Shaped Supercontinuum for Precision Frequency Transfer

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***Summary*—We optimize a supercontinuum spectrum for high power at three clock wavelengths, a C-band reference, and an f-2f pair by phase shaping with a chirped fiber Bragg grating. We generate about 100 nW per comb line, with fractional frequency instability of about 10^{-17} at 1 s, sufficient for frequency comparisons of most optical clocks.**

***Keywords*—supercontinuum; frequency transfer; pulse shaping**

I. Introduction

Coherent supercontinuum is needed for extending frequency combs to specific wavelengths for clock comparisons, and conversion of optical clock frequencies to the microwave domain. A supercontinuum spectrum is easily optimized for one or two wavelengths by nonlinear fiber length and pump power, but achieving sufficient power at several wavelengths is very difficult with standard methods, particularly when frequency doubling is needed [1]. As multiple wavelengths are needed for frequency transfer, multiple supercontinuum branches are usually used [2], with each branch optimized for a specific task at the cost of adding significant phase noise from the different fiber paths.

We present a new supercontinuum shaping method using temperature control of the group velocity dispersion of a chirped fiber Bragg grating [3]. The altered dispersion modifies the phase of the seed pulse and the resulting supercontinuum spectrum. We optimize the supercontinuum to generate high power at three wavelengths for Yb, Ca, and Sr clocks, a C-band reference, and an f-2f pair from a single branch of an erbium fiber laser. Interference with an unshaped supercontinuum yields frequency instability values of about 10^{-17} at 1 s for all target wavelengths relative to the fundamental, making this a viable method for frequency comparisons between all but the best optical clocks.

II. Supercontinuum Shaping

To shape the supercontinuum spectrum, we use a chirped fiber Bragg grating pair to stretch and recompress the seed pulse, nominally adding no extra dispersion. We modify the group delay dispersion of one of the gratings by mounting it on a 32 element heater array as in [3] for computerized phase shaping. This in-fiber method is more practical than previous supercontinuum shaping methods using spatial light modulators with Ti:sapphire systems for simpler shaping targets [4].

Our system is illustrated in Fig. 1. A femtosecond erbium fiber oscillator at 100 MHz repetition rate seeds two supercontinuum branches. The lower branch includes FBG phase shaping, while the upper branch is unshaped with only power tuning, but has an acousto-optic frequency shifter so that optical interference between the two arms is at 70 MHz. The FBG should be stablilized to less than 1 K. We mount both FBGs on a cold plate stabilized to within a few mK inside a temperature stabilized box, using conventional temperature controllers.

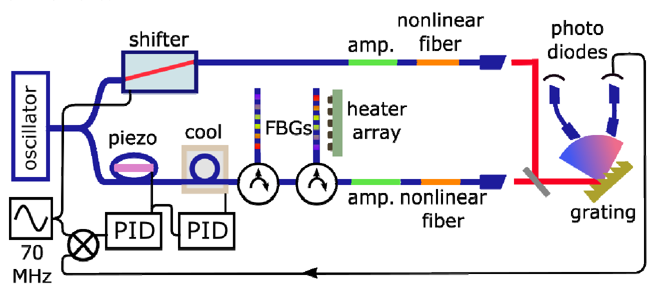

Fig. 1: Experimental layout. An oscillator seeds two supercontinuum branches, one is shaped by the thermal profile of an FBG, and the other is frequency shifted for comparison to a conventional unshaped supercontinuum.

The shaped spectrum used in the measurements below, and its unshaped version, is shown in Fig. 2 with about 100 nW or more per target comb tooth after shaping. The comb tooth power is estimated by scaling the spectrum to the average power of 174 mW. Without shaping, the power at specific wavelengths is effectively random and may be low as 20 nW in the comb line. The heater profile needed is found by recording spectra for random heater settings, and then sorting the resulting spectra for power at the target wavelengths. The top few are manually tested and tweaked as needed. Overnight measurement is likely enough to find a useful heater setting, but more optimization can improve the target powers further, and specific wavelengths can be prioritized in the sorting calculation as needed. We considered 100 nW to be sufficient, having a low relative intensity shot noise floor of -115 dBc/Hz, but we have also made spectra with about 200 nW at the target wavelengths with longer search times.

