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AN ELECTRON BEAM MODULATION LASER FOR STEADY-STATE MICROBUNCHING*

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Abstract

Steady-state microbunching (SSMB) represents an innovative scheme for generating high-power coherent radiation. This approach is expected to generate kilowatt-scale extreme ultraviolet (EUV) radiation for lithography in the semiconductor industry. During the second phase of the SSMB proof-of-principle experiment (SSMB PoP II), the creation of quasi-steady-state microbunches requires specific modulation of the electron beam. This modulation is achieved through a phase-locked laser with a high repetition rate, which enables the detection of continuous coherent radiation over multiple turns. To meet the requirements of SSMB PoP II, a high-power, high-repetition-rate, phase-stabilized pulsed laser has been developed. The single-frequency pulsed laser has been achieved using a ultra-stable seed laser, a pulse generator stage, three amplification stages, and a phase-locked feedback system. Here we report on the development and test results of the electron beam modulation laser.

INTRODUCTION

Accelerator-based light sources find extensive applications across various fields. In 2010, Ratner and Chao proposed a novel mechanism known as steady-state microbunching (SSMB), which combines the advantages of synchrotron radiation light sources and free-electron lasers with the promise to achieve both high peak power and high repetition rates [1]. The basic concept of SSMB is to replace conventional beamline systems in electron storage rings, typically microwave RF cavities, with laser modulation systems comprising stabilized lasers and undulators. This innovative technology is expected to generate high average power radiation from terahertz to EUV wavelengths, potentially meeting the demand for kilowatt-scale EUV light sources for semiconductor lithography.

Electron beam modulation lasers play a key role in the SSMB mechanism. In the SSMB PoP I experiment, the turn-by-turn operation mechanism of SSMB was validated using a conventional Q-switched nanosecond laser for electron beam modulation in a single pass [2]. Building upon this foundation, the SSMB PoP II experiment aims to achieve quasi steady-state microbunches. To fully validate the SSMB mechanism, a specialized phase-stabilized pulsed laser will be employed for multi-turn coherent modulation. The ultimate goal is to realize true SSMB, which necessitates coupling optical enhancement cavities (OECs) with undulators and utilizing intracavity megawatt-power lasers for high-intensity modulation. At present, the SSMB laser project team has made some progress in research and development of OEC and cavity mirrors [3-5].

This conference focuses on research advancements in the electron beam modulation laser for SSMB PoP II. To coherently modulate the electron beams in the undulator over many turns (hundreds or thousands), a phase-stabilized high-repetition-rate high-peak-power nanosecond pulsed laser with special time structure is necessary. In particular, the laser requires precise phase stability to ensure consistent interaction with electron beams. Common techniques for generating nanosecond laser pulses include Q-switched modes and external modulation of continuous-wave (CW) lasers. The latter allows easy adjustment of laser pulse parameters. Additionally, electro-optic combs based on this principle enable the realization of optical frequency combs with GHz repetition rates [6]. Despite extensive research on high-power single-frequency nanosecond lasers in terms of higher output power and higher single-pulse energy [7-8], little attention has been devoted to their phase stability. Here, we present recent advances in laser systems developed to meet SSMB PoP II requirements. Beyond SSMB applications, such phase-stabilized, high-power, single-frequency pulsed lasers have potential for LIDAR [9], coherent beam combining (CBC) [10], nanosecond enhanced cavities [11], and terahertz source generation [12].

THE LASER SETUP AND CHARACTERISTIC

In single-frequency mode, several effects such as stimulated Brillouin scattering (SBS), stimulated Raman scattering (SRS), transverse mode instability (TMI), and amplified spontaneous emission (ASE) affect the low-noise operation of lasers. Among them, SBS effect significantly limits the power scaling of narrow linewidth nanosecond

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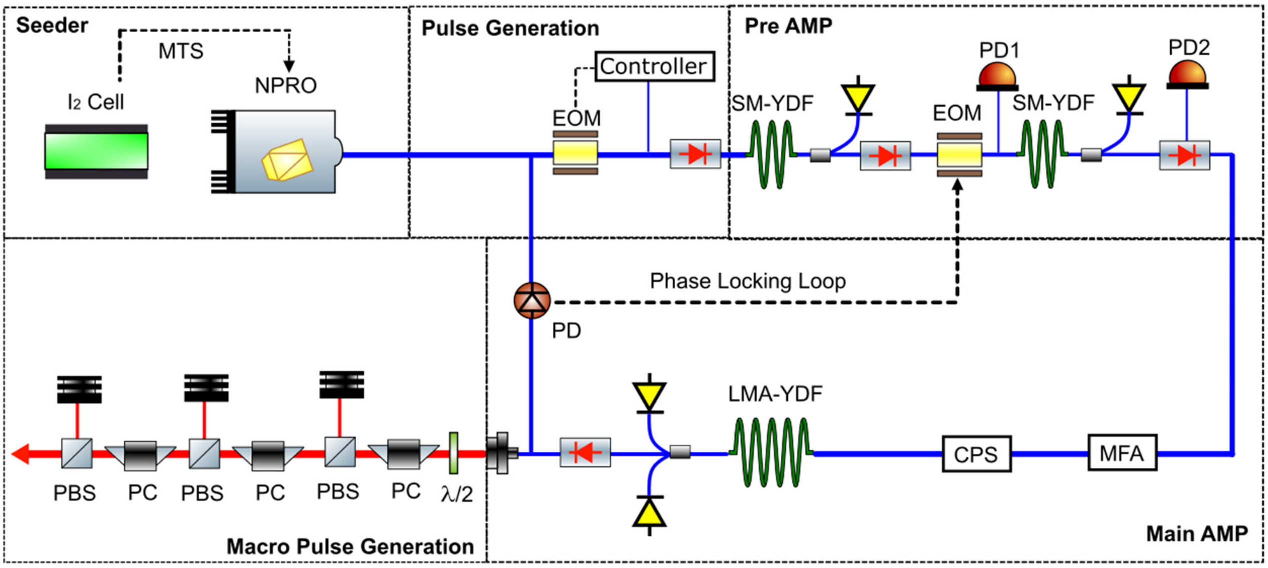

