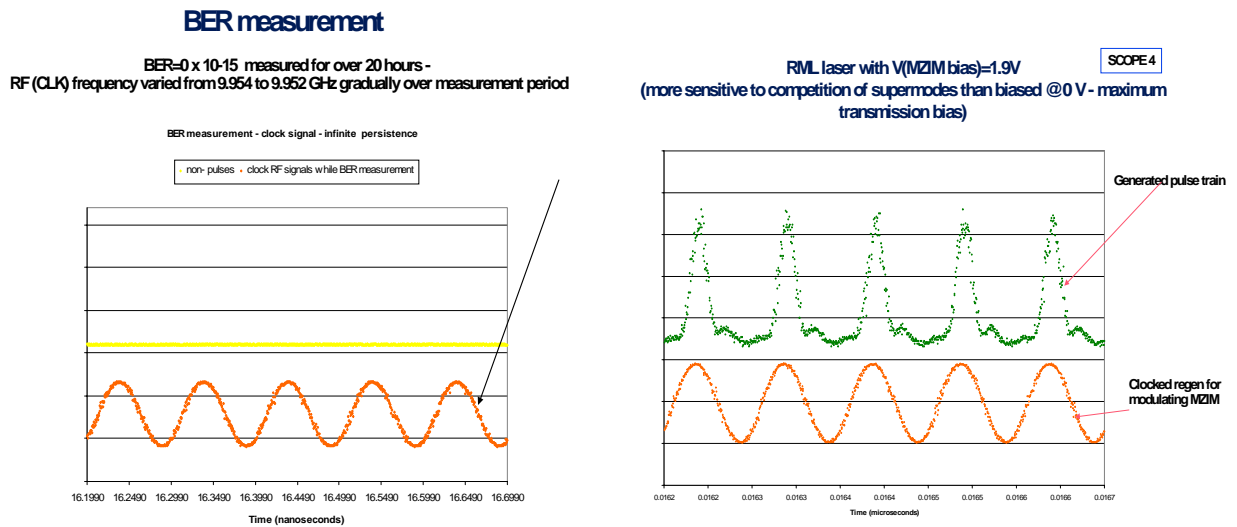


Figure 4(a) Output pulse trains and clock recovered signals of the 10 G regenerative MLRL when the modulator is biased at the positive going slope of the modulator operating transfer curve (b) BER measurement - opto-electronically detected signals from the generated output pulse trains for BER test set measurement. The waveform is obtained after 20 hours persistence.

Auto-correlated pulse
 V(bias) = 1.55 volt - phase quadrature neg slope
 FWHM $\Delta\tau = 4.48$ ps
autocorrelator set thumbwheel 6 and 0 (100ps range @10ps/s delay rate)

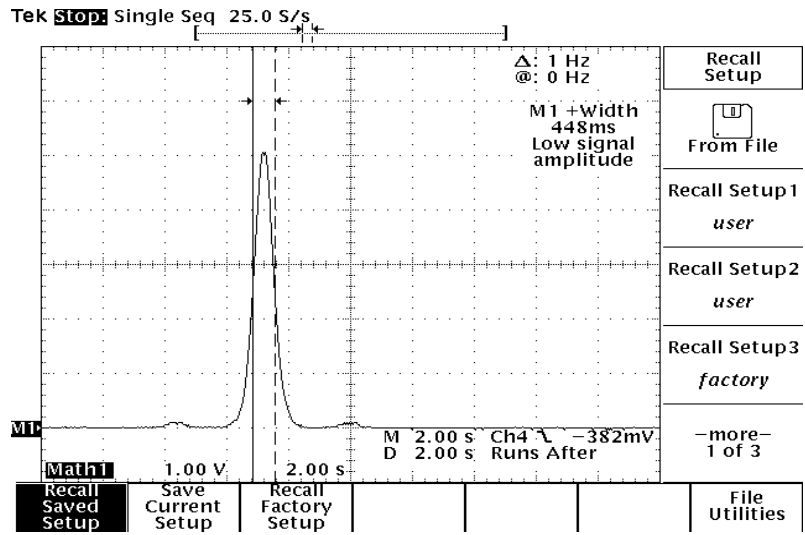


Figure 5 Auto-correlation trace of output pulse trains of 9.95 GHz regenerative MLFRL