Sub-femtosecond Relative Timing Jitter in an All-Fiber Dual-Color Laser at 1.0 µm and 1.5 µm

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ABSTRACT

We demonstrate a dual-color 1.55/1.03 µm all-fiber femtosecond laser exhibiting sub-femtosecond relative timing jitter. The 1.03 µm channel is generated via resonant dispersive-wave emission in a short segment of highly nonlinear fiber pumped by a sub-30-fs, 1.5-µm laser. Despite the commonly assumed high intrinsic noise of dispersive-wave generation in highly nonlinear fiber, we show that optimized nonlinear-conversion conditions combined with a low-noise pump enable sub-femtosecond timing synchronization between the dispersive wave and the signal at 1.5 µm. This work demonstrates the feasibility of low-jitter multicolor ultrafast sources spanning fiber-amplifier gain bands at 1.0 µm, 1.5 µm, and beyond 1.8 µm in a fully integrated all-fiber architecture without active feedback control.

Keywords: Timing jitter, Dispersive wave, All-fiber, Sub-femtosecond, Ultrafast laser, BOC, Synchronization

1. INTRODUCTION

Low-noise ultrafast laser sources capable of simultaneously delivering multiple wavelength channels (1.0, 1.5, and 1.8–2.0 µm) with intrinsic, tight synchronization remain a major challenge, particularly when operation without active stabilization is required. In particular, sources spanning the near- and mid-infrared with femtosecond-level or better relative timing stability enable applications ranging from optical frequency metrology and coherent waveform synthesis to nonlinear spectroscopy and ultrafast pump-probe experiments [1-3]. In these contexts, excess timing jitter between wavelength channels directly degrades temporal resolution, coherence, and signal-to-noise performance, motivating the development of multi-wavelength sources operating at the fundamental noise limits.

Such intrinsically synchronized multiwavelength source is commonly generated by pumping a short segment of highly nonlinear fiber operating in either the normal- or anomalous-dispersion regime to achieve octave-spanning supercontinuum generation. Although it is well established that pumping in the normal-dispersion regime can enable low timing jitter and low intensity noise supercontinuum generation [4,5], high pulse energy and peak power are typically required due to rapid temporal broadening of the pump pulses. Consequently, generating dual- or triple-color sources spanning the 1.0 µm, 1.5 µm, and 1.8–2.0 µm spectral channels within fiber gain materials remains extremely challenging. In many cases, free-space-to-fiber coupling is required, preventing a fully integrated alignment-free laser architecture and introducing a risk of short-term fiber end-facet damage.

In contrast, supercontinuum generation in the anomalous-dispersion regime enables octave-spanning spectra at substantially lower pulse energies, driven by soliton self-compression, Raman self-frequency shift, and resonant dispersive-wave emission [6]. This approach naturally leads itself to simple, all-fiber implementations, eliminating the alignment drift and long-term instability associated with free-space to fiber coupling. Despite these advantages, resonant dispersive-wave (DW) emission in anomalous-dispersion nonlinear media are widely regarded as intrinsically noisy, owing to strong amplification of pump-laser fluctuations during ultrafast spectral broadening [7]. On the other hand, it has been shown that pumping anomalous-dispersion fibers with ultrashort pulses and using sufficiently short lengths of nonlinear fiber can significantly enhance the coherence of the generated supercontinuum and reduce the relative intensity noise of individual spectral components. However, how tightly the different supercontinuum spectral components, such as dispersive waves, are temporally synchronized to the pump pulses has not yet been experimentally demonstrated, although some numerical simulations suggest that resonant dispersive-wave timing jitter could reach the few-hundred-attosecond level in hollow-core fibers [8].

In this work, we demonstrate 1-µm dispersive-wave emission generated from a supercontinuum source that exhibits sub-femtosecond relative timing jitter (RTJ) with respect to its 1.5 µm counterpart, forming a tightly synchronized dual-color all-fiber source. To the best of our knowledge, this represents the first experimental demonstration of a 1-µm dispersive wave exhibiting sub-femtosecond (sub-fs) relative timing jitter.