Figure 1: Schematic setup of the nanosecond MOPA fiber laser system. EOM: electro-optical modulator, SM-YDF: single-mode Yb-doped fiber, MFA: mode field adaptor, CPS: cladding power stripper, LMA: large-mode-area, PC: pockels cell, PD: photodiode, MTS: modulation transfer spectroscopy.

fiber laser. Specifically, the peak power threshold of SBS can be expressed as,

$$P_{SBS} = 21A_{eff}/g_B L_{eff}. \quad (1)$$

where A_{eff} represents the effective cross-sectional area of the interaction region, g_B is the peak Brillouin gain, and L_{eff} is the effective interaction length of the pump laser with Stokes wave [13]. Additionally, the response time of SBS is influenced by the acoustical phonon lifetime, which is approximately 10 ns. During the development process, the phase noise associated with each component of the laser system was thoroughly investigated and optimized. To improve phase stability, the interaction length and pulse width are reduced to suppress SBS, while a large mode-field single-mode fiber is used to reduce other nonlinear effects. In addition, we incorporate an additional phase-locked closed loop for precise phase feedback control.

Figure 1 is the schematic of SSMB PoP II laser system, which consists of five modules: seed laser, pulse generation, preamplifiers, main amplifier and macro pulse generation. A monolithic iodine-stabilized semi-non-planar ring oscillator with a wavelength of 1064 nm serves as CW seed laser, which is frequency stabilized by modulation transfer spectroscopy method. The laser exhibits a narrow linewidth of 1.2 kHz, an output power of 53 mW, and an RMS power stability of 0.17% over a 10-hour period. The reliability of this laser technique is well-established, with excellent power and frequency noise characteristics [14]. It has been shown that the phase noise of amplified lasers mainly depends on the quality of seed laser source. A frequency-stabilized seed source facilitates the frequency and phase stabilization of the amplified laser [6]. The seed oscillator is placed in a passively shielded box to isolate it from noise and temperature variations.

The generation of nanosecond pulses occurs through direct modulation using an electro-optic modulator (EOM) with a DC bias electrical control circuit. The seed pulse repetition rate is 6.25 MHz, corresponding to the repetition rate of the electronic storage ring. By controlling the modulating signal via an arbitrary waveform generator, the full width at half maximum (FWHM) of pulse width becomes adjustable, ranging from 0.7 to 3 ns. The power of seed pulse is then amplified by two single-mode ytterbium-doped fiber (SM-YDF) with core inner/outer cladding diameters of 10/125 μm. The final high-power output is realized by a 14/125 μm large-mode-area (LMA) YDF main amplifier pumped by two 976 nm laser diodes. A mode field adapter is spliced to improve coupling between the preamplifier and the main amplifier. In the phase-locked loop, CW seed laser and amplified pulsed laser are coupled within a fiber to generate interference signals, which are detected by a photodetector (PD). The feedback loop actively controls the laser's phase by modulating the phase modulator using a hill-climbing algorithm. The goal is to maintain the interference signal at its maximum value. Isolators are used to protect the components from stokes waves caused by reversed light, such as ASE and SBS. The fiber optic output port features three polarization beam splitters and three pockels cells, which acts as an optical switch to select pulses and improve the macro-pulse extinction ratio. All modules, except for the seeder, are mounted in a specially designed monolithic aluminum enclosure (832*614*147 mm). In order to dissipate the heat efficiently at high output power, the bottom is connected to a water-cooled bench, which is regulated at 25 °C and monitored by temperature sensors in critical areas. In the final experiment, additional optical and electronic devices will be installed to synchronize the interaction of the laser with the electron beam.

