10GHz Waveguide Interleaved Femtosecond Pulse Train

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Abstract: We demonstrate a 10GHz fs-pulse train by external repetition rate multiplication in four phase-tunable Mach-Zehnder interleavers implemented in planar waveguide technology. A minimum RF suppression ratio of -27dB can be achieved with thermal tuning.

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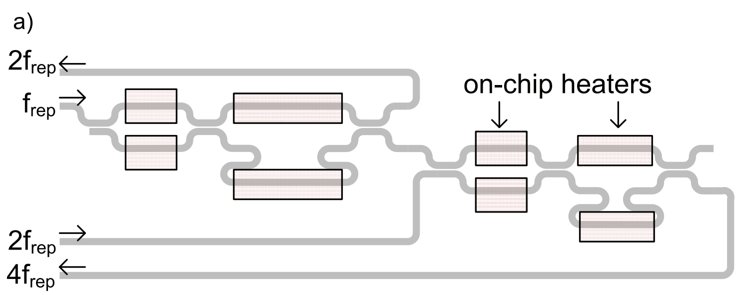
1. Introduction

High repetition rate femtosecond oscillators with wide frequency spacing between individual comb lines are attractive for optical arbitrary waveform generation, high-resolution sampling and frequency metrology [1]. To scale fundamentally mode-locked fiber lasers to the multi-GHz regime, external multiplication of the repetition rate is commonly employed. We present an integrated, compact and robust interleaver system implemented in planar waveguide technology on a chip that quadruples the repetition rate and thus has a distinct advantage over free-space methods in multiplying the repetition rate. By cascading two interleaver chips, a repetition rate multiplication by a factor of 16 is achieved. An integrated system for a 500MHz waveguide laser and a two-stage interleaver produced a 2GHz fs-pulse train [2], however, the maximum RF suppression was limited to -15dB. To improve the sideband suppression ratio, we designed and fabricated a thermally tunable waveguide interleaver. With an Er-doped fiber laser source, the repetition rate, input polarization and pulse duration can be adjusted; and we can thermally compensate for fabrication tolerances on the chip to achieve an optimized system performance.

2. Experimental Results and Discussion

Fig. 1a) illustrates the schematic of a thermally tunable interleaver that quadruples the repetition rate in two stages. In each interleaver stage, the input signal is divided by a coupler into two pulse trains, one of which experiences a differential delay, before both are re-combined. An additional coupler and a thermally tunable waveguide section are included for each Mach-Zehnder interferometer stage so that the fabrication tolerances in the couplers can be compensated and exact phase delays can be obtained. The transmission of the interleaver for a 2.5GHz output was simulated in Fig. 1b). For an ideal coupling ratio, the encountered dispersion in the delay line limits the suppression of the sub-harmonics (blue line); the red circles indicate the suppression levels for a design repetition rate of 625MHz. However, for deviations in the coupling ratio, as outlined for 60% to 40% couplers by the black stars, the suppression is significantly reduced, e.g. for the first sideband at 625MHz from -51dB to -24dB, and a minimum suppression of only -19dB can be achieved. Therefore, compensating for these fabrication tolerances in the coupling ratio by thermal tuning is crucial to obtain good suppression levels relevant for any application.



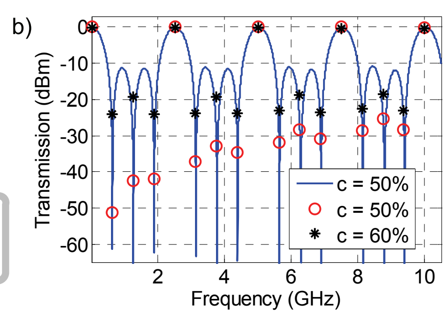


Fig. 1: a) Schematic of the interleaver to quadruple the repetition rate, based on a Mach-Zehnder interferometer with integrated heaters for tuning the coupling ratio and delay line length. b) Simulated transmission for a 2.5GHz interleaver considering the dispersion in the delay lines. The suppression for an ideal coupling ratio of 50% is compared to a coupling of 60% as marked by the red circles and black stars for a 625MHz input.

The interleaver is fabricated from passive Ge-doped 4µm x 4µm waveguides. Mode-converters adjust the mode size to facilitate coupling to fiber. Fig. 2 depicts the compact interleaver chip with a 19.4mm x 10.5mm footprint. The heater connection pads are wire-bonded to a printed circuit board, allowing each heater to be individually controlled with a digital-to-analog convertor (DAC) board.

A soliton mode-locked fiber laser serves as the input source; the fiber laser cavity consists of a 12.5-cm long Er-doped gain fiber (Liekki Er80-8/125 with anomalous dispersion of -20 fs^2/mm) that is imaged onto a saturable Bragg reflector (SBR) (see [3]). A polarizer in the free-space section ensures a constant polarization for the femtosecond fiber output pulse train (around 500fs FWHM pulse duration) that is amplified in an Er-doped fiber amplifier before being coupled into the waveguide. With a polarization control unit, the input polarization into the interleaver is optimized to the preferred waveguide mode. The laser repetition rate is tunable around 625MHz so that the laser frequency comb can be lined up to the interleaver filter response and fine-adjusted by thermal tuning.