2. EXPERIMENTAL SETUP

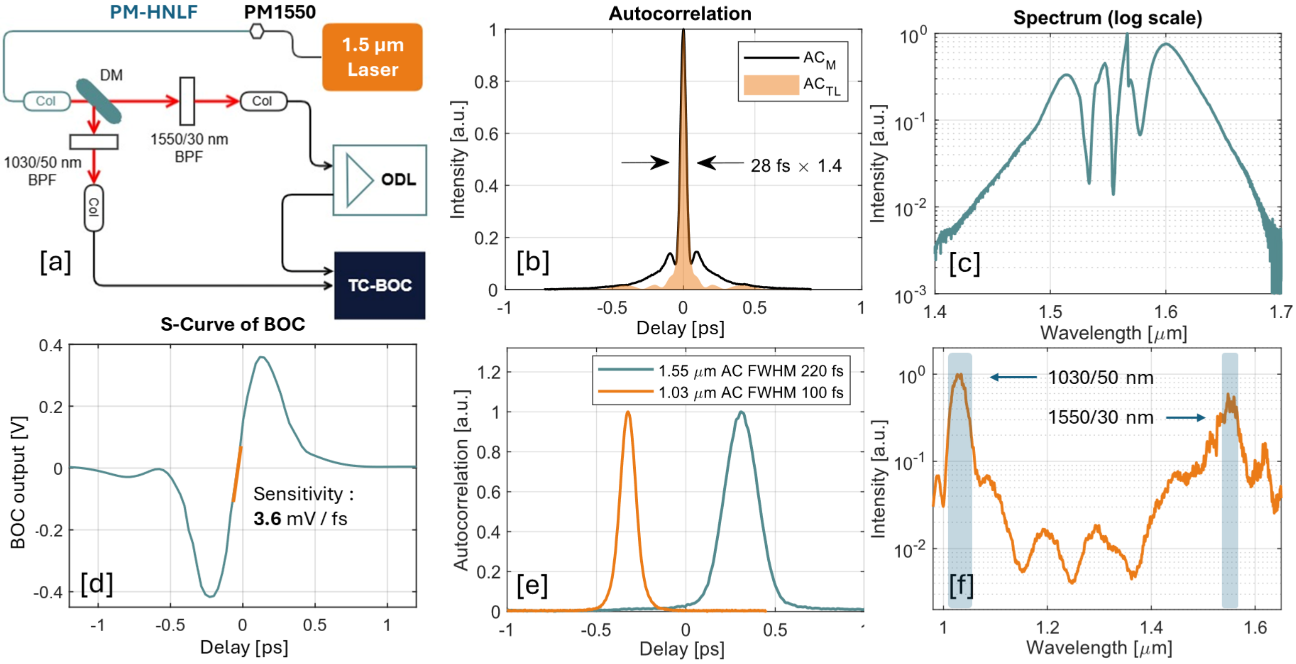

Figure 1. (a): Experimental setup of the dual-color femtosecond laser used for relative timing-jitter measurements. DM: dichroic mirror; PM-HNLF: polarization-maintaining highly nonlinear fiber; Col: collimator; BPF: bandpass filter; ODL: optical delay line; TC-BOC: two-color balanced optical cross-correlator. (b): Autocorrelation (AC) trace of the 1.5 µm pump pulses and the AC trace of the transform limited pump pulses (c): Optical spectrum of the 1.5 µm pump laser (log scale). (d): Sensitivity curve of the TC-BOC used for timing-jitter measurements. (e): Autocorrelation traces of the filtered 1.03 µm and 1.55 µm pulses generated after the PM-HNLF. (f) Output spectrum from the PM-HNLF, showing both the 1.03 µm dispersive-wave component and the residual 1.55 µm pump.

The experimental setup is shown in Fig. 1(a). The laser source consists of a 1.55 µm pump laser (Cycle's SOPRANO-mini) delivering sub-30 fs pulses at an 86 MHz repetition rate with 240 mW average power. The autocorrelation (AC) trace and optical spectrum of the pump output are presented in Fig. 1(b) and Fig. 1(c), respectively. A short piece of polarization-maintaining highly nonlinear fiber (PM-HNLF) is used to generate a synchronized 1.03 µm dispersive wave alongside the residual 1.55 µm pump pulses. The resulting broadband spectrum from the PM-HNLF is shown in Fig. 1(f). Due to the limited wavelength range of the optical spectrum analyzer, the experimental spectrum can only be measured up to 1.65 µm. After filtering with two bandpass filters centered at 1.03 µm and 1.55 µm, the isolated pulses exhibit AC widths of 100 fs and 220 fs, as shown in Fig. 1(e).

