The Measurement of Ultrashort Laser Pulses

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Abstract

We review the state of the art of ultrashort-laser-pulse measurement. One such set of techniques (and the first) is the well-known class of frequency-resolved-optical-gating (FROG) techniques, which can measure the intensity and phase vs. time (and frequency) for essentially arbitrary pulses without requiring any assumptions about the pulse. Another set includes two methods for measuring the intensity and phase vs. *time and space* of arbitrary pulses, either on a single shot or with subwavelength spatial resolution.

1. The Measurement of Light: Frontiers

Very few people realize that most great scientific discoveries are the result of advances in the *measurement of light*. But consider these developments: Nineteenth-century spectrometers revealed atoms' discrete spectra and led to quantum mechanics. The Michelson interferometer's optical-phase measurements laid the groundwork for special relativity. Microscopes have given us biology, and telescopes astronomy. Indeed, our most important source of information about our universe is light, and our ability to extract information from it is limited only by our ability to measure it.

At the same time, light is also a powerful practical tool in our kit of phenomena for the development of new life-enhancing and life-saving technologies, from medical diagnostics to telecommunications to next-generation computing to navigation (GPS). Again, our ability to utilize this wonderful tool is limited only by our ability to measure it.

So what advances in light-measurement technology would most likely lead to important new discoveries and technologies? Alas, simple short pulses of narrow-band (single-color) light are rare in our universe—or physically impossible, prohibited by the uncertainty principle. Thus, new light-measurement techniques must measure long pulses of broadband light, which necessarily involve ultrafast variations in intensity, which occur on timescales of less than 0.000000000001 seconds! Such light pulses are also necessarily extremely complex.

To further complicate matters, the intensity vs. time is only half the information in a light wave. The other half is light's phase, or color, variation in time. They occur on the same ultrafast timescale and so are also necessarily complex.

In addition, as most objects in our universe are also complex in *space*, so is any light emitted by them. Indeed, it's light's temporal *and* spatial complexity in both its intensity and phase that contains the vast amount of information present in essentially everything in our highly complex universe. And as we seek to understand ever more complex systems, we will need to be able to measure ever more complex light waves.

Finally, the resulting devices should also be simple—not so complex that they're more likely to introduce a distortion than to measure it!

As a result, we have been developing simple, elegant techniques for measuring, ever more completely, light with ever more complex, ultrafast variations in time and ever more complex, submicron details in space.

2. The Temporal Challenge and Its Solution: FROG

The challenge in measuring ultrafast light is that it contains intensity variations on time scales shorter than the shortest events ever generated. So there is rarely a shorter event available with which to measure it. As a result, we begin with the simplest such light: ultrashort laser pulses, which are simple in shape, e.g., Gaussian in time, and with a nearly flat temporal phase.

Introduced in 1991, the first technique for measuring the intensity and phase of such an ultrashort pulse without assumptions was frequency-resolved optical gating (FROG) [1], shown in Fig. 1.

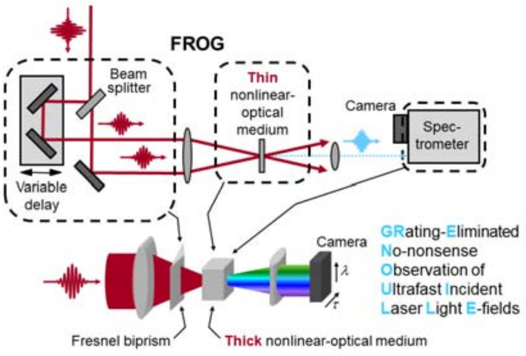

Fig. 1. FROG and its simpler, more robust, and elegant version, GRENOUILLE.

FROG (and GRENOUILLE) generate spectrograms of the light wave, in which a pulse gates another pulse, and the gated pulse spectrum is measured vs. delay. It can be shown that a light pulse can even gate itself, and, in all such cases, the resulting trace yields the pulse's complete intensity and phase vs. time. Figure 2 shows an example of a FROG measurement of a somewhat complex "continuum" pulse.[2]

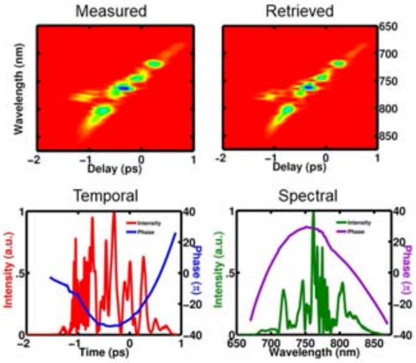

Fig. 2. Measured FROG trace and the corresponding intensity and phase vs. time and frequency. The "retrieved" trace is that computed from the retrieved pulse, and it should agree with the measured trace. Otherwise, we can infer that the measured pulse train is unstable (see Fig. 3).