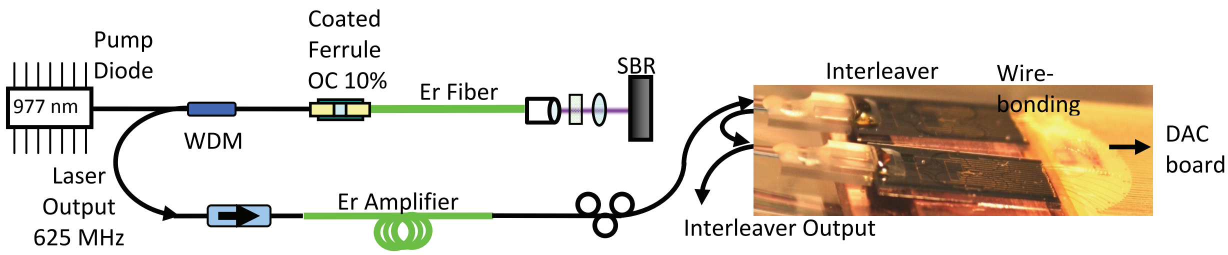


Fig. 2: Schematic of the interleaver system: An erbium-doped (Er) fiber laser is combined with an Er amplifier as the input for the interleaver waveguide chip. One interleaver chip multiplies the repetition rate from 625MHz to 2.5GHz. For a 10GHz pulse train, a second interleaver chip is cascaded after the amplified output of the first interleaver chip. Thermal tuning is performed with heaters controlled by a digital-to-analog convertor (DAC) board.

The resulting pulse train characteristics, for one interleaver output at 2.5GHz, are presented in Fig. 3a) and b). Without thermal tuning, the sub-harmonics are suppressed in the RF domain by -18dB from the desired signal at multiples of 2.5GHz in Fig. 3a). By thermal tuning, the sub-harmonics can be further reduced to -30dB, as shown in Fig. 3b). The amplified 2.5GHz pulse train is then transmitted through a second interleaver chip, multiplying the repetition rate to 10GHz. The initial RF suppression around -15dB can be significantly enhanced in the thermally tuned system, as demonstrated in Fig. 3c), resulting in a sideband suppression between -27dB and -33dB. The overall suppression is partially limited by uncompensated dispersion of the waveguide. In addition, to offset coupling and waveguide losses, the input signal into each waveguide stage is amplified by at least 10dB and post-amplification of the interleaved signal is necessary at some point in the system. Due to nonlinear mixing, however, the sidebands can be amplified disproportionately more than the desired signal. As the RF suppression was maximized by tuning of the heaters that primarily adjust the coupling ratio, optical heterodyne beat measurements between the interleaved pulse train and a narrow-linewidth tunable laser source can confirm the phase-coherence of the interleaved pulses and provide insight into the achievable optical suppression.

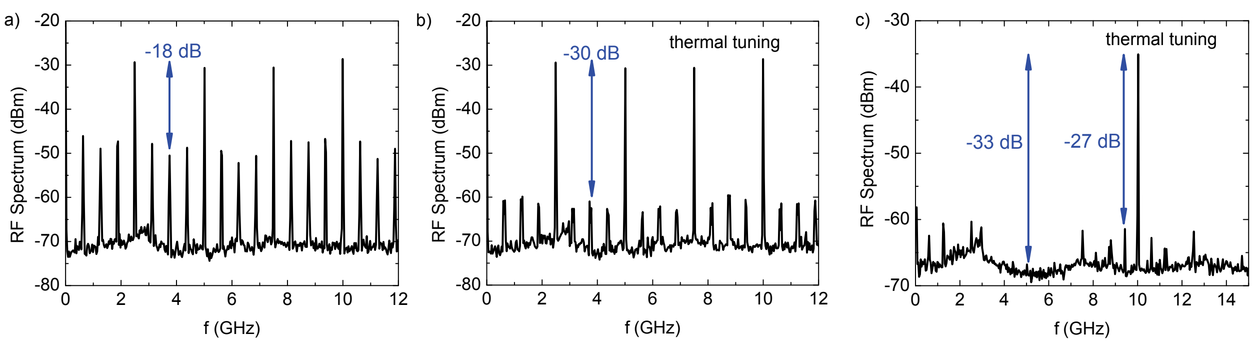


Fig. 3: Comparison of the minimum RF spectrum suppression of subharmonics: a) and b) feature the one-stage interleaver with a 2.5GHz output: thermal tuning reduced the sidebands from -18dB to -30dB. c) 10GHz pulse train from two cascaded interleaver chips with -27dB minimum RF suppression after thermal tuning of the coupling ratios.

4. References

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