

Due to low pulse energy from our laser/amplifier set up, all of the previously described measurements were averaged over ~ 100 pulses. With more amplification, however, we were able to make true single-pulse measurements and, for example, confirm that the amplified pulse's temporal intensity and phase were not varying from shot-to-shot. This is the case for the results shown in Fig. 6b, where the energy of a single pulse was slightly above our single-shot detection level. The higher error in that measurement is due to the higher noise in the trace due to the low signal level (after standard noise filtering). Most ns lasers have higher power than our fiber laser set up, so single-shot measurements for them using the ns FROG should be straightforward and low-noise.

Finally, we mention that, in the results shown in Fig. 6a and b, the FROG spectra are slightly different from those measured with spectrometers. These differences are likely because all the spectrometers in these measurements were at their limits of spectral resolution. and spectral structure is slightly washed out in them all by varying degrees. Thicker etalons would resolve this issue and should be used in future devices for measuring such pulses.

7. Discussion

The measurements above demonstrate our single-shot FROG's ability to measure even complex pulses in the 175ps to 3ns range, using a very simple, all-optical device. The table below summarizes the parameters of our ns FROG.

Table 1. Summary of the parameters of the ns-FROG used here.

Spectral Resolution	Spectral Range	Temporal Resolution	Temporal Range	Maximum TBP	Measurable pulses at 1064nm
0.37pm (~ 4 ns)	27pm (~ 60 ps)	13ps Or 60ps	8.5ns Or 1.8ns	~ 30	130ps to 4ns or 60ps to 1.8ns

In addition to the previously mentioned issues, the measurement range of our ns FROG is also limited somewhat by the need to image through the spectrometer etalon. Because there is a large optical path-length difference between the light that exits the etalon on the first and last bounces, a large *depth of field*, equal to this distance, is required. Given the required depth of field of ~ 1.5 m (the pulse-front tilt), we can solve for the smallest resolvable feature, which we find to be $\sim 350\mu\text{m}$. Our SHG crystal had a width of 2mm along the delay axis. So by choosing the correct imaging lenses, ~ 30 temporal features can fit across the crystal and be accurately imaged through the 532nm etalon. Therefore, the maximum measurable TBP of our device was ~ 30 . This is the reason for the two options in the above table.

The next limitation in measurable pulse complexity is given by the finesse of the SHG spectrometer etalon, which is ~ 90 for our current setup. Of course, the FROG could also measure broader- or narrower-bandwidth pulses simply by using narrower or thicker etalons.

The single-shot ns FROG should work for a large range of center wavelengths, with the bandwidth of the etalon's coatings providing the only limitation in this regard. A different center wavelength simply changes the output angle of the tilted pulse from the PFT etalon, much as the diffracted angle from a grating would change. But because we image the etalon onto the SHG crystal, angle changes will not affect the alignment of the FROG, although the slit may need adjusting. Changes in the input pulse center wavelength should simply move the FROG trace up and down along the wavelength axis and may require tilting the SH crystal to maintain the phase matching angle.

In short, this simple and inexpensive device should prove an essential accessory in ns laser labs. It will allow users and laser developers to monitor the performance of their ns lasers on a shot-by-shot basis and provide the information required to vastly improve the most numerous and popular class of lasers in the world.

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