The PM-HNLF is fusion-spliced to a short segment of PM1550 fiber terminated with an FC/APC connector and directly connected to the pump laser output, while the opposite end is connected to a dual-color fiber collimator. The entire system, including the pump laser, maintains an all-fiber architecture. By adjusting the length of the PM1550 fiber between the pump laser and the PM-HNLF, thereby tuning the pre-chirp of the pump pulses, efficient 1.03 µm dispersive-wave generation is achieved. The two-color pulses are then directed through an optical delay line and into Cycle's highly sensitive two-color balance cross correlator (TC-BOC) for timing-jitter measurements.

3. EXPERIMENTAL RESULTS

With a calibrated timing sensitivity of 3.6 fs/mV (Fig. 1(d)), the measured relative timing-jitter spectral density between the two-color pulses is shown in Fig. 2(a). Although the generation of the 1-µm dispersive wave is a strongly nonlinear process that could, in principle, amplify quantum noise through mechanisms such as modulation instability, Raman scattering, or polarization-mode instability, no significant growth of high-frequency timing jitter is observed. Instead, the dominant contribution to the measured RTJ originates almost entirely from the detector noise floor above 1 MHz, as the intrinsic detector noise floor exceeds the actual signal at high frequency, and a small part of the low-frequency region between 1 Hz and 200 Hz also contribute the ~0.3 fs timing jitter, which is attributed to technical noise sources such as a small intensity fluctuation from pump laser, residual environmental perturbations, consistent with the fact that the experimental setup is not fully enclosed or vibration isolated. The timing jitter integrated between 200 Hz to 1 MHz remains negligible. Since quantum-noise-driven fluctuations typically dominate at higher frequencies, the minimal RTJ contribution in the frequency range from 200 Hz to 1 MHz indicates that quantum-noise amplification in this dispersive-wave generation process is very weak. The integrated RTJ within this band is much lower than 0.05 fs.

For comparison, the relative intensity noise power spectral density (PSD) of the generated 1-µm pulses is shown in Fig. 2(c). The relative intensity noise (RIN) spectrum exhibits a behavior closely resembling that of the RTJ spectrum, with dominant low-frequency contributions below 200 Hz arising from technical noise, while quantum-noise contributions at higher frequencies play a minor role in the integrated RIN. These observations suggest that further improvements in enclosure and environmental isolation of the setup, together with additional suppression of low-frequency pump-laser technical noise, for example, via active feedback to the 1.5-µm pump diode, may further reduce the RTJ by approximately 0.3 fs and simultaneously lower the RIN of the 1-µm pulses.

