dB was limited by the detector noise floor. Therefore, it is possible that the actual maximum suppression was greater than the measured value. For these measurements the RF suppression was maximized by tuning of the heaters that primarily adjust the coupling ratio. Thermal tuning of the delay lines mostly influenced the optical suppression of each individual line, as discussed in the following section.

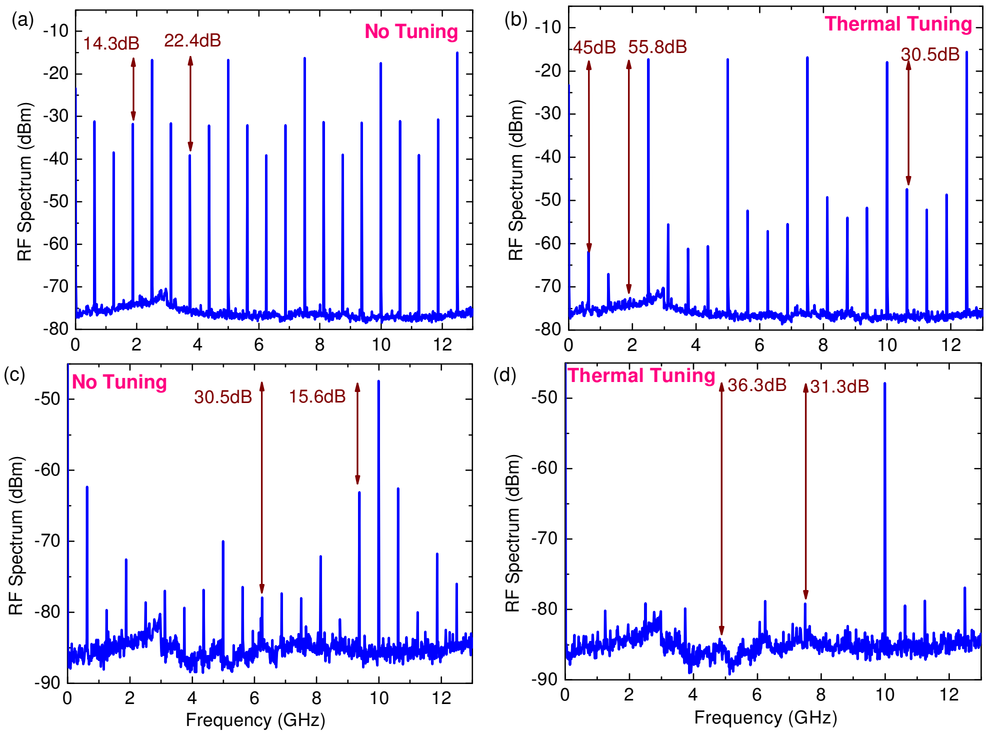

Fig. 4. RF Spectrum: (a) Minimum suppression of 14.3 dB for 2.5 GHz output without thermal tuning. (b) Minimum suppression of 30.5 dB for 2.5 GHz output with thermal tuning. (c) Minimum suppression of 15.6 dB for 10 GHz output without thermal tuning. (d) Minimum suppression of 31.3 dB for 10 GHz output with thermal tuning. All measurements were recorded with a resolution bandwidth of 300 kHz.

3.4 Optical heterodyne beat measurements

To confirm the phase-coherence of the interleaved pulses and to gain insight into the achievable optical suppression, optical heterodyne beat measurements between the interleaved pulse train and a narrow-linewidth tunable laser source were performed.

An optical heterodyne system, as shown in Fig. 5(a), was employed to determine the optical suppression for the individual optical modes in a frequency comb, in particular of interest for frequency metrology applications: The interleaver output was combined with a single frequency narrow-bandwidth line of a stable tunable laser whose polarization was matched to the interleaver output with an external polarization control unit. The signal was recorded by a photo-detector InGaAs EOT ET-3500F. An electronic signal analyzer was the preferred instrument of choice (over a RF power meter) to not only record the amplitude but also the frequency position of the beat notes.

The measured heterodyne optical beat is determined by the respective electric field strengths of the tunable laser source E_{TLS} and the interleaver $E_{TLS}{\cdot}E_{Int}$. Thus, the detected beat note in the RF spectrum analyzer is proportional to the optical interleaver power and the measured suppression corresponds directly to the optical suppression. As the cw transmission

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plots described in Section 3.2 record the transmitted optical power through the interleaver device, both measurements provide an independent evaluation of the optical suppression.

