Swamp Optics, LLC:

Everything You've Always Wanted to Know About Ultrashort Pulses, But Were Afraid to Ask

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In order to measure an event in time, you need a shorter one. So how do you measure the *shortest* one? This dilemma initiated a scientific odyssey that culminated in the founding of Swamp Optics.

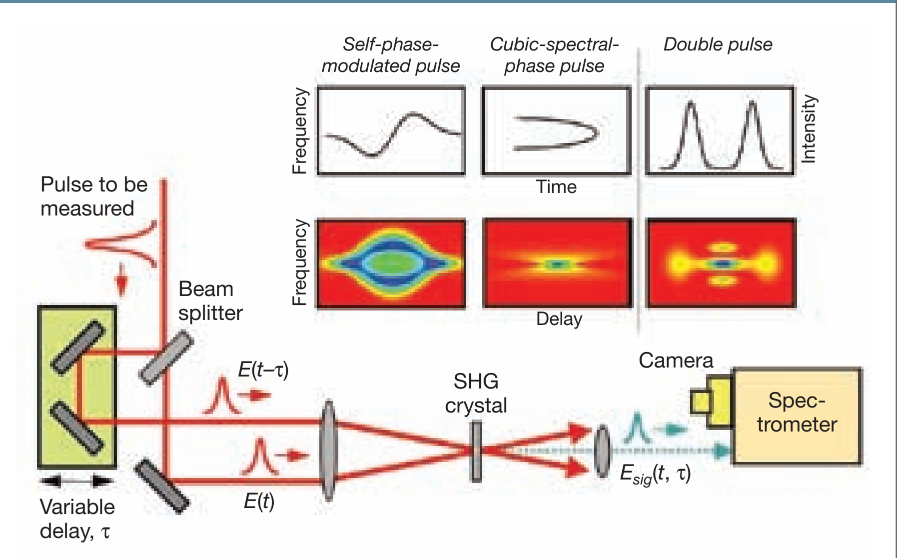
The shortest events ever created are ultrashort laser pulses. The results of experiments and applications using them depend sensitively on their properties, so a technique for measuring them is crucial. In the 1960s, researchers realized that the best they could hope to do was to use the event to measure itself and so introduced a technique called autocorrelation based on this approach.

But the pulse is only *as short as* itself; it's not *shorter*. As a result, autocorrelation smears out most of the structure in the pulse intensity vs. time and only gives a rough estimate of the pulse width. In fact, more complex, highly structured pulses actually yield simpler, smoother autocorrelations. Any attempt to retrieve the pulse's intensity vs. time from its autocorrelation is equivalent to the well-known but ill-posed one-dimensional phase-retrieval problem.

To determine the pulse's width, it's necessary to assume—with no justification—a pulse shape. And it unfortunately became customary to choose a hyperbolic-secant-squared pulse shape, mostly because it yields shorter pulses than, say, a Gaussian shape. Everyone wanted to claim the shortest pulse.

In 1991, Dan Kane and I realized that a spectrally resolved autocorrelation could do much better. With the proper inversion algorithm, it yields the complete intensity vs. time with no need to assume anything about the pulse. It also yields the phase (color) vs. time, about which autocorrelation says nothing (an interferometric version of autocorrelation yields some phase information, but little more than that contained in the spectrum). Thus, while autocorrelation yielded a fuzzy, low-def, black-and-white picture of the pulse, we could now obtain a sharp, high-def, full-color image of it.

[Frequency-Resolved Optical Gating (FROG)]



FROG: a spectrally resolved autocorrelation. Two pulse replicas cross in a second-harmonic (SH) generation or other nonlinear medium, and the SH spectrum is measured vs. the pulse relative delay. FROG yields the pulse intensity and phase vs. time (and frequency). Upper right: FROG traces (below) for some pulses (above).

Kissing the FROG

To meet *Optics Letters'* do-or-die three-page limit, our technique needed a name with a simple abbreviation, so we chose a cute one: Frequency-Resolved Optical Gating—FROG.

Retrieving the pulse's intensity and phase in FROG is equivalent to an essentially well-posed problem called the *two-dimensional* phase-retrieval problem. Phase-retrieval problems of various dimensions have been studied by image scientists, who found that certain imaging techniques work because they are 2D, not 1D. Another way to look at FROG is that it's a spectrogram of the pulse, with both temporal and spectral resolution, which circumvents the need for the shorter event—the spectral domain yields the fine temporal resolution.

With the help of brilliant post-docs Ken DeLong and David Fittinghoff, we showed that FROG works beautifully. It can reliably measure pulses of any wavelength, pulse width, rep rate or complexity. It operates multi-shot or single-shot. It has measured few-cycle near-IR pulses, attosecond XUV pulses, and the most complex pulse ever measured. And, unlike autocorrelation, FROG has built-in feedback that confirms the measurement.

