

# Crossed-beam spectral interferometry: a simple, high-spectral-resolution method for completely characterizing complex ultrashort pulses in real time

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**Abstract:** We present a high-spectral-resolution and experimentally simple version of spectral interferometry using optical fibers and crossed beams, which we call SEA TADPOLE. Rather than using collinear unknown and reference pulses separated in time to yield spectral fringes—and reduced spectral resolution—as in current versions, we use time-coincident pulses crossed at a small angle to generate *spatial* fringes. This allows the extraction of the spectral phase with the full spectrometer resolution, which allows the measurement of much longer and more complex pulses. In fact, SEA TADPOLE achieves spectral *super-resolution*, yielding the pulse spectrum with even better resolution. Avoiding collinear beams and using fiber coupling also vastly simplify alignment. We demonstrate SEA TADPOLE by measuring a chirped pulse, a double pulse separated by 14 ps, and a complex pulse comprising two trains of pulses with a time-bandwidth product of  $\sim 400$ .

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OCIS codes: (320.7100) Ultrafast Measurements; (260.5540) Interference

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## 1. Introduction

In principle, spectral interferometry (SI) is a simple linear technique for measuring the spectral-phase difference between two light waves [1]. It involves simply measuring the spectrum of the sum of the two pulses. If a known reference pulse whose spectrum contains that of the unknown pulse is available, SI can be used to completely characterize the unknown pulse [2, 3]. SI is very sensitive and has been used to measure trains of pulses as weak as 42 zeptojoules [2]. Also, its phase-retrieval algorithms are direct and quick.

Unfortunately, SI has some serious limitations. Fourier-transform spectral interferometry (FTSI), the most reliable algorithm available to retrieve the phase information from the SI spectrum [1], has limited spectral resolution. It requires separating the reference and unknown pulses in time by more than their respective pulse lengths, in order to yield spectral fringes, and then Fourier-filtering out the dc term (the two spectra) and one of the interference terms from the fringes in the measured SI spectrum. Because the spectral resolution required in this approach is the reciprocal of the maximum temporal extent of the waveform (the two pulse lengths plus the time between them), the required spectral resolution is typically about a factor of five better than that required to measure only the unknown pulse spectrum (in the absence of the reference pulse). As a result, the spectral phase is found with only a fraction (usually about one fifth) of the available spectral resolution. This severely limits the length of the pulses that can be measured with SI. And, in practice, SI has never, to our knowledge, measured a pulse longer than a few hundred fs.

Also, while simple in principle, in practice SI has a rather unwieldy experimental setup. It comprises a Michelson or Mach-Zehnder interferometer, variable-delay line, and a spectrometer that the two pulses must enter perfectly collinearly. The spatial modes of the interfering beams must also be identical and the device mechanically very stable. These complexities and constraints have prevented the spectral interferometer from becoming a practical device.

As a result, SI is not usually used for perhaps its most obvious potential application: measuring *shaped* pulses. In pulse shaping, an appropriate reference pulse is always available in the form of the unshaped pulse, whose spectrum always contains that of the shaped pulse. Also SI's very fast direct inversion algorithm could be very useful in pulse-shaping, where it is common to use feedback loops in which a pulse is repeatedly shaped and measured until the desired intensity and phase are achieved [4-6]. Unfortunately, current implementations of SI lack the spectral resolution (shaped pulses are often several ps long) and are far too alignment sensitive for practical use, except by highly skilled individuals willing to spend the time realigning the device frequently.

While frequency-resolved optical gating (FROG) is easier to work with and has been used for this application [4, 7], SI would be faster. Spectral phase interferometry for direct electric-field reconstruction (SPIDER) [8] is in principle faster, but it is experimentally very complex, and its most reliable retrieval algorithm is also FTSI (SPIDER is a nonlinear form of SI) which results in a similar loss of spectral resolution. As a result, SPIDER cannot measure relatively long (> few hundred fs) shaped pulses. Furthermore, the accuracy of SPIDER, in general, was recently shown to be critically dependent on extremely accurately measuring and maintaining its internal double-pulse separation parameter [9], rendering it unlikely to ever be able to accurately measure the quadratic phase (the most important phase term), and hence the length, of any pulse.

