Simultaneous measurement of two different-color ultrashort pulses on a single shot

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We experimentally demonstrate the ability of double blind frequency-resolved optical gating to simultaneously measure two independent pulses at very different wavelengths on a single shot. Our device uses polarization-gate geometry, allowing pulses at any two wavelengths and unlimited operating bandwidth. The retrieval algorithm is robust and is capable of ignoring most forms of noise in the measured spectrograms.

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1. INTRODUCTION

Measuring the complete intensity and phase of ultrashort laser pulses is important in order to understand experiments and applications that use them. Techniques such as frequency-resolved optical gating (FROG) [1,2] and its simplified version GRENOUILLE [3–5] have been developed in the past few decades to make such measurements. In modern ultrafast-optical experiments, however, there is often the need to measure two unrelated unknown pulses simultaneously. For example, in pump-probe experiments, used to characterize the material properties, both the pump and probe pulses must be measured. Also, applications involving nonlinear-optical processes, such as continuum generation in optical fiber [6–8], which generate pulses at a different wavelength, require measuring both the input and output pulses. Thus, a measurement technique capable of simultaneously measuring two unknown pulses simultaneously would be useful. Indeed, a technique that can measure two pulses of different colors and do so on a single shot would be even more helpful, especially for the above-mentioned applications.

Various methods had been proposed to solve the two-pulse measurement problem, including blind FROG [9–11] and VAMPIRE [12], but they require additional information, such as the spectra of the pulses, to completely determine the unknown pulses. We recently demonstrated a technique called double blind FROG (DB FROG) using the polarization-gate (PG) geometry, which allows two unknown pulses to be measured simultaneously on a single shot without prior knowledge of the pulse spectra [13]. And we used it to measure pulse pairs with the same center wavelength, for which it worked well. Theoretically, this device should be capable of measuring more complex pulse pairs and pulse pairs with different center wavelengths and bandwidths. Indeed, here, we demonstrate that it can measure a complex pulse pair and pulse pairs with the very different center wavelengths of 400 and 800 nm.

2. BACKGROUND

DB FROG relies on the idea that, in any two-beam geometry, as one pulse gates the other, at the same time, the other also gates the one. Extending the idea behind other FROG variants to measure two pulses, signal light is spectrally resolved in both arms and two traces are generated in each measurement, one trace for each arm. In the PG geometry, the two unknown pulses gate each other in a $\chi^{(3)}$ nonlinear medium (fused silica in our setup). It requires that each pulse passes through a pair of crossed polarizers (see Fig. 1). The polarizations of the pulse pair are set 45° relative to each other, for example with pulse 1 at 0° and pulse 2 at 45°. It is well known that, when two pulses with 45° relative polarization interact in a $\chi^{(3)}$ medium, each induces birefringence by the third-order nonlinear polarization and so will cause polarization rotation in the other. The pulses with rotated polarization then pass through the crossed polarizer pairs and are spectrally resolved to generate the FROG traces. Single-shot operation is achieved by crossing them at an angle, which maps the delay between the two pulses onto transverse position in the nonlinear medium.

Implementation of DB FROG in the PG geometry inherits the advantages of standard PG FROG. The most important one is that the third-order nonlinear-optical process involved in polarization rotation is always phase-matched for pulses with any wavelengths, bandwidths, and crossing angles. This can be seen from the nonlinear polarizations, P_i^{NL}, given by

$$P_1^{\mathrm{NL}} \propto \chi^{(3)} E_2 E_2^* E_1, \tag{1}$$

$$P_2^{\mathrm{NL}} \propto \chi^{(3)} E_1 E_1^* E_2, \tag{2}$$

where E_1 and E_2 are the electric fields of pulse 1 and pulse 2 respectively, and $*$ denotes the complex conjugate. We observe that P_1^{NL} is proportional to $|E_2|^2 E_1$, which implies that the k-vectors from E_2 (the gate for E_1) will always cancel

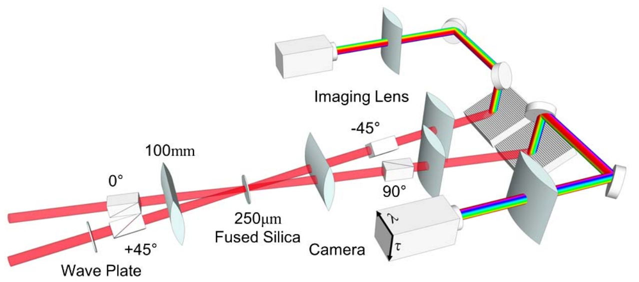

Fig. 1. (Color online) Schematic of single-shot DB PG FROG for measuring an unknown pulse pair.

