mature as Er systems, there is no fundamental reason to believe the intensity noise of Tm lasers would be higher compared to Er-based supercontinuum systems. In principle, the intensity noise of Tm mode-locked lasers may be lower as nonlinear supercontinuum broadening, and the associated noise, is not necessary to achieve the 2000 nm light. However, here it is shown that well-developed Er-fiber based technology can be exploited for the generation of an ultrafast (39 fs) frequency comb near 2000 nm which exhibits excellent noise characteristics and long-term stability.

The noise characteristics and stability of the source may be the limiting factor of spectroscopic measurements; therefore, it is important to consider these qualities in the context of implementing the source with a spectrometer. In the current case, correlations of intensity fluctuation in the 2 μm region of the spectrum indicate that intensity fluctuations are not independent comb tooth fluctuations, but rather correlated/anti-correlated fluctuations of the spectral envelope. The long-term deviation of the 2 μm peak power is at the percent level, and such fluctuations could be accounted for with a modest number of spectral background measurements during real-time data acquisition. Furthermore, it is important to consider fluctuations on the time scale of the spectrometer detector integration. Currently, the most rapid detection and acquisition techniques are in the regime of 1 μs to 1 ms, thus noise on this time scale must be minimized. Newbury and colleagues have investigated technical noise-limited SNR of dual-comb spectroscopy [33], including the limitation introduced by laser RIN. Within this framework, the additive technical noise is introduced as a small perturbation to the signal response, and a quality factor, QF, given as the product of the technical noise-limited SNR per unit time and number of resolved spectral elements, can be calculated. The high-frequency RIN value of approximately -125 dBc/Hz of the 2 μm portion of the supercontinuum would imply that a RIN-limited QF of 1.0×10^6 $\mathrm{Hz}^{1/2}$ would be achievable in a dual-comb spectroscopic experiment using a single balanced photodetector. A typical RIN-limited QF for fiber-laser systems lies in the range of 10^6 $\mathrm{Hz}^{1/2}$ to 10^7 $\mathrm{Hz}^{1/2}$ [33]. The 2 μm light generated by current system is at the edge of a supercontinuum, where the RIN is higher compared to the RIN of the seed source. Nonetheless, the RIN-limited QF of the source presented here is still on the lower end of the typical range expected with mode-locked fiber lasers. In the context of the source integrated into a spectroscopic system, the laser RIN may be the limiting noise contribution at a detected optical power higher than roughly 50 μW. At lower power, the system would limited by either detector or shot noise.

4. Summary

A tunable PM Er:fiber-based frequency comb in the 2 μm region was developed via supercontinuum generation from the amplified output of a Er mode-locked laser. A prism pair was used to compress the 2 μm portion of the supercontinuum to 39 fs. The coherence of the 2 μm portion of the comb was investigated by a free-running heterodyne measurement with a single-frequency laser, and a 45 dB SNR beat note was observed at a resolution bandwidth of 10 kHz. Noise characteristics, including source RIN and long-term spectral stability, were investigated. The results of the RIN measurements indicated that the integrated high-frequency noise of the 2 μm portion of the source were 0.17%. Furthermore, the total output power of the system was stable at the level of a few percent over a time scale of days. Spectroscopic measurements of atmospheric gases near 2 μm, including carbon dioxide, will be pursued using the source presented in this work. While 2 μm oscillator sources exist [9], there are excellent all-PM oscillators at 1.5 μm [22] that, when coupled with the present PM broadening, could lead to a very attractive, fully-integrated, all-PM, completely fiber-based 2 μm source.

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