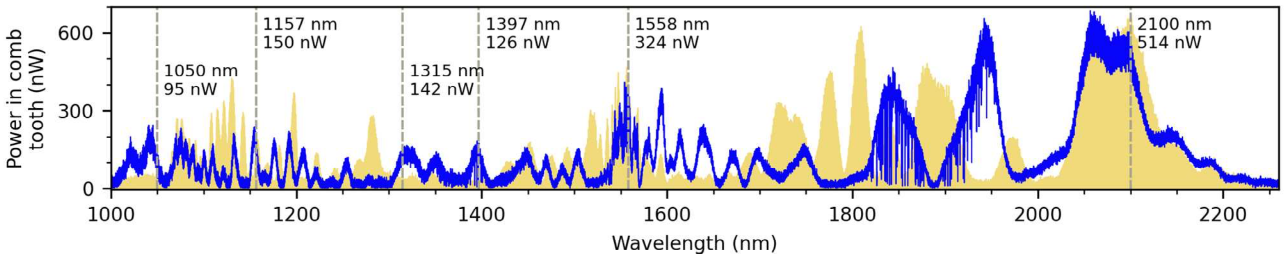

Fig. 2: Blue curve: shaped supercontinuum spectrum optimized for six wavelengths. Filled background: spectrum with all heaters off.

III. Stability Measurements

After optimizing the spectrum, we performed various tests on the shaped supercontinuum. One test was to use the red and blue ends of the spectrum for f-2f interferometry. The f-2f beat note had a signal to noise ratio of about 40 dB at 100 kHz resolution bandwidth, and we stabilized it with an electro-optic modulator in the oscillator. The in-loop beat note had an integrated phase noise of 0.2 rad from 3.5 MHz to 0.2 Hz, indicating clean locking of the carrier envelope offset frequency.

A grating filtered the supercontinuum to isolate the target wavelengths with 1 nm bandwidths. We recorded the 1050 nm component of the shaped beam, finding a 2% standard deviation in the average power over 50 minutes. We had two fibers receiving different wavelengths: one was the fundamental at 1558 nm, and the other was tuned to one of the other target wavelengths. Photodiodes measured the 70 MHz beating between the shaped and reference supercontinuum beams. The beat note signal to noise for the target wavelengths was from about 40 to 50 dB at 100 kHz resolution bandwidth.

With meters of fiber, the interference is sensitive to small temperature drifts. To reduce their effect, we locked the length of the shaped branch to the reference branch with a piezoelectric fiber stretcher and thermoelectric fiber cooler, locking the 1558 nm beat to the shifter's driving frequency. The stability of the interference at the other wavelength is then a measure of the coherence between the target and fundamental wavelengths.

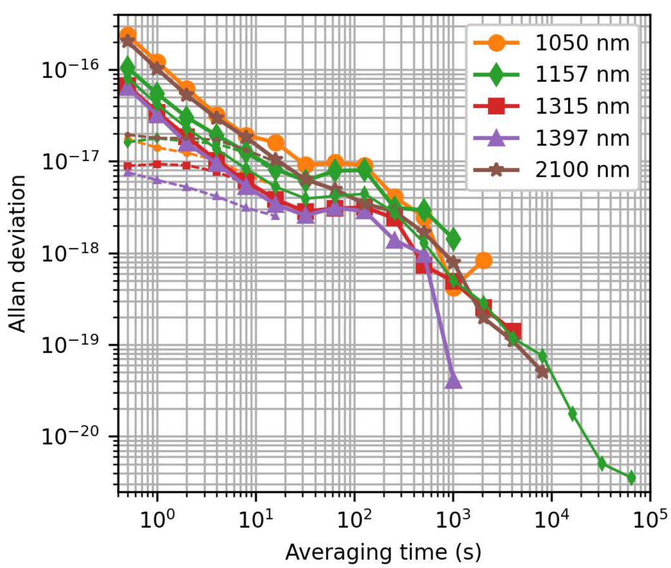

Fig. 3: Allan deviation of fractional optical frequency stability of target wavelength to the fundamental at 1558 nm.

We recorded the phase of the two beats over time, with Allan deviations plotted in Fig. 3. The solid curves are for the phase measured at the end of the 0.5 s interval (Π type), and the dashed curves are for the average of the phases measured within each 0.5 s interval (Λ-like) for rejecting white phase noise. The plot includes a calculated correction by subtracting the frequency offset of the 1558 nm signal with a scaling factor for the measured wavelength in fused silica (eg. $(1558/n_{1558})$ / $(1157/n_{1157})$). The instability at 1 s is about 10^{-17}, which is suitable for comparing most optical clocks [1]. The longer line is a measurement of about 2 days at the noisiest clock wavelength to verify longterm stability.

IV. Conclusions

Supercontinuum shaping with fiber Bragg grating phase shaping can generate high powers at specific wavelengths for optical clock and frequency comb measurements with verified frequency stability compatible with most optical clocks. It has the flexibility to adjust to different experiments such as changing target wavelengths, or favouring certain wavelengths for frequency doubling through computer control without disruptive physical changes like fiber length modification. We have shown that supercontinuum shaping can improve comb tooth power without adding the noise inherent to a multi-branch system.

An interesting next step would be using phase shaping to improve the supercontinuum stability. When clock accuracy surpasses the stability of standard supercontinuum sources, fine tuning the seed pulse by phase shaping may reduce pulse shape defects that impair self-phase modulation, increasing the overall stability of the supercontinuum generation process.

References

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