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The laser output pulse width can be adjusted from 0.7 ns to 3 ns. We conducted measurements of the laser characteristics at 0.7 ns, 6.25 MHz output setting. Figure 2 illustrates the output power and the backward power as a function of pump power. The inset in the figure shows the output spot at maximum power. Specifically, we achieved an average power of 80 W, with a pump-to-signal conversion efficiency of 75%. Notably, there is a nonlinear increase in backward power, suggesting SBS effect limits the maximum output. The polarization extinction ratio is approximately 38.5 dB. Additionally, the temporal FWHM of the pulse is approximately 0.74 ns, and the maximum peak power reaches about 17 kW. By utilizing the macro pulse generation module, we achieved adjustable macro pulses with a repetition rate spanning from 0 to 1000 Hz, as well as the number of micropulses from 0 to 1000. Furthermore, the extinction ratio of the macro pulses reaches 65.2 dB after passing through three Pockels cells.

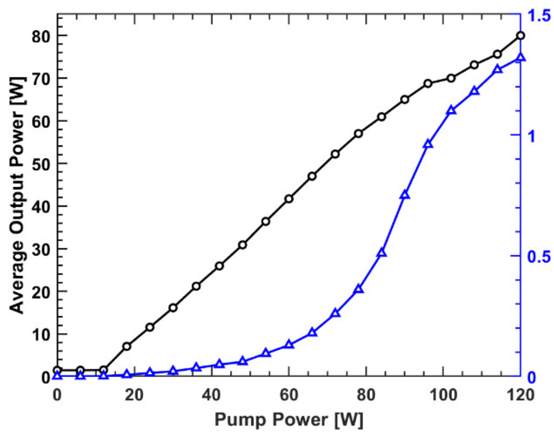

Figure 2: Output power and backward power of the main amplifier versus the pump power.

We use optical heterodyne method to measure the phase noise of the laser at full power with the phase-locked loop on. This involves coupling the amplified pulsed laser with CW seeder in the same fiber. We then measure the optical beating signal of the comb that is closest to the CW laser frequency. This optical signal is converted to an electrical signal by highly linear PD and IQ demodulated to obtain the power spectral density (PSD) of the phase noise, as depicted in Figure 3. The integration is performed over a frequency range spanning from 10 Hz to 1 MHz, resulting in a rms phase error of 113 rad and a rms frequency jitter of 261 kHz. For feedback control of the phase modulator, we utilize a hill-climbing algorithm to lock the interference signal at its maximum value, as illustrated in Figure 4. However, occasional resets on the order of Hertz occur since the limited operating range of the phase modulator. We are actively working on algorithmic and hardware improvements to mitigate these resets.

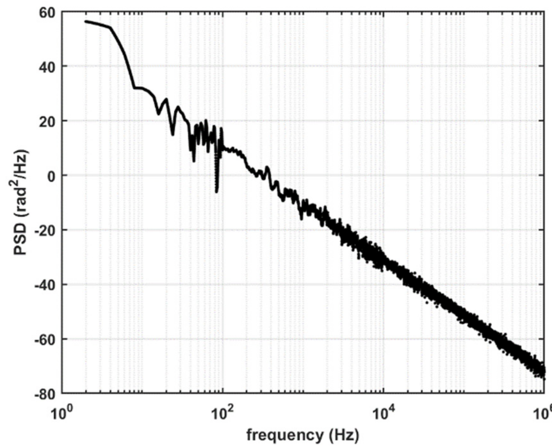

Figure 3: Power spectral density of phase noise at full power output.

To achieve higher output power, gain fibers with higher SBS threshold should be utilized. For instance, employing a shorter fiber length and a heavier Yb-doped fiber with higher absorption can raise the threshold. Fibers with larger mode area and photonic crystal fibers (PCFs) [15] can also be employed to increase the threshold and generate pulses with higher peak power.

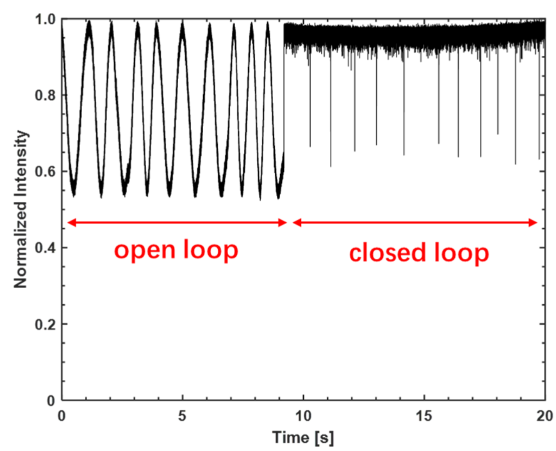

Figure 4: Open and closed loop states of the phase-locked loop.

CONCLUSION

We have developed a phase-stabilized, single-frequency, high-repetition-rate nanosecond pulsed laser operating at 1064 nm with a peak power of 17 kW for SSMB PoP II experiment. The laser system comprises an iodine-stabilized CW seeder and a low phase-noise fiber MOPA structure. The single-frequency output laser operates at a repetition frequency of 6.25 MHz, with an adjustable pulse duration ranging from 0.7 ns to 3 ns. Feedback control is facilitated by a closed-loop phase feedback system. After optimization, the rms phase noise of one comb, measured between 10 Hz and 1 MHz, remains below 300 kHz, indicating the potential for coherent interaction with the electron beams.

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