SI, on the other hand, could, in principle, be preferred, especially for shaped pulses, as it is linear and hence much more sensitive, and the reference pulse required for it is always available in pulse-shaping applications. High-resolution SI techniques have been introduced [3, 10], but only at a cost of adding even more complexity to the experimental setup and using multi-shot algorithms.

In this paper, we introduce a version of SI that is simultaneously experimentally very simple and high-spectral resolution. It has a quick, direct inversion algorithm, and it measures the spectral phase with the full resolution of the spectrometer. In fact, our inversion technique actually achieves *better* spectral resolution than that of the spectrometer involved. Even more importantly, it is also very easy to align. We believe that this is the first practical implementation of SI and that it will be especially useful in pulse shaping. Indeed, we demonstrate its use for measuring extremely complex pulses.

In our method, we combine the two pulses using two short, equal-length optical fibers. We then cross the two beams emerging from the fibers at a small angle, yielding spatial fringes along the vertical axis, and we spectrally resolve the light along the horizontal axis. This results in a measured two-dimensional trace,  $S(\omega, x)$ . Unlike traditional SI, our method involves overlapping the pulses in time, and we deliberately avoid generating spectral fringes (by having zero delay between the two pulses). SI techniques using spatial fringes due to crossed beams have been used in the past, but in all of these techniques either the phase was not retrieved or complicated curve fitting methods were used [11-13]. To retrieve the phase from  $S(\omega, x)$ , we instead use an algorithm that Fourier-filters the trace in the spatial coordinate, rather than the spectral coordinate, to remove the dc component and one of the interference terms [14]. In view of previous work using such a spatially encoded arrangement (SEA) and also work using the combination of SI and FROG to measure the reference pulse (called TADPOLE), we call our technique SEA TADPOLE, or Spatial Encoded Arrangement for Temporal Analysis by Dispersing a Pair of Light E-fields [2, 14]. Of course, a FROG measurement of the reference pulse is not necessary if only the spectral-phase difference between the two pulses is desired.

## 2. Details of the method

If two temporally overlapping, spatially uniform light pulses cross at a small angle at the entrance slit of an imaging spectrometer, the intensity at the exit is given by:

$$S(\omega, x) = S_{ref}(\omega) + S_{unk}(\omega) + 2\sqrt{S_{ref}(\omega)}\sqrt{S_{unk}(\omega)} \cos(2kx \sin \theta + \varphi_{unk}(\omega) - \varphi_{ref}(\omega)) \quad (1)$$

where  $\theta$  is half the crossing angle.

This is similar to the trace measured in traditional SI, except that the light is both spectrally and spatially resolved, and there is a linear term in the position,  $x$ , (rather than in  $\omega$ ) in the argument of the cosine. A simple one-dimensional Fourier transform of the expression

in Eq. (1) with respect to  $x$  then isolates the phase-containing term from the rest of the information without reducing the spectral resolution. Figure 1 illustrates the phase retrieval process.