It is not enough for a pulse-measurement technique to be able to make such measurements. It must also be able to tell when it *cannot* make them, for example, when it averages over many different pulse shapes, and no one shape can be correct. This type of instability is very common in ultrafast-optics labs, and is difficult to detect; no "pulse-shape stability meter" exists. So this task necessarily falls to the pulse-measurement technique. We have studied FROG and an alternative method, called SPIDER, yields extremely short pulses, independent of the pulse complexity and instability. FROG, on the other hand, exhibits discrepancies between measured and retrieved traces when pulse-shape instability is present.[3-4]

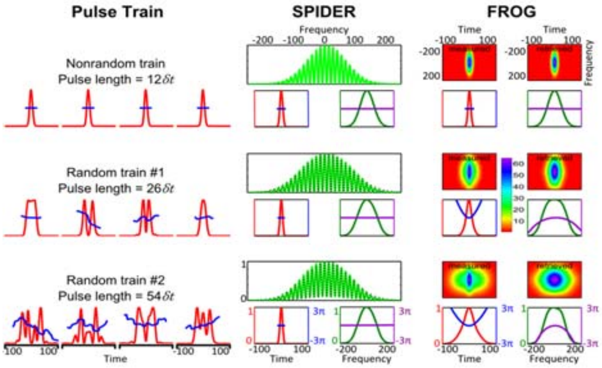

Fig. 3. Nonrandom- and random-pulse trains of varying complexity, and simulated multi-shot SPIDER (an alternative pulse-measurement technique) and FROG measurements of them. Note that SPIDER can measure the nonrandom pulse train, but vastly under-estimates the pulse length and complexity for random pulse trains. The same is true for random double-pulsing and also variable amounts of chirp (frequency sweeps), which are also very common in ultrafast-optics labs.

3. The Spatiotemporal Challenge and Its Solution: STRIPED FISH

Once FROG measures a pulse with smooth spatial profile, this pulse can be used as a reference pulse to measure another pulse vs. time and space. This can be accomplished using two difference techniques, one called SEA TADPOLE, which can measure pulses with submicron spatial resolution and sub-fs temporal resolution, averaging over many pulses. Another method, called STRIPED FISH cannot achieve submicron spatial resolution, but it can operate single-shot.[6-8]

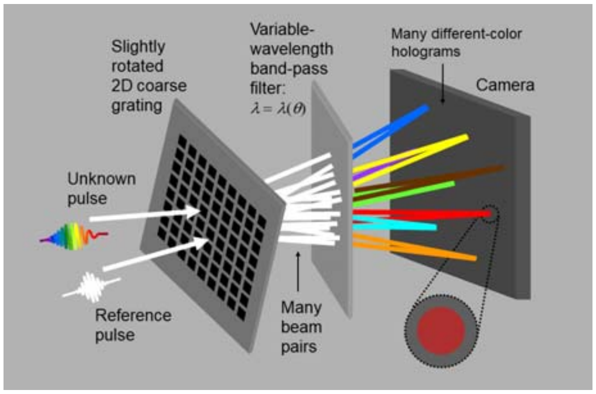

Fig. 4. STRIPED FISH technique for measuring an arbitrary ultrashort pulse on a single shot. Multiple holograms are generated, each at a different wavelength. Each hologram yields the spatial intensity and phase of the pulse at that frequency. Their sum, coupled with the knowledge of the reference pulse yields the complete spatiotemporal intensity and phase of an arbitrary unknown pulse without assumptions.

Figure 5 shows some complex pulses emerging from a multi-mode fiber, measured using STRIPED FISH.

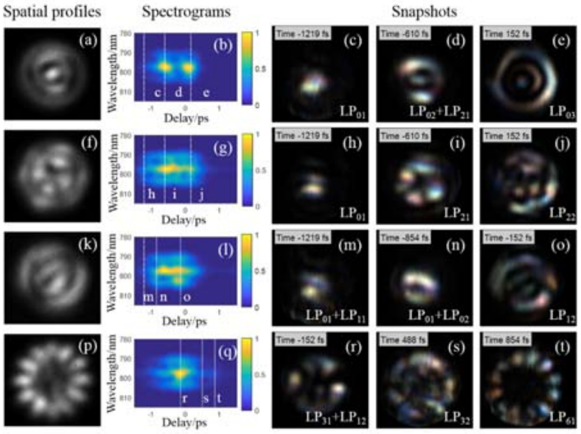

Fig. 5. Measured results of multi-mode fiber output pulses for four different fiber coupling situations. The left column shows the time-averaged measured pulses. The next column shows spectrograms of the pulses, averaged over space. Finally, the rightmost three columns show the pulse intensity and phase (using color for the frequency, as would be seen by the human eye) for different times.[8]

The pulses shown in Fig. 5 are plotted using color for the actual color as would be seen by the human eye (computed by computing spectrograms for the pulse at every time). Also, the intensity shown indicates the pulse intensity.

STRIPED FISH also operates in a multi-shot version, using multiple delays in order to achieve a longer temporal range. While single-shot measurements have ben made of pulses emerging from multi-mode fiber, this multi-shot version was used to measure the more complex pulses shown in Fig. 5.

4. Conclusions

It is now possible to measure essentially arbitrary ultrashort pulses in space and time without the need to make assumptions about the pulses. Pulses with time-bandwidth products as large as 65,000 have been measured in time. And pulses with space-time-bandwidth products of similar values have been measured. While applications exist for light pulses with even greater complexities, these numbers make a wide range of otherwise impossible measurements possible. If history is a valid predictor of such results, it will be interesting to see what breakthroughs may occur as a result.

5. Acknowledgements

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6. References

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