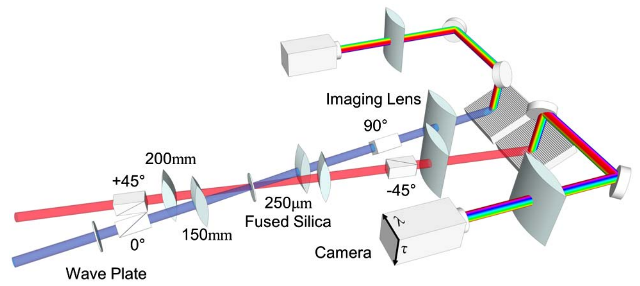

Fig. 3. (Color online) Schematic of single-shot DB PG FROG for measuring an unknown pulse pair at different wavelengths (400 and 800 nm in our experiment).

out, guaranteeing phase-matching. The same analysis applied to P_2^{NL} yields the same result. This convenient property of the PG geometry holds for beams of any color and bandwidth, allowing DB PG FROG to measure a pulse pair with very different center wavelengths and extremely large bandwidths.

On the other hand, the PG geometry requires high-quality polarizers with extinction coefficients no less than 10^5. Fortunately, commercially available laser-grade calcite polarizers offer sufficiently high extinction coefficients. While they are usually thick, and therefore introduce dispersion and distortion to the pulse, this is usually not a problem, and only the polarizer before the nonlinear medium needs to be considered. After the pulse is retrieved, it is easy to numerically backpropagate the pulse to eliminate the effect of the polarizer or any other optics in the beams to obtain the original input pulses. This is possible because the full intensity and phase vs. time and frequency are retrieved from a FROG or DB FROG measurement.

The measured DB FROG trace is essentially a cross-correlation FROG (XFROG) trace [14]. The DB FROG retrieval algorithm is employed to retrieve the unknown pulse pair. It is modified from the standard XFROG algorithm and runs between the two XFROG traces alternatively (see Fig. 2). In brief, the algorithm starts with random guesses for both pulses and assumes one of them is the correct gate pulse (even when is not) to retrieve the other. Once the retrieval is close to complete for the one, it switches to retrieve the other one. The cycle repeats until the retrieved traces converge to the measured ones. The convergence is defined by the "G error" (the root-mean-square difference between the measured and retrieved traces), like other FROG techniques [1]. More details of how DB FROG works and its algorithm can be found in our previous work [13].

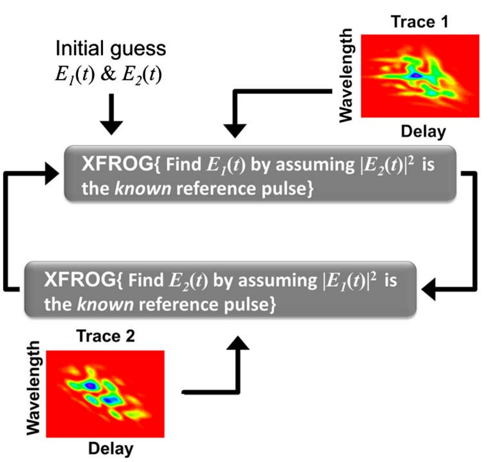

Fig. 2. (Color online) Pulse retrieval algorithm in DB PG FROG.

3. EXPERIMENTAL SETUP

We use a 70 fs pulse with center wavelength of 800 nm at a 1 kHz repetition rate from a Ti:Sapphire regenerative amplifier (Coherent Legend Elite). We use the setup depicted in Fig. 1, but modify it to measure a pulse pair at the wavelengths of 400 and 800 nm, respectively. The 400 nm pulse was generated by second harmonic generation of 800 nm using a 1 mm thick BBO crystal with type I phase matching. The beams had a diameter of 7 mm and crossed in a 250 μm fused silica window at an angle of 7° to map delay onto transverse position at the crystal and hence achieve single-shot operation by imaging the crystal onto a camera. As in our previous work, we implemented the PG geometry in our setup, in which each arm had a pair of crossed polarizers. The blue arm (400 nm) of the device used a pair of crossed polarizers at 0° and 90°, while the red arm (800 nm) used a +45° and −45° pair.

