### Integrated Low-Jitter 400-MHz Femtosecond Waveguide Laser

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Detailed Terms
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Abstract—An integrated passively mode-locked waveguide laser generating 440-fs pulses at 394-MHz repetition rate is demonstrated on an 18 mm × 44 mm silica waveguide chip. The laser self-starts, and uses a saturable Bragg reflector for mode-locking.

Index Terms—Erbium waveguide, femtosecond pulse, high repetition rate, integrated laser, low jitter, soliton mode-locking.

I. INTRODUCTION

HIGH repetition rate, low jitter sources of femtosecond laser pulses are necessary for a variety of applications including optical arbitrary waveform generation, frequency metrology [1], and ultrafast sampling [2]. Passive mode-locking enables low jitter femtosecond pulses while alleviating the need for an external microwave oscillator. In the past, both polarization additive-pulse mode-locking and/or saturable Bragg reflector (SBR) mode-locking [3], [4] have been used with fiber and waveguide lasers, the latter leading to more compact cavities and fewer components. Recent experimental demonstrations of high repetition rate fiber lasers based on the SBR approach achieved repetition rates as high as 3 GHz [5] and timing jitter as low as 20 fs in the frequency range [1 kHz, 10 MHz] [6]. Nevertheless, integrated versions of such lasers have the additional benefits of being mass-produceable with reduced footprint, and increased stability. Early attempts at passively mode locking with an erbium-doped waveguide (EDW) as a gain medium and an SBR as a mode-locking element were limited to lower repetition rate and picosecond pulse operation [7], [8]. Femtosecond operation of such lasers [9] was only achieved by employing nonlinear polarization rotation mode-locking in an extended cavity, which is difficult to integrate. In addition, in all of these cases the cavity utilized free-space optics between the SBR and the EDW.

Monolithically integrated mode-locked semiconductor lasers have achieved femtosecond pulses at repetition rates of tens of gigahertz [10], [11]. However, due to the fast gain dynamics of the semiconductor gain medium, the measured timing jitter of integrated femtosecond laser diodes is typically hundreds of femtoseconds to a picosecond [12], [13]. Actively mode-locked laser diodes have shown subfemtosecond timing jitter, but they too rely on high-quality external oscillators and sophisticated control circuitry [14], [15]. As a result, there is a clear need for a source which would combine all the aforementioned characteristics: integration, high repetition rate, low jitter and self-driven operation, as well as compatibility with mass-production technologies.

In this letter, we demonstrate a 394-MHz, self-starting, passively mode-locked femtosecond laser based on planar silica waveguide technology. The laser generates 440-fs pulses with an average output power of 1.2 mW for a pump power of 400 mW and with timing jitter of 24 fs [10 kHz, 10 MHz].

II. EXPERIMENTAL SETUP

The experimental setup is depicted in Fig. 1. The laser cavity consists of a 5-cm section of erbium (Er)-doped alumino–silicate waveguide with a group-velocity dispersion of 30 fs²/mm. A 20-cm section of phosphorous (P)-doped silica waveguide with a dispersion of −25 fs²/mm is used to obtain a net anomalous intracavity dispersion to enable soliton mode-locking [16].

The length of the Er-doped section is determined to generate the necessary intracavity power, while the length of silica

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waveguide is determined in order to achieve appropriate dispersion for soliton operation. Decreasing the average dispersion shortens the pulsewidth, but too little dispersion can lead to instability due to the insufficient suppression of the continuum. A loop mirror is used at one end to provide 10% output coupling, while the other end is butt-coupled to an external SBR. The length of the loop mirror can be adjusted to minimize the footprint of the waveguide cavity while maintaining a constant effective silica section length, namely 20 cm. The SBR is a commercial unit with 14% modulation depth, a 2-ps recovery time and a saturation fluence of 25 J/cm². Pump power is provided by an external 976-nm laser diode coupled to the waveguide chip.