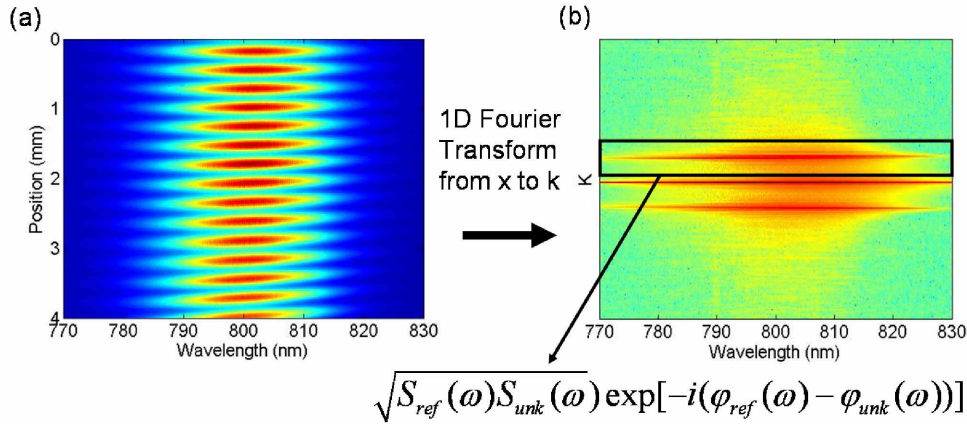


Fig. 1. Phase retrieval in SEA TADPOLE: (a) A typical experimental SEA TADPOLE trace. (b) A 1D-FT of the interferogram with respect to position (showing only the magnitude of the complex data). The side-bands are the interference terms. The phase of either of the side-bands yields the spectral-phase difference between the signal and reference pulses.

To achieve such a trace in an experimentally simple manner, we couple the reference and signal pulses separately into short, equal-length, single-mode fibers. See Fig. 2. One fiber output is slightly above the optic axis and the other is slightly below it. A spherical lens collimates both beams and crosses them in the vertical plane at a small angle ( $2\theta$ ). The beams overlap and yield horizontal fringes at a camera at the exit plane of a home-made spectrometer comprising a diffraction grating and cylindrical lens. The spectrometer spectrally resolves the light horizontally, and the camera records the 2D SEA TADPOLE trace. Overfilling the camera in the vertical dimension as we have done in figure 1a has no effect on the frequency axis and therefore causes no error in the pulse retrieval even though we Fourier transform in that dimension.

Using such an arrangement, the sign of the phase difference that we obtain from one of the interference terms is known, because we know which beam travels upward and which travels downward where the beams cross. Therefore, there is no direction-of-time ambiguity in the processed data in SEA TADPOLE.

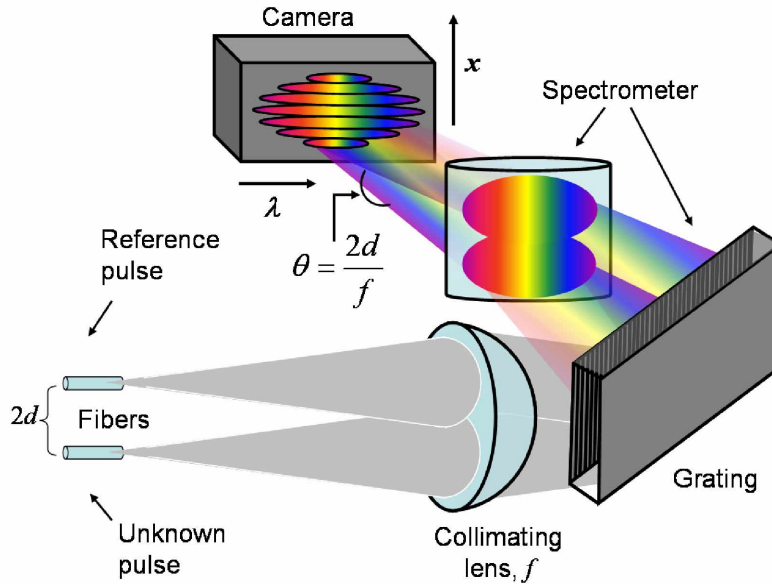


Fig. 2. Experimental setup for SEA TADPOLE: The reference and unknown pulses enter the device via equal-length, single-mode optical fibers. In the horizontal dimension, the light is collimated and then spectrally resolved at the camera using the grating and the cylindrical lens. In the vertical dimension, the light emerging from the two fibers crosses at a small angle and makes horizontal spatial fringes at the CCD camera.