In our two-color DB PG FROG setup, instead of using a single lens to focus the beams onto the fused silica window for both arms, individual lenses for each beam were used to avoid chromatic aberration (see Fig. 3). Focusing lenses with focal lengths of 150 mm and 200 mm were used in the blue and red arms, respectively. The same focal lengths were used as the collimating lenses for the same reason. The diffraction grating in the blue arm had 1200 lines/mm and the one in the red arm had 600 lines/mm.

4. RESULTS

We first present the measurement of a pair of complex same-wavelength pulses with a time-bandwidth product (TBP) of 4 using the experimental setup shown in Fig. 1 in order to demonstrate that DB FROG can measure more complex pulses than previously considered. One of the pulses was a chirped pulse train generated by passing a pulse train generated from an etalon through a 2 cm long SF11 glass block. The other was a chirped double pulse created by passing a double pulse generated from a Michelson interferometer through a 4 cm long SF11 glass block. Both of the pulses exhibited characteristics of chirped-pulse beating. The pulses had pulse energies of 120 μJ. In our experimental setup, simple pulses like flat-phase Gaussian pulses required 50 μJ to generate a good signal to noise ratio, while more complex pulses required more energy to do so.

The resulting DB PG FROG measurements of these two pulses are shown in Figs. 4 and 5. The G-errors of both

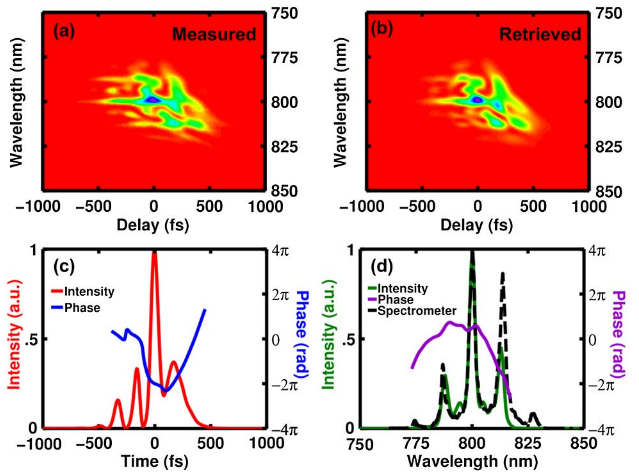

Fig. 4. (Color online) (a) Measured trace 1 for a chirped pulse train; (b) Retrieved trace 1 with a FROG error of 0.81%; (c) Retrieved pulse intensity and phase in temporal domain showing structures from chirped pulse beating; (d) The measured spectrum and the spectral phase compared with measurement made by a spectrometer.

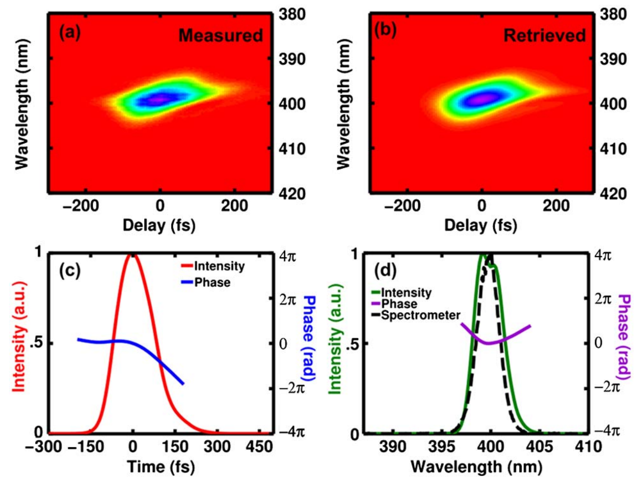

Fig. 6. (Color online) (a) Measured trace for a simple pulse at 400 nm; (b) Retrieved trace with a FROG error of 0.32%; (c) Retrieved pulse intensity and phase in temporal domain showing structures from chirped pulse beating; (d) The measured spectrum and the spectral phase compared with measurement made by a spectrometer.

arms were about 0.8% for the 512×512 arrays. Distortion in the temporal domain is observed in both arms, a clear indication of chirped-pulse beating, as expected. Independent measurements of the spectrum made with a spectrometer (Ocean Optics, Model HR-4000) for both arms are plotted as black dashed lines. The spectral peak locations match very well between the DB PG FROG and spectrometer measurements. The good agreement between the spectra and our knowledge of the pulse characteristics based on its generation apparatus confirm that our retrieved pulses are correct.