To detect the heterodyne beat note, two variations of the measurement set-up were pursued. In the first configuration, the photo-detected signal was low-pass filtered with a cut-off frequency at 450 MHz, as illustrated in the schematic in Fig. 5(a). During each measurement, the beat notes with two neighbouring optical lines were captured, if the TLS line was positioned accordingly. For the first interleaver stage, shown in Fig. 5(b), we found that the optical suppression featured a minimum value of 31 dB at 1560 nm. However, even though the measurement sensitivity of the instrument was optimized to the signal input power, the lower optical beat note disappeared in the noise floor. To obtain the optical suppression for subsequent lines and to examine two or more cascaded interleavers, multiple measurements were made while the tunable laser wavelength source was swept over the desired wavelength range. In Fig. 5(c), three such optical heterodyne measurements for two cascaded interleaver stages were superimposed. The measurements were each taken with 5 pm spacing (corresponding to the initial 624.5 MHz repetition rate) so that neighbouring lines were resolved. The best suppression measured 34.2 dB for the immediate adjacent sidemode, whereas the other two optical lines were suppressed by 22.5 dB. By choosing these wavelength spacings, the optical heterodyne beat corresponding to the previous measurement was recorded again. As identical amplitudes for the same beat note were detected, the consistency of the measurements was confirmed over the recorded interval. However, due to the number of measurements required, this method is only suitable for an interleaver analysis with few stages.

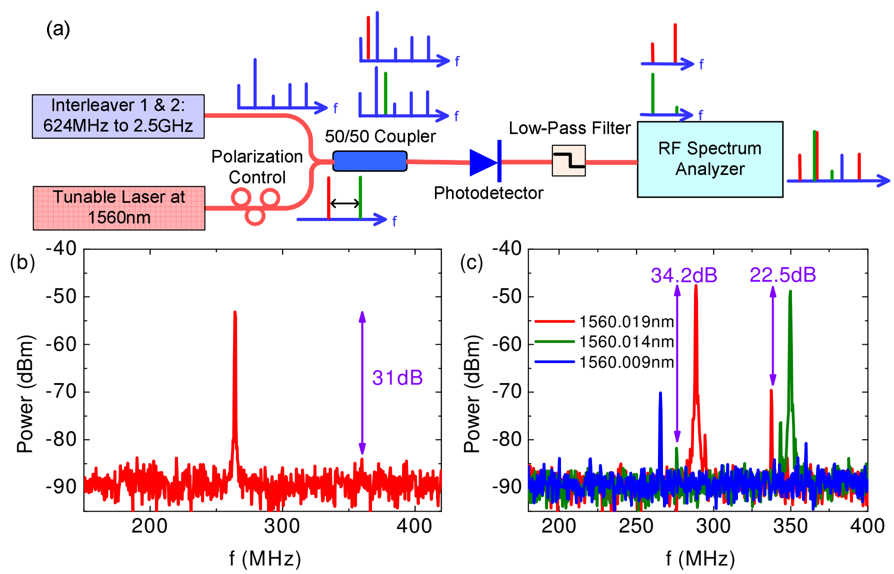

Fig. 5. (a) Measurement set-up to detect the optical heterodyne beat for two cascaded interleaver stages. Different colors (red, green) indicate two different wavelengths of the tunable laser. (b) Minimum optical suppression of 31dB at 1560 nm for 1.25 GHz interleaver. (c) Maximum optical suppression of 34.2 dB around 1560 nm for 2.5 GHz interleaver. Three measurements at different wavelengths are combined in one plot to obtain information about the suppression over one free spectral range. All measurements featured a resolution bandwidth of 300 kHz.

To maximize the optical suppression information obtained within one measurement, a second measurement configuration with a wide-band frequency approach (without the low-pass filter in Fig. 5(a)) was pursued. In this set-up, the beat notes between the single wavelength laser and all optical interleaver lines were detected simultaneously. Results for the 2-stage interleaver at 2.5 GHz are shown in Fig. 6. Here, the minimum suppression ratio

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varied between 25.2 dB and 29.9 dB. In this particular state, the system was optimized by tuning the coupler and delay line heaters for a symmetric suppression of the sidemodes. This more uniform power distribution obtained is in particular attractive for astrocomb calibrations. During each measurement the harmonics of the repetition rate lines (plotted in grey in Fig. 6) were detected together with the optical heterodyne beats (highlighted in red). As the repetition rate signal and its harmonics were given by a convolution of all optical lines, they possessed significantly more power (up to 25 dam). Thus, the sensitivity towards the low-power optical beat notes had to be reduced for the higher power RF lines not to saturate the detector. This can partially explain the difference in maximum sidemode suppression of 29.9 dB compared to the first measurement result of 34.2 dB. In addition, each state depended highly on the thermal tuning and input polarization. The good optical suppression over the measurement interval indicates that after thermal tuning the delay line lengths were well matched to the frequency comb lines, as otherwise the suppression would have significantly worsened with higher harmonics.

The optical suppression can be evaluated with this measurement for subsequent stages. Repeating this measurement for the whole 10 GHz interleaver stage showed that maximum suppression levels around 31 dB could be obtained for individual lines.