III. WAVEGUIDE FABRICATION AND CHARACTERISTICS

The fabrication of Er-doped films of aluminosilicate glass was done by radio-frequency (RF) sputtering on oxidized Si substrates. Waveguide cores were defined using conventional lithography and etching, and finally a silica upper cladding was deposited [17]. A similar process using P-doped glass was applied to fabricate the passive waveguide section. The Er-doped section and the P-doped silica–glass section have effective mode areas of 10 and 40 μm², respectively, and are connected through a mode convertor with loss less than 0.15 dB. The P-doped section is tapered to be wider near the chip edge to minimize the coupling loss to the single-mode fiber, as shown in Fig. 2.

The Er-doped waveguides were characterized using a separate chip with straight Er-doped waveguides. Fig. 3 shows the measured gain spectrum for three different power levels from the 976-nm pump diode and confirms that the peak gain at 1532 nm is 1.8 dB/cm. The measured pump absorption at 976 nm was 0.4 dB/cm.

IV. EXPERIMENTAL RESULTS

The laser was operated with 400 mW of pump power at 976 nm; the intracavity signal power was measured to be 12 mW, corresponding to a 30-pJ intracavity pulse energy. The output pulses with an average power of 1.2 mW are then amplified to 18 mW using an Er-doped fiber amplifier (980-nm pump, 350 mA), detected using a 10-GHz photodiode, and measured with a 500-MHz sampling scope and a signal source analyzer (Agilent E5052).

Fig. 4 depicts the measurement results. The 5-s persistence trace shows excellent signal stability, while the RF spectrum in (c) indicates a sidemode suppression ratio of 80 dB. The 8.4-nm full-width at half-maximum (FWHM) optical bandwidth before amplification implies 300-fs-duration transform-limited pulses. After amplification, the optical bandwidth decreases to 7.4 nm, corresponding to 340 fs. The autocorrelation measurement yielded a pulse duration of 440 fs. The difference is attributed to incomplete compensation of the chirp added by the Er-doped fiber. The laser is self-starting; and, as the pump power is increased, the laser first operates in a mode-locked-switching state before transitioning to a continuous-wave soliton mode-locked state at a pump power of 160 mW. Pump powers much higher than 400 mW resulted in pulse breakup as the intracavity energy was too high to sustain a single soliton for the given round-trip dispersion. Fig. 4(f) shows the phase noise of the first harmonic (394 MHz) of the laser. The timing jitter integrated from 20 MHz progressively down to 1 kHz is also shown. The timing jitter integrated from 10 kHz to
20 MHz is 24 fs, which is close to the noise sensitivity limit of the Agilent E5052 signal analyzer. We expect that the timing jitter can be further reduced to the few-femtosecond or even the few-femtosecond range [18].

V. NUMERICAL SIMULATION

The experimentally observed pulse characteristics can be compared with theoretical predictions based on the split-step Fourier method, using our waveguide and SBR parameters. The second-order dispersion, the Kerr effect, and gain filtering with parabolic gain shape are considered in the simulation. The SBR is modeled using the rate equation for a slow saturable absorber [16]. Table I summarizes the values used in the simulation, while Table II compares the predicted and experimental laser characteristics.

Good agreement, within 3%, between the experimental and predicted spectral characteristics is obtained. To remove the effect of uncompensated chirp, the comparison is based on the transform-limited pulses both for the simulated and measured results. Some discrepancy may be attributed to the nonuniform dispersion profile of the SBR, as its dispersion can change as much as 1000 fs² within the optical bandwidth of the laser output (inset of Fig. 1).

VI. SUMMARY

We demonstrated a stable, passively mode-locked integrated femtosecond waveguide laser with an SBR as a mode-locking element. The laser generates 440-fs pulses at 394 MHz, with the cavity being composed of a 5-cm section of Er-doped alumino-silicate waveguide and a 20-cm section of P-doped silica waveguide for dispersion engineering. Such a design provides a compact and robust integrated low-jitter femtosecond source without the need for driving electronics for active modulation. The laser provides good stability in a simple and potentially scalable design. No polarization control or active stabilization is required, and the laser is self-starting. Higher repetition rates can be achieved by further reducing the cavity length while optimizing the pumping scheme.

REFERENCES