We then switched the experimental setup to the one shown in Fig. 3 for a two-color measurement. A pair of simple pulses with center wavelengths of 400 and 800 nm were used to test the setup. The red pulse was not compressed to its shortest possible pulse width in this case and instead allowed to remain chirped. This is because we used pre-chirping of the 800 nm pulse to improve the SHG efficiency. The pulse energies used were 105 μJ for the blue and 70 μJ for the red. The measured and retrieved DB PG FROG traces are shown in Figs. 6 and 7. The G errors were 0.32% and 0.30% for the blue and red pulses, respectively.

Independent measurements made by GRENOUILLE (Swamp Optics, Model 8–50), plotted in black dashed lines, show excellent agreement with the intensity and phase retrieved from DB PG FROG. The temporal full width at half maxima of the 800 nm pulse were 73.2 and 73.5 fs, as measured by GRENOUILLE and DB PG FROG, respectively. The spectrum at 400 nm, measured by the spectrometer, also agrees well with the spectral intensity retrieved by the DB PG FROG. Both pulses in this measurement have TBPs of about 1.1.

Next, we generated a well-separated double pulse at 800 nm using a Michelson interferometer and allowed the 400 nm pulse to remain simple. The DB PG FROG measurement is shown in Figs. 8 and 9. The G errors were 0.83% for the blue pulse and 0.52% for the red one. Independent measurements of the spectrum were made for both pulses shown in

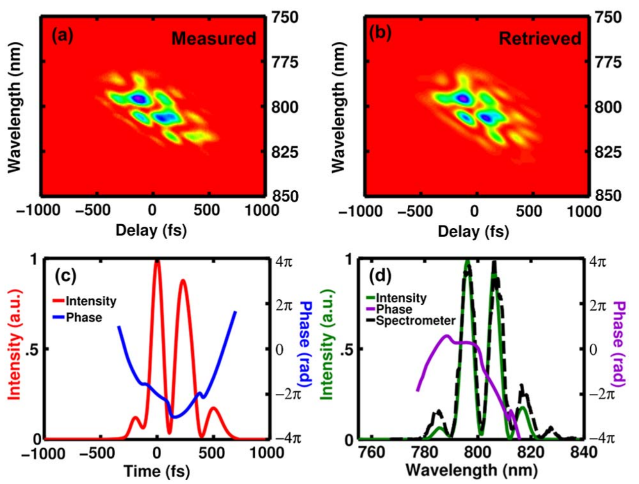

Fig. 5. (Color online) (a) Measured trace 2 for a chirped double pulse; (b) Retrieved trace 2 with a FROG error of 0.74%; (c) Retrieved pulse intensity and phase in temporal domain showing structures from chirped pulse beating; (d) The measured spectrum and the spectral phase compared with measurement made by a spectrometer.

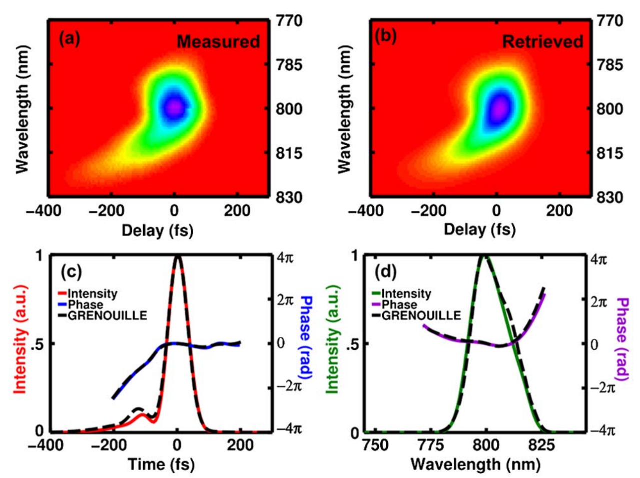

Fig. 7. (Color online) (a) Measured trace for a simple pulse at 800 nm; (b) Retrieved trace with a FROG error of 0.30%; (c) Retrieved pulse intensity and phase in time compared with an independent GRENOUILLE measurement; (d) The measured spectrum and the spectral phase compared with those made using a GRENOUILLE.