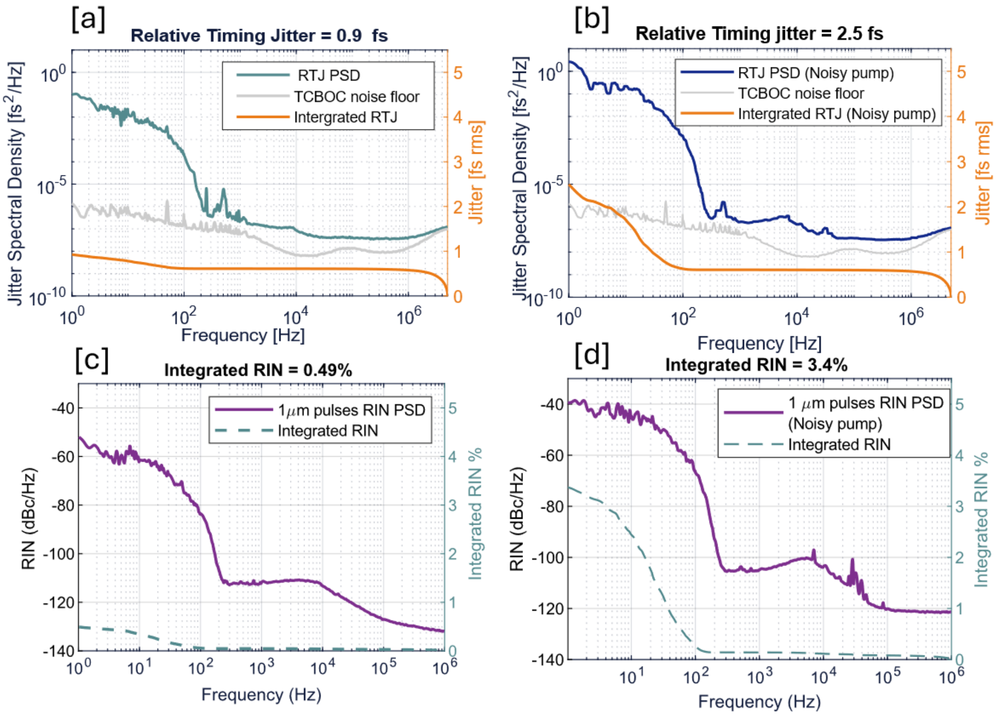

Figure 2. Measured RTJ PSDs (a,b) between 1-µm dispersive wave and filtered 1.5 µm pulses generated with 1.5 µm pump laser. Measure RIN PSDs (c,d) of 1-µm dispersive wave. (a,c) are measured with a low-noise 1.5 µm pump laser and (b,d) are measured with a nosier pump laser.PSD: power spectral density; RTJ: relative timing jitter; RIN: relative intensity noise.

To further examine the influence of pump-laser technical noise, the pump diode of the 1.5-µm laser was replaced with a diode exhibiting approximately 10 dB higher RIN, and the measurements were repeated. The corresponding RTJ spectrum is shown in Fig. 2(b). In this case, pump-laser technical noise becomes non-negligible and contributes an additional 1.6 fs of timing jitter accumulated from 200 Hz, while the high-frequency RTJ PSD remains essentially unchanged, indicating that the quantum-limited timing jitter is unaffected by the increased pump noise. Because the experimental configuration is identical for the measurements in Figs. 2(a) and 2(b), residual environmental noise contributions are expected to be the same in both cases. The observed increase in RTJ can therefore be attributed directly to the higher pump-laser noise, corresponding to an additional timing jitter of approximately 1.6 fs.

The corresponding RIN spectrum of the 1-μm pulses generated with the noisier pump laser is shown in Fig. 2(d). As expected, the overall RIN of the dispersive wave increases by approximately 10 dB, in direct correspondence with the increased pump-diode noise. This behavior confirms that the intensity and timing noise of the dispersive wave are weakly affected by quantum-noise amplification and are primarily governed by pump-laser technical noise at low frequencies in this source setup.

4. DISCUSSION AND CONCLUSION

In summary, we demonstrate a sub-fs, tightly synchronized 1.55/1.03 μm dual-color source based on dispersive-wave generation in anomalous-dispersion fiber driven by a low-noise, ultrashort 1.5-μm pump laser. Relative timing-jitter measurements performed using a TC-BOC confirm that the dominant contribution to the timing jitter originates from low-frequency technical noise below 200 Hz, whereas the high-frequency timing jitter remains negligible and is ultimately limited by the detector noise floor. When driven by a low-noise 1.5-μm pump laser, the integrated relative timing jitter approaches the sub-femtosecond regime. However, the final timing-jitter performance is strongly influenced by the pump-laser noise. In a comparison experiment, increasing the pump-laser diode RIN by 10 dB results in an increase of the integrated timing jitter to the few-femtosecond level. The amplification of quantum noise during nonlinear dispersive-wave generation remains weak due to the use of ultrashort pump pulses and a short segment of PM-HNLF.

In the experiment, only the relative timing jitter between the 1.0 μm dispersive wave and the 1.5 μm spectral component is directly measured. However, numerical simulations of supercontinuum generation using the experimental parameters reveal the presence of a Raman soliton centered near 1.85 μm that is not experimentally observed due to instrumentation limitations. The simulations further indicate that the relative timing jitter between the Raman soliton and either the dispersive wave or the 1.5 μm spectral component also remains at the sub-femtosecond level. These results suggest that, with an appropriate pump-laser design, tightly synchronized, low-timing-jitter multicolor supercontinuum sources can be realized with moderate pulse energy in a fully integrated all-fiber architecture spanning fiber-amplifier gain bands at 1.0 μm, 1.5 μm, and beyond 1.8 μm.

Overall, this work presents the first experimental demonstration of dispersive wave exhibiting sub-femtosecond relative timing jitter in an all-fiber-based supercontinuum source. The results establish a compact, all-fiber route toward low-noise dual-color ultrafast laser simultaneously covering fiber-amplifier gain bands at 1 μm and 1.5 μm, with direct relevance to precision timing distribution, ultrafast spectroscopy, and nonlinear frequency-conversion applications.

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