# The First Measurements with Octave-Spanning Femtosecond Laser Frequency Combs

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**Ultrafast meets ultrastable**

In the summer of 1998 we both began NRC postdocs at JILA, sharing an office and working across the hall from each other in the labs of Jan Hall and Steve Cundiff. However, as the coming months were to demonstrate, the barrier of a hallway did not prove to be a significant obstacle to the merging of science and technology from the worlds of the ultrastable and the ultrafast. Those were exciting days at JILA as we were involved in the first optical frequency measurement measurements with octave-spanning frequency combs and the first measurement and stabilization of the carrier-envelope offset frequency for a train of femtosecond laser pulses. Jan was closely involved in all the experiments we performed—helping us to measure and understand the noise sources in the femtosecond lasers and then teaching us the electronics skills to overcome them. And on many nights, he was in the "driver's seat" steering one of his special servos as critical data was collected. Moreover, Jan was a truly inspirational mentor and leader, with an infectious excitement for making great science happen. We owe him a tremendous debt of gratitude for all that he has given to us.

**Femtocombs for frequency metrology**

As NRC post-docs, one of us (SD) set to work building a new kind of comb generator that employed parametric gain, while the other (DJ) quickly built up a femtosecond fiber laser that was intended to be used for nonlinear propagation studies. While we were involved in these projects, we began to hear rumblings out of Germany about new prospects involving femtosecond lasers and their use as frequency combs in addition to the exciting possibility of controlling the carrier envelope phase of a pulse emitted from such a laser. We both thought this sounded like more compelling research than our current projects, and so together we began to try to see what might be possible with the femtosecond laser that existed in Steve Cundiff's lab. Initially, Jan had been somewhat skeptical about the prospects of femtosecond lasers in precision frequency metrology—fearing that the intense fields and associated nonlinearities inside the laser might lead to excess noise on the mode comb. However, his opinion was quickly changed after making a trip to the lab of Ted Hänsch in late 1998 where he saw the clean beat between a CW laser and one tooth of the frequency comb generated from a Ti:sapphire laser. Work with the femtosecond laser frequency comb, or "femtocomb" as Jan liked to call it, began in earnest at that point.

We started our experiments with the femtosecond laser Steve Cundiff had brought with him from Bell Labs. This laser could generate a pulse approximately 10 fs in duration and therefore had sufficient spectral width to enable us to see a beats with Jan's CW Ti:sapphire laser that was stabilized to the Rb two-photon transition near 778 nm. To us, this beat was exciting proof that the femtocomb concept could work, but what we really wanted to do was to make a frequency measurement with the laser. For some years Jan's group had been working on a small frequency chain that enabled the measurement of the iodine-stabilized YAG laser in terms of the 633 nm iodine-stabilized He-Ne and the Rb two-photon transition (both of which had been previously measured in Paris). While at that point the femtocomb was not broad enough to reach 633 or 532 nm, with some additional nonlinear broadening in standard fiber, we could generate just enough light (~10 pW per mode) at 1064 to see a beat with the stabilized YAG laser on one of Jan's well-designed photodetectors. The 104 THz gap between 778 nm and 1064 nm was thus spanned with the rep-rate stabilized comb, thereby enabling a new measurement of the iodine-stabilized YAG laser in terms of the the Rb two-photon transition [1].

**“Seriously nonlinear fiber” and f-2f**

We knew that if we could somehow generate an octave of spectral bandwidth with the femtosecond laser, we would be able to measure the carrier-envelope offset frequency ($f_0$), which was key to controlling the entire frequency comb. Early in 1999, we had attempted to obtain an octave with specialized (high nonlinearity) optical fiber made from chalcogenide glass, but we did not have much success broadening the fs laser’s spectrum. With these thoughts in mind, we all headed to Baltimore for the big annual laser conference (CLEO, Conference on Lasers and Electro-Optics) in May 1999. We were looking forward to sharing some of our new results and hopefully to learn about the latest lasers and techniques that might help our quest for a still-broader spectrum from the femtosecond laser.

When the postdeadline papers came out (in those days they were paper copies distributed at the meeting), we were immediately drawn to a submission by Jinendra Ranka, Andy Stenz, and Robert Windeler from Lucent Technologies: Bell Labs. Using a unique air-silica waveguide design for a radically new type of optical fiber, they were able to confine 800 nm light to an exceedingly small mode field area of ~1 μm. Combined with the long interaction length, this fiber was …“seriously nonlinear…”* When pumped with low energy pulses (~10 nJ) from a fs Ti:Sapphire oscillator, the resulting continuum spanned almost two octaves while maintaining a single spatial mode [2].

All of us at JILA knew we had to try this fiber, and if it successfully allowed control of the offset frequency, the resulting capabilities would be monumental. After Ranka finished his presentation and we were waiting to talk with him, one of us (DJ) remembers Jan barely being able to contain himself. He was erupting with pure and joyous enthusiasm for science that will not be forgotten. The next day, we sat down with Steve Cundiff in the convention center lobby to compose an email to Jinendra Ranka, outlining our plans and requesting a sample of the fiber. And we began to prepare in the lab for its arrival.

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* We can, without much thought and with a smile, guess whose words these are...

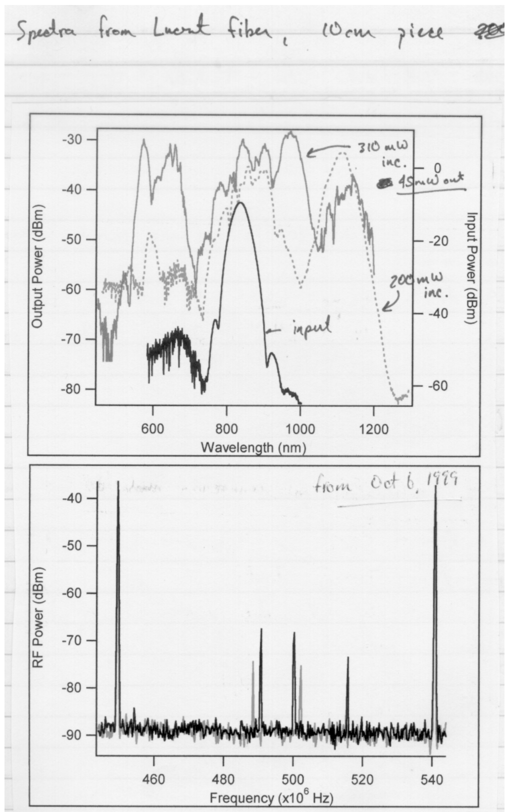


**Figure 1:** Page from lab book on Oct. 6, 1999 showing (top) octave spanning spectrum obtained with Lucent microstructure fiber, and (bottom) the first record of the carrier-envelope offset frequency ($f_0$). Harmonics of the rep rate are at 450 and 540 MHz. Two sweeps of the spectrum analyzer are shown, verifying that $f_0$ indeed moved with cavity fluctuations (and did it ever move in the open air cavity!) The peak near 515 MHz is spurious.

As July rolled into August, we were still anxiously awaiting the fiber. As we waited, we had various discussions that centered on a key concern: could the comb coherence be preserved through the broadening process? In earlier fiber broadening experiments, the coherence was maintained. But this new fiber was much more nonlinear. Could the Raman (or some other) effect work to destroy the coherence? September