> Someone asked me what SWAMP stood for. Of course, it stood for nothing, but I thought for a moment and came up with: "Simply Wonderful Apparatus for Measuring Pulses."

Interestingly, pulses measured with FROG almost always turn out to be longer than they are when measured using an autocorrelator because pulses rarely have the hyperbolic-secant-squared shape. Also, FROG reveals a never-before-seen intensity structure and variations in the color vs. time.

We also developed a simplified version of FROG, which we called GRENOUILLE (French for "frog"). And with my superb grad student Selcuk Akturk, we showed that it also measures two key spatio-temporal distortions—spatial chirp and pulse-front tilt. It's important to measure these distortions because they lengthen pulses and distort experiments, and we soon discovered them in most of the pulses we measured.

By the mid-1990s, many researchers had built FROGs, and many achieved results that had never before been imagined. FROG became the gold standard of pulse measurement.

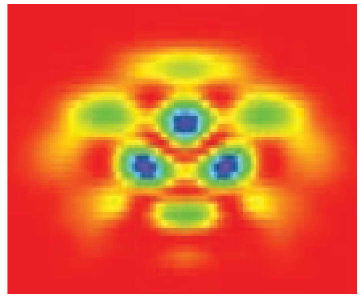
Into the Swamp

In 2001, with my university's encouragement, and with a wonderful engineer (Mark Kimmel), I formed a company to sell FROGs, GRENOUILLEs and other pulse-measurement devices with equally colorful amphibious names, such as TADPOLE and POLLIWOG. Mark's wife Carolyn became our manufacturing department, and my wife Linda provided administrative support. Dan and Ken formed companies to sell elegant and fast software to accompany our devices. We designed a cute logo, and because frogs live in swamps, we called ourselves Swamp Optics.

For funding, Linda found credit cards with teaser interest rates of 0 percent. Several withdrawals later, I was $130,000 in debt, and Swamp Optics was off and running—or, should I say, swimming.

Mark designed and built very nice, compact, elegant, alignment-free devices, and we included infinite free consulting on pulse measurement with every device. *R&D Magazine* declared GRENOUILLE one of the top 100 inventions of the year, and *Photonics Spectra* named it one of the top 25. Researchers responded by buying hundreds of FROGs and GRENOUILLEs, and we paid off the credit cards without paying a single penny of interest.

But obsolete technologies rarely die quietly. Hold-outs, for reasons of their own, refuse to move on. (Some people still prefer records over CDs.) Those who cling to autocorrelation occasionally succeed in publishing a paper reporting a pulse that they feel is better measured using that technique—but ignoring the infinitely many others that are not. Also, the big advantage of FROG—and, as it turns out, also its big disadvantage—is that it reveals pulses' flaws and true widths.



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Autocorrelation, on the other hand, hides their blemishes, transforming ugly, froglike pulses into much more princely looking ones. And in a field where flawless and thinner are always preferred (not unlike Hollywood), FROG might not help to *sell* ultrafast lasers. Indeed, one high-ranking laser-company manager declined to sell FROGs with his lasers, unashamedly proclaiming, "We don't want our customers knowing that much about their pulses."

A Kafkaesque situation, to say the least. We explained that better measurement would, in the long run, benefit everyone—especially his company, whose pulses were actually quite short and structureless. However, to this day, the company sells autocorrelators and not FROGs.

Most laser companies now use FROGs to develop ultrafast lasers, but only a few actually report FROG measurements of their pulses. Others admit, "We're not ready to do that yet."

The next Swamp thing

With GRENOUILLE's new measurement capabilities, we noticed that the main cause of spatio-temporal distortions in ultrashort pulses is the ubiquitous pulse compressor. Because redder colors travel faster than bluer ones in materials (an effect called group delay dispersion), pulses lengthen as they propagate, and the pulse compressor compensates for this. It's a sequence of four prisms, in which redder colors pass through the bases of the second and third prisms, allowing bluer colors, which pass through their tips, to catch up. It can be simplified to two prisms and a roof mirror, but it's still not that simple.

Unfortunately, if the prism incidence angles aren't all precisely equal, the output pulse will have angular dispersion, spatial chirp and pulse-front tilt. And pulses with these distortions are always *longer* than those without them.

So we invented an improved version of the already well-accepted prism pulse compressor. Ours has only one prism, so it's more compact, less expensive and easier to use. It's also inherently distortion-free and so generally compresses pulses to shorter lengths than do currently available prism pulse compressors.

Of course, our pulse compressor isn't quite as revolutionary as the FROG. On the other hand, it'll make pulses *shorter*, so we're hoping everyone will like it. Perhaps users might also wish to *measure* precisely how short and distortion-free their resulting pulses are.

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[References and Resources]

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