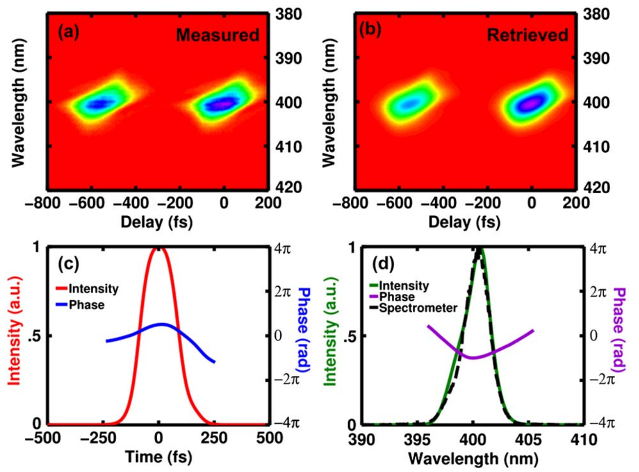

Fig. 8. (Color online) (a) Measured DB PG FROG trace for a simple pulse at 400 nm; (b) Retrieved trace with a FROG error of 0.83%; (c) Retrieved pulse intensity and phase in temporal domain; (d) The measured spectrum and the spectral phase compared with a measurement made by a spectrometer.

black-dashed line. The fringes in the 800 nm pulse spectrum measured by a spectrometer and DB PG FROG overlap very well. The measured average fringe separation in the 800 nm pulse measured by the spectrometer and DB PG FROG were 3.82 and 3.91 nm, respectively. Since the spectral fringes are created by a double pulse, the pulse separation can be easily calculated from the fringes spacing with known center wavelength. Using the average fringe spacing measured by the spectrometer, the calculated pulse separation was 558 fs. The pulse separation retrieved by DB PG FROG was 547 fs, consistent with our calculation. The TBP of the well-separated double pulse at 800 nm was about 6.2 and that of the simple pulse at 400 nm was about 1.1.

5. DISCUSSION

Our results confirm the ability of DB PG FROG to fairly accurately measure even complex and/or very-different-color pulses. Not every detail in every pulse achieved perfect agreement with the independently measured quantities by the GRENOUILLE or the spectrometer, but laser amplifier systems are unstable and experience shot-to-shot fluctuations and long-term drifts. Specifically, even though the fringe separation was consistent from shot to shot, the envelope of the spectrum tended to vary. Figure 10 shows four spectra measured within a short period of time. Fluctuations were observed, indicating slight instability of our laser amplifier system. Because simultaneous measurements of the same pulse by DB PG FROG and also by a spectrometer or GRENOUILLE are difficult, we did not attempt to do so, which could be responsible for the observed minor discrepancies, such as why the fringe separation in Fig. 9 matches well, but some of the peaks have different intensity.

In addition to the drift of the laser system, the imperfect spatial profile of our beam, especially the 400 nm beam, may contribute to the discrepancy. The measurement made by the spectrometer only samples a small portion of the beam and thus the spatial profile-effect is not prominent.

Another possible reason for the noticeable discrepancies is that higher frequency fringes were observed in the measured traces but not in the retrieved ones. One of measured traces with higher frequency fringes is shown in Fig. 11. The average fringe spacings were found to be 0.21 and 0.80 nm for the 400 nm arm and 800 nm arm, respectively. We believe the higher frequency fringes are the result of multiple reflections from the 250 μm fused silica window. The fringes generated at wavelength, λ, from a window with thickness, L, and refractive index $n(\lambda)$ can be calculated by Eq. 3:

$$\Delta\lambda = \left|\frac{\lambda^2}{2n(\lambda)L}\right|. \tag{3}$$

Our calculation shows that the fringe spacings due to the fused silica window were 0.20 nm at 400 nm and 0.83 nm at 800 nm. The results are consistent (within 5%) with the average fringe spacings measured from the traces. We would like to point out that, despite the presence of the non-pulse-related (and hence unphysical) higher frequency fringes, the retrieval algorithm is able to retrieve the pulse and essentially ignore