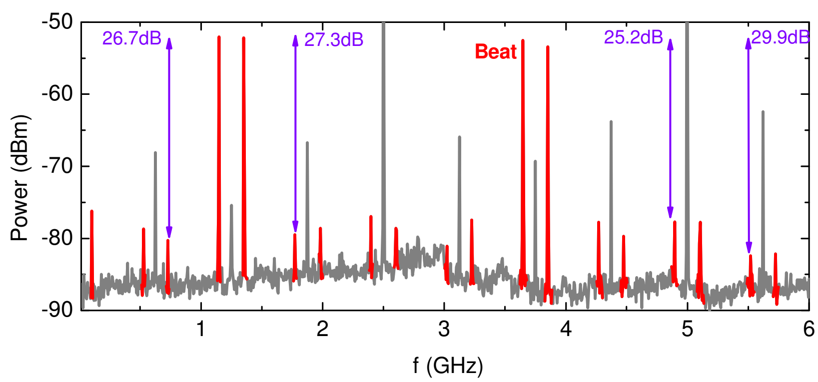

Fig. 6. Heterodyne beat measurement for thermally tuned 2.5 GHz interleaver. The optical beat notes are denoted in red, the grey lines depict multiples of the initial repetition rate.

4. Discussion

Different performance metrics of thermally tunable planar waveguide interleavers were analyzed. The optical transmission measurements confirmed expected device performance and provided insight into how well the fabrication met the target design. It is extremely beneficial to have such a verification that is independent of the fiber oscillator operation and any challenges that come by adding complexity to the system. In addition, these optical suppression values correspond directly to the optical heterodyne beat. While the maximum optical cw transmission suppression for the first interleaver stage amounted to 26.5 dB, the heterodyne beat measurement inferred a value of at least 31 dB. As discussed already in Section 3.2, for the first interleaver stage with narrow minima, the full depth of the notches might not be detected due to the limited wavelength resolution and precision of the TLS. The variation between the two measurements can additionally be explained by different thermally tuned states. For subsequent stages at GHz operating frequencies, the maximum measured optical suppression for the two cascaded interleaver stages from the transmission and heterodyne beat measurement both independently verified corresponding suppression levels, in one case of 34.2 dB, whereas for another operating point the optical suppression was measured to be 29.9 dB. This underlines further how critical the thermal tuning is and how small offsets in the delay lines can affect the optical suppression levels significantly.

The measured harmonics of the repetition rate in the RF spectrum are composed by a convolution of all optical frequency lines in the frequency comb; including the lower power

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wings of the spectrum (± 15 nm from 1558 nm) that do not necessarily feature an optimized sidemode suppression. The coupling coefficients deviate more strongly from the ideal splitting ratio in this regime since the directional couplers are wavelength dependent and dispersion can limit the suppression of some individual lines. In addition, phase effects can cancel or enhance certain harmonics of the repetition rate and the delay line lengths might not be matched as well as for the center part of the wavelength spectrum. Therefore, it is crucial to measure the optical and the RF suppression individually.

One limiting factor on the sidemode suppression over a wide bandwidth range was established to be waveguide dispersion and delay line offsets which have to be controlled to within a small fraction of the wavelength. Minimizing waveguide dispersion further or incorporating dispersion compensating designs could reduce this impact. In addition, scaling the fundamental repetition rate of the fiber oscillator to higher repetition rates in the GHz regime allows decreasing the delay length line in the interleaver, which in turn reduces the accumulated dispersion and improves the accuracy of the fabricated delay line length. Furthermore, multiple stages of the same interleaver can be cascaded or the same device double-passed to obtain better overall suppression levels. In addition, current efforts are underway to optimize the interleaver design and the fabrication to reduce the excessive losses in the interleavers. As the excess losses stem mostly from the high front-end reflections of the waveguide interleaver chip, improving the coupling from the fiber array to the chip can reduce the excess losses. Moreover, polarization conversion losses can be minimized by integrating design options to guide only one single polarization.

For a first demonstration of this technology, a free-running fiber laser source was used. Since the laser source was well isolated, the observed repetition rate drifts were below 0.3 kHz over a time span of 10 minutes and fluctuations in the carrier-envelope phase shift were expected to have been even smaller. Therefore, these drifts were not considered to impose limitations on the measurement results. With more optical power available in each line, a fully stabilized laser source and reduced interleaver excess losses, we are optimistic that even better performance metrics can be achieved for generating wide-spaced frequency combs.

5. Conclusion

We demonstrated a compact system of a repetition rate tunable fiber laser combined with four interleaver stages to multiply the repetition rate by a factor of 16, from 625 MHz to 10 GHz. An amplified femtosecond pulse train was coupled from the fiber oscillator source into interleavers defined in planar waveguide geometry. The optical and RF sidemode suppression of the frequency lines was analyzed. The minimum RF suppression of 30 dB up to 12 GHz was found to be partially limited by waveguide dispersion and delay line length offsets. In the optical domain, minimum suppression levels around 30 dB were confirmed by heterodyne beat measurements. Thus, we demonstrated the promising potential of thermally tunable interleavers in planar waveguide geometry for coherent pulse interleaving for applications in astrocomb calibration, frequency metrology and low-noise microwave signal generation.

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