### 3. Experimental results

We performed measurements to demonstrate SEA TADPOLE using a KM Labs Ti:Sa oscillator with a center frequency of 800nm. First, to test the accuracy of SEA TADPOLE, we measured the GDD of a 1.85-cm thick SF11 glass window by placing it in the unknown-pulse arm of the device so that the phase difference between the interfering pulses yields the GDD of the glass. Figure 3(a) shows the SEA TADPOLE trace obtained in this measurement. The fringes appear parabolic, because the spectral phase difference between the unknown and reference pulses is encoded in the curvature of the fringes. Figure 3b shows the retrieved spectral phase of the pulse. We found the GDD to be 1840 fs<sup>2</sup>/rad, in reasonable agreement (4% error) with the theoretical value of 1770 fs<sup>2</sup>/rad.

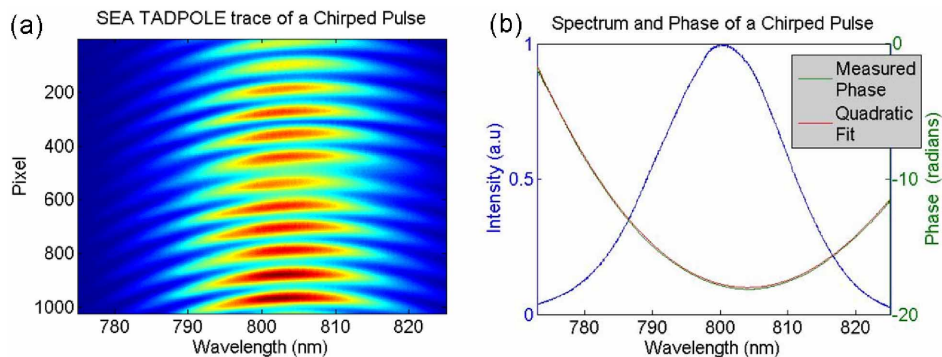


Fig. 3. (a) The SEA TADPOLE trace of a chirped pulse. (b) The retrieved spectrum and spectral phase. The red curve is a quadratic fit to the spectral phase, in close agreement with the chirp predicted by the known Sellmeier equations for SF11.

To demonstrate the high spectral resolution of our technique, we measured the spectral phase of a 14-ps double pulse (two identical pulses with 14 ps between them) generated by a Michelson interferometer. See Fig. 4. Ordinarily, SI devices lack the spectral resolution to measure such a long pulse due to the fine structure in the pulse spectrum and spectral phase. In SEA TADPOLE, however, the spectral fringes, as well as the jumps in the spectral phase, are easily seen. To confirm that our reconstructed electric field is correct we measured the ratio of the intensities of the pulses from our Michelson interferometer and found them to be 1:2, in agreement with our result shown in Fig. 4(b). We also confirmed that the pulse separation was in fact 14 ps by making an independent measurement of the spectrum, which is shown in blue in Fig. 5(a). The inserts in Fig. 4(b) show a linear temporal phase for the pulses because our spectrum was not precisely centered on the wavelength axis.

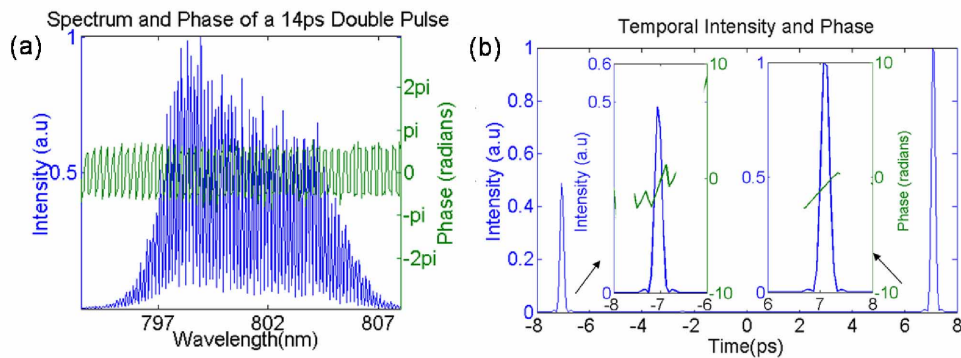


Fig. 4. The reconstructed electric field of a 14-ps double pulse generated by a Michelson interferometer: (a) Spectral intensity and phase of the double pulse. (b) Temporal intensity and phase. Inserts are expanded views of two of the pulses with their phases shown.

