Precise synchronization of qcw pumped active-passive mode locked picosecond lasers

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Abstract. We present designing qcw diode pumped Nd:YAG picosecond laser with 50 ps jitter of output pulse relative to active mode locking signal. Adjustment of signal delay in negative feedback circuit provides generation of transform-limited laser pulses. Obtained level of jitter is mainly attributed to phase noise of radio-frequency active mode locking signal generator. Further jitter decrease by means of enhancement of radio-frequency signal filtering and suppressing of phase noise is discussed.

1. Introduction

Precise synchronization of mode-locked pico- and femtosecond lasers integrated in technological and research complexes is a crucial issue for many applications. Jitter of output optical pulse respective to periodic reference signal in continuous wave (cw) lasers can be effectively suppressed up to femtosecond level by means of feedback controlled cavity adjustment [1]. Cross modulation approach gives even more synchronization accuracy [2]. However, high peak power laser systems with precise optical synchronization option based on cw oscillators are overly complex and expensive for most practical applications.

High peak power mode-locked picosecond lasers with pulsed (qcw) pump are applicable for such fields as high precision laser micromachining [3], soft X-ray generation [4], laser photo injection for electron accelerators [5], routine time-resolved spectroscopic measurements [6], laser ranging [7] etc. Pulsed laser systems based on qcw pumped oscillators with generation process development in each laser shot may have definite advantages in comparison with cw ones, providing high pulse energy at the oscillator output, better efficiency of energy consumption, lower thermal loading, relative simplicity and compactness. At the same time, typical duration of generation process development ~10^{-5} s is too short both for phase detector operation and for cavity adjustment which are convenient techniques for cw lasers. In paper [8] 130 ps jitter relative to external synchropulse was measured in pulse pumped picosecond laser with active mode locking. This is minimal jitter, to our knowledge, that was achieved in lasers with pulsed pump. Authors of [8] explained such level of jitter by imperfection of radio-frequency (RF) oscillator for active mode locking. Nevertheless, time position of ultrashort pulse which goes several hundreds roundtrips during generation process development in each pump pulse is defined by several factors such as amplification in active element, passive mode-locking mechanism, actions of feedback and active mode locking signal. Minimal jitter is mainly...
determined by width of “temporal transparency window” which is formed by cumulative action of the above factors in the oscillator.

In the present paper, we discuss experimental results on jitter decreasing in picosecond pulse-diode-pumped Nd:YAG laser within output pulse duration level of several tens of picoseconds.

2. Experimental setup

The optical scheme for studying jitter arising during picosecond pulse generation process is shown in figure 1. Resonators formed by HR@1064 nm flat mirrors M1 and M4. Concave mirror M3 compensates beam divergence and provides stability of resonator. Active element AE with length l_{AE} = 11 mm, diameter d_{AE} = 5 mm, Nd concentration of 1.1 % is pumped by a pulsed diode bar with a fiber output (maximum peak power P_{max} = 70 W, wavelength 808 nm). Pump pulses with a width τ_{P} = 200 μs at repetition frequency f_{P} equal to 25 Hz from the output of a fiber 0.6 mm in diameter are focused into the AE after reflection from AR@808 nm M2. In the experiments the maximum peak pump power is limited at the level of 55 W.

This highly reflecting resonator is aimed at for making a picosecond pulses with minimal optical losses under signals of negative feedback (NFB) and active mode locking (AML), which are applied during the end part of each pump pulse to a two-crystal thermocompensate electro-optical modulator EOM1 from an RTP crystal [9]. The resonator is dumped and generated picosecond pulse is output by applying a half-wave voltage pulse to electro-optical modulator EOM2. In this case, output pulse energy is only ~1 μJ and pulse duration is ~ 200 ps. Further output pulse energy increase can be obtained using regenerative amplification stage. Minimum value of pulse duration can be achieved using combined active-passive mode-locking scheme [10].

The distance between the mirror M1 and the AE is chosen to be 15 cm to exclude the formation of a standing wave inside pumped region of AE near the resonator end mirror M1 [11] when generating pulses with a width less than 1 ns. Optical length of resonator is 113 cm that corresponds to quarter period of AML signal at frequency f_{AML} ~ 66.4 MHz. In our experiments we use AML frequency equal to half of round trip frequency. This gives us possibility to apply driving signals (bias, harmonical AML signal, NFB signal and generated AML radiation) to fibre-coupled photodiode of negative feedback circuit.

Figure 1. Simplified optical scheme of picosecond laser. M1, M3, M4 – HR@1064 nm mirrors, M2 – HR@808 nm and AR@1064 nm mirror, AE – active element, BS – beam splitter, P1, P2 – polarisers, EOM1, EOM2 – electro-optical modulators, NFB – radiation to fibre-coupled photodiode of negative feedback circuit.

Figure 2 Jitter of output picosecond pulse relative to phase of driving RF oscillator at variation of frequency detuning of AML signal. Zero detuning corresponds to minimal jitter. Amplitude of AML signal is set to maximum.
[9]) on EOM1 independently [10]. Radiation of a pulse reflected from the beam splitter (BS) is focused into fiber which is coupled with photodiode. This photodiode signal is used in the NFB circuit on EOM1. Length of the fiber is chosen to provide minimal losses associated with NFB circuit for laser pulse at the next round trip.

Temporal behavior of radiation inside resonator is registered with p-i-n photodiode SFH250V and digital oscilloscope Tektronix DPO4104. Photodiode has response time about 5 ns nevertheless temporal position of its signal can be measured with accuracy about 10 ps by fitting of registered response with proper function having variable time shift parameter. Jitter of laser pulse is measured as standard deviation of time delay of simultaneously registered AML and optical signals. Time shape of output laser pulse is controlled with streak camera.

3. Results and discussion

One of most important parameters that define laser generation behavior is detuning of AML frequency from round trip one. Results on measurements of jitter depending on frequency detuning are shown in figure 2. Unlike to cw pumped lasers, where frequency detuning on the level of sub-1 kHz from round trip frequency about 100 MHz brings to chaotic behavior of generation [12], finite round trips number at pulsed pump approach allows larger range of AML frequency detuning without sufficient jitter increasing.

Efficiency of jitter suppression at variation of amplitude of AML signal and duration of generation process are illustrated by figure 3 and figure 4 correspondingly. Both measurements are fulfilled at AML frequency adjusted to optimal value. Note that amplitude of AML signal directly on EOM1 is very difficult to measure because of very small capacity of RTP crystal and complex structure of driving signal [10]. Although part of AML signal from capacitive divider connected directly to the EOM1 crystal is used for jitter measurements, exact value of division coefficient is known only approximately. Therefore we show in figure 3 jitter dependence on relative units of AML amplitude. Our estimation shows that at maximum AML signal corresponds to almost complete modulator EOM1 closure. It is clear from figures 3 and 4 that jitter goes to value about 50 ps at increasing of amplitude of AML signal and duration of generation process. To find reason of that jitter asymptotic behavior we applied digital synchronous detection procedure to AML signal and obtained phase modulation with regular and noise component. Amplitude of noise component corresponds to jitter with observed value. We attribute origin of this
noise to insufficient filtering of digital synthesizer output that is used for AML signal. Enhancing of filtering scheme should provide further decrease of jitter.

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