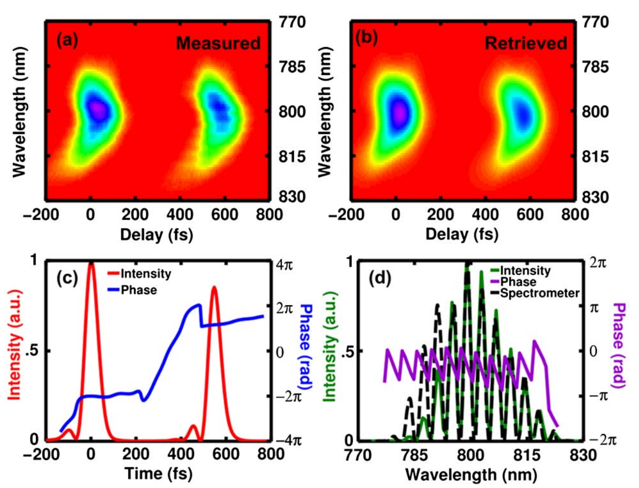

Fig. 9. (Color online) (a) Measured DB PG FROG trace for a well separated double pulse at 800 nm; (b) Retrieved trace with a FROG error of 0.52%; (c) Retrieved pulse intensity and phase in temporal domain; (d) The measured spectrum and the spectral phase compared with a measurement made by a spectrometer.

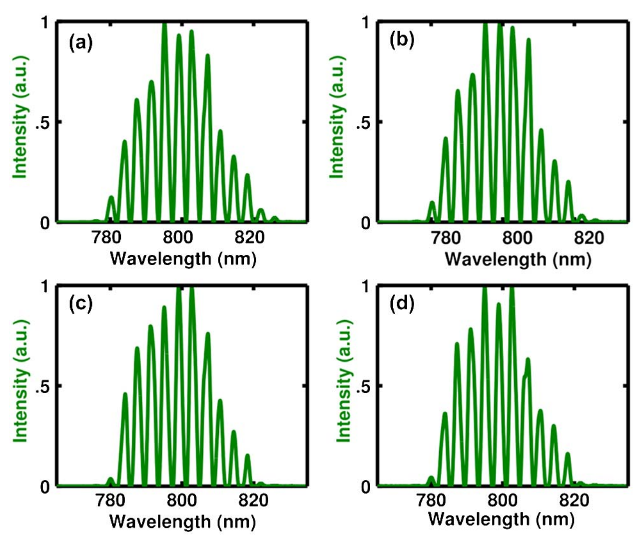

Fig. 10. (Color online) Four spectra of the same pulse measured at different times. The spectra have same fringes separation but a slightly different envelope.

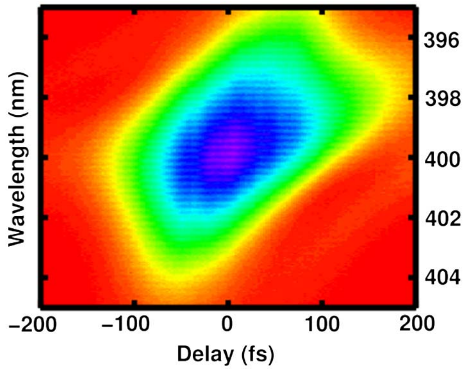

Fig. 11. (Color online) Higher resolution plot of the DB PG FROG trace captured in the 400 nm arm showing the higher frequency fringe artifact due to etalon effects in the nonlinear medium.

them. Thus, the retrieved traces are free of the higher frequency fringes, and the retrieved pulses do not suffer any ill effects from their presence. So we have not attempted to remove them, although future experiments could use an anti-reflection-coated nonlinear medium if the reduced damage threshold that results is acceptable.

6. CONCLUSION

We have demonstrated the use of DB PG FROG to measure a more complex pulse pair, both with TBPs of about 4. We have also demonstrated its ability to measure two unknown different-color pulses with center wavelengths of 400 and 800 nm. We find the retrieval algorithm to be robust and able to ignore unphysical distortions of the trace and still return the correct pulses. The unlimited bandwidth of DB PG FROG should make it extremely versatile in single-shot pulse measurements. In future work, we will measure even more complex pulse with broader bandwidths and higher TBPs.

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