We also measured a very complicated pulse generated by a Michelson interferometer and an etalon to produce two trains of pulses. The intensity and phase measured by SEA TADPOLE are shown in Fig. 5, which nicely reveals the double train of pulses and shows the high complexity of the pulse, whose time-bandwidth product is  $\sim 400$ . The spectral phase shows the jumps of the double pulse and also a slower modulation, which is the phase introduced by the etalon. We used a well calibrated etalon whose reflectivity was 50% at 800 nm, and the spacing between the partial reflectors was 52  $\mu\text{m}$ , yielding a 350 fs round trip time. The intensity of the first and second reflections of the pulse in the time domain should be 25% and 6% and this is close to what our reconstructed temporal intensity in Fig. 5(b) shows.

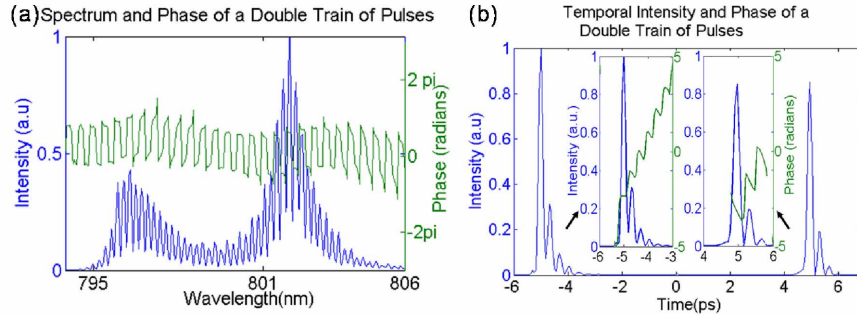


Fig. 5. The reconstructed electric field of a double train of pulses generated by a Michelson interferometer and an etalon. (a) Spectral intensity and phase. (b) Temporal intensity and phase. The time between the peaks in the train is about 350 fs, in agreement with the known thickness of the calibrated etalon used to generate the train.

Although we routinely monitor our pulses' intensity and phase using a Swamp Optics GRENOUILLE to confirm their approximately flat phase, in these experiments the key quantity was only the spectral-phase difference between the unknown and reference pulses, which was the phase introduced by the SF11 glass in the first experiment, the phase due to the double-pulse behavior in the second experiment, and the phase of the double train of pulses in the last experiment. To measure the phase of an arbitrary unknown pulse, it is, of course, necessary to use FROG to characterize the reference pulse.

In all of our measurements, we retrieved the unknown-pulse spectra from the same interference term used to obtain the spectral phase (the last term in Eq. (1)). Noting that the amplitude of this term is proportional to the geometric mean of the reference and unknown spectra, we simply squared this amplitude and divided by the spectrum of the known reference pulse. This not only worked well, but, interestingly, it achieves a type of spectral super-resolution.

Consider that, with one arm of our SEA TADPOLE device blocked, it is a simple spectrometer. Using the device in this manner, we measured spectra of the various unknown pulses, shown as the blue curves in Fig. 6. Also shown in Fig. 6 (in green) are the spectra obtained from the above SEA TADPOLE algorithm from the interference pattern. Note the significantly higher spectral resolution in the SEA TADPOLE spectra.

