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Integrated 2 GHz femtosecond laser based on a planar Er-doped lightwave circuit

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Abstract: An integrated passively mode-locked 2-GHz waveguide laser generating 285-fs pulses is demonstrated. It is based on a 500-MHz repetition rate laser integrated together with a pulse interleaver on a 45×50 mm silica waveguide chip.

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1. Introduction

High repetition rate 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 (P-APM) [3] and/or saturable Bragg reflector (SBR) mode-locking [4,5] have been used with fiber and waveguide lasers, with the latter leading to more compact cavities and fewer required components. Recent experimental demonstrations of high repetition rate fiber lasers based on SBR mode-locking achieved fundamental repetition rates as high as 3 GHz [6] and a timing jitter as low as 20 fs in the frequency range [1 kHz, 10 MHz] [7]. Nevertheless, integrated versions of such lasers have the additional benefits of being mass-producible with reduced footprint, and increased stability. Femtosecond operation of such lasers [8] was achieved recently using planar silica waveguide technology without free-space optics between the SBR and the erbium-doped waveguide (EDW), producing 440-fs pulses at a repetition rate of 394 MHz. In this paper, based on the same waveguide technology, we demonstrate an integrated chip comprising a 500-MHz femtosecond laser and an interleaver multiplying the repetition rate to 2 GHz. The 500-MHz laser generates 285-fs pulses (inferred by optical spectrum and soliton characteristics) with an average output power of 0.4 mW for a pump power of 175 mW. The pulse repetition rate is multiplied to 2 GHz using a two-stage interleaver achieving 15 dB sideband suppression.

2. Experimental results and discussion

The experimental setup is depicted in Fig. 1. The waveguide chip contains three sub-components; a laser cavity to generate femtosecond pulses at a fundamental repetition rate of 500 MHz, a pulse interleaver to multiply the repetition rate to 2 GHz, and an amplifier. The laser cavity consists of a 5.0-cm-long erbium doped waveguide with a group-velocity dispersion of 60 fs²/mm. A 14.8 cm section of phosphorous-doped (P-doped) silica waveguide with a dispersion of -24 fs²/mm is used to obtain a net anomalous intracavity dispersion and enable soliton mode-locking [9]. 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 SBR is a commercial unit (Batop) with 14% modulation depth, a 2 ps recovery time, and a saturation fluence of 25 μJ/cm². Pump power is provided by an external 980 nm laser diode coupled into the waveguide chip. The laser was operated with 175 mW of cavity-coupled pump power; the intracavity signal power was measured to be 4 mW, corresponding to a 10 pJ intracavity pulse energy. The laser output is split by a 3-dB coupler, to feed the interleaver and a separate output port.
Each stage of the interleaver splits the input beam into two paths, delays one of them by the corresponding half period of the input pulse train, and combines the original pulse train with its delayed version, such that the repetition rate is doubled. Two stages of the pulse interleaver convert the repetition rate from 500 MHz to 2 GHz. The amplifier recovers the optical power lost through pulse interleaving and further increases the output power of the overall integrated system.

Figure 2 depicts the measurement results obtained so far. The 8.8 nm full-width half-maximum (FWHM) optical bandwidth enables 285 fs duration transform-limited pulses. The laser typically operates at 1560 nm as in [8], but, at that wavelength, the SBR is positively dispersive with +1200 fs². This is sufficient positive dispersion to make the total cavity dispersion positive and disable soliton mode-locking, because the integrated laser cavity by itself is negatively dispersive with only -1100 fs² per round trip. In order to achieve net negative dispersion, we slightly adjusted the butt-coupling losses between the SBR and the waveguide chip which shifted the operating wavelength to 1545 nm, where the SBR has negative dispersive of -1500 fs². As a consequence, stable soliton mode-locking was obtained although the increased cavity losses significantly reduced the available output power. In the future, positive dispersion of the erbium doped waveguide can be reduced and the negative dispersion of the P-doped waveguide can be increased by increasing the waveguide height. Then, the negative dispersion of the laser cavity itself could be as large as -4000 fs² per round trip so that even the positive dispersion of +1200 fs² the SBR at 1560 nm would not interfere with soliton formation.

The laser is self-starting. As the pump power is increased, the laser first operates in a mode-locked Q-switching state before transitioning to a continuous-wave soliton mode-locked state at a pump power of 150 mW. The RF spectrum at the 500-MHz output port indicates a stable pulse train at a repetition rate of \( f_{rep} = 500.5 \) MHz. The first and second stages of the pulse interleaver suppress the sidebands at the 1 and 2 GHz harmonic by more than 30 dB and 15 dB, respectively. The incomplete suppression can be attributed to mismatched delay lengths and/or deviation from ideal coupling ratios of 50:50. Simulations indicate that a coupling ratio deviation to 40:60 would account for the measured amplitude of sidebands. This issue can be easily improved by adding tuning capabilities for both the delay and the coupling ratio.

3. Conclusion

We demonstrated a 2 GHz optical pulse train from an integrated waveguide chip that consists of a mode-locked femtosecond waveguide laser and a repetition rate multiplication device. The laser generates 285-fs pulses at 500 MHz, with the cavity being composed of a 5.0 cm section of erbium-doped alumino-silicate waveguide and a 14.8 cm section of P-doped silica waveguide for dispersion engineering. The repetition rate of 500 MHz is multiplied to 2 GHz with more than 15 dB suppression via integrated pulse interleavers.

4. References