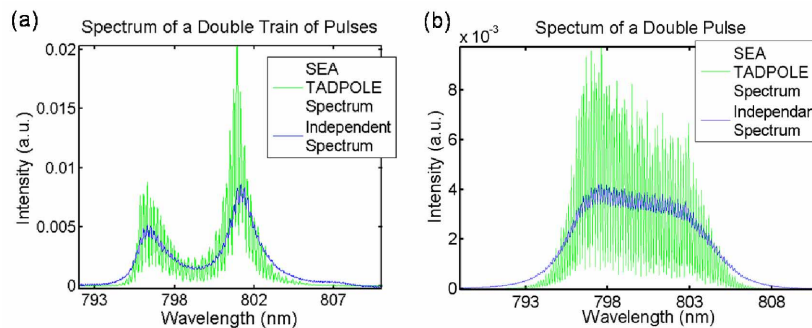


Fig. 6. The measured spectra from Figs. 4a and 5a (the green lines) reconstructed from SEA TADPOLE traces compared with independently measured spectra (the blue lines) using the same spectrometer (simply by blocking the reference beam). (a) The spectrum of the 14 ps double pulse. (b) The spectrum of the double train of pulses. Note the significantly better spectral resolution of the SEA TADPOLE-measured spectra, despite the use of the identical spectrometer for both measurements.



This improvement in resolution occurs because the SEA TADPOLE interference term yields the spectral *field* rather than the spectral intensity, as is usually the case. (It is actually a product of the reference and unknown fields, but the reference field is generally smooth and broad band so multiplying the complicated unknown field by the reference field makes almost no difference.) For simple spectra and spectral fields (e.g., Gaussians), the spectral field (in such cases, the square root of the spectrum) is broader than the spectrum itself, and so requires less resolution. For this reason we expect SEA TADPOLE to better resolve the spectrum than a spectrometer with the same spectral resolution as SEA TADPOLE. We see a second and much larger enhancement in spectral resolution, particularly, for the double pulse and the double train of pulses, because these pulses have *zero crossings* in their fields (the real part). This occurs because the convolution of an oscillatory field with the spectral response function of the spectrometer continues to possess such zeros and so maintains its spectral structure.

To illustrate the difference between resolving a potentially negative-going spectral field and the always-positive spectrum, we simulated resolving a 4-ps double-pulse spectrum and field with a Lorentzian spectral response function with a width of 0.4 nm. We used an equal-height double pulse, which has a purely real spectral field (a Gaussian times a cosine). Figure 7(a) shows the field before (blue) and after (green) it has been convolved with the Lorentzian. Figure 7(b) shows the spectra of these fields and the spectrum after it has been convolved with the same Lorentzian. These plots show that convolving the field preserves the spectral-fringe structure much better than convolving the spectrum. The price for this benefit appears to be a concurrent reduction in sensitivity and dynamic range (the fringe amplitude decreases).

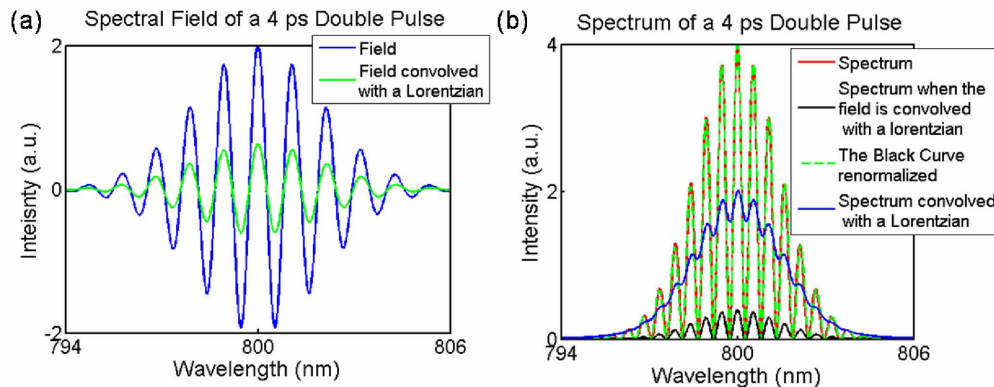


Fig. 7. Convolving the field versus convolving the spectrum when zero crossings are present in the field. (a) The field of the double pulse before (blue) and after (green) convolving it with a (0.4 nm wide) Lorentzian. (b) The precise spectrum of the field (red), the spectrum after the field has been convolved with the Lorentzian (black), the same curve, but normalized to have the same area as the red curve (green), and the spectrum convolved with the Lorentzian (blue). This shows that convolving the field preserves spectral structure better than doing so with its magnitude squared.

#### 4. Other issues and comments

There are several advantages to using optical fibers for coupling the beams into SEA TADPOLE. Because SEA TADPOLE is extremely sensitive (it is a linear-optical method), a nanojoule of pulse energy at the camera is more than sufficient for a measurement. Thus, only a small amount of a beam need be coupled into the device, so beams generally need not



be carefully focused to small spots at the fibers. Instead, loosely focused beams can overfill the input fibers, and the small cores then act as simple attenuators. As a result, once the fibers are in place with respect to the collimating and spectral-resolving optics, any walking of the beams before the fibers will only slightly vary the attenuation and not affect the alignment of SEA TADPOLE. This insensitivity to input-beam position and direction means that SEA TADPOLE can operate for extended periods without realignment. Indeed, the fibers' roles as attenuators are useful for balancing the intensities of the signal and reference pulses to optimize the fringe contrast.

To maintain identical polarizations of both pulses, polarization-maintaining fibers can be used. Alternatively, because dispersion that occurs equally to both pulses cancels out in the SEA TADPOLE trace, a polarizer can be placed at the output of the fibers.

Calibration can be necessary to account for any phase differences between the two arms of the device due to potentially different fiber lengths or any other imbalances, such as potential unequal collimations.

It is worth mentioning that optical fibers are often avoided in interferometers due to unavoidable drifts in the "constant" phase difference, which in SEA TADPOLE would cause the spatial fringes to drift slowly in time. This fringe drift is irrelevant in SEA TADPOLE because the relative phase of the reference and unknown pulses is generally uninteresting, and no particular phase difference is required. Indeed, by crossing the beams at an angle, the relative phase between the pulses is *intentionally* designed to vary by many  $\pi$  along the spatial coordinate. Of course, if this phase were to fluctuate rapidly during a measurement, undesirable fringe washout could occur, but it is straightforward to make a short-time or single-shot SEA TADPOLE measurement using a fast shutter due to the minimal pulse energy required.

Finally, it should be pointed out that SEA TADPOLE does not suffer from the extreme sensitivity with respect to the pulse separation recently shown to be a serious problem in SPIDER measurements. This is because the spectral-fringe phase in SPIDER (and SEA SPIDER) is the *derivative* of the pulse spectral phase, so that tiny changes in the pulse separation yield large errors in the important pulse *quadratic* phase. SEA TADPOLE directly yields the spectral phase (not its derivative), so any delay between the reference and unknown pulses just results in a shift in the position of the temporal intensity on the time axis. Thus it is not necessary to accurately know the pulse separation (that is, the crossing angle or the delay between the unknown and reference pulses) in SEA TADPOLE, and we have found that we were able to neglect our SEA TADPOLE device for several weeks and return to a well aligned device, with no need for re-alignment or recalibration of any kind.

## 5. Conclusions

We have introduced a new technique, which we call SEA TADPOLE, and we have shown that it can accurately determine the pulse intensity and phase, even for quite long pulses with fine spectral structure; it uses the spectrometer's full spectral resolution and even supersedes it; with our compact home-made spectrometer, it can measure pulses as long as 14 ps; and it is experimentally much simpler and more convenient than other implementations of SI. It is also computationally simple and fast, making it ideal for real-time implementation. And it can measure quite complex pulses. We believe that SEA TADPOLE will finally make SI practical and will be especially useful for measuring, confirming, and optimizing shaped pulses.

## Acknowledgments

This work was supported by an endowment provided by the Georgia Research Alliance and NSF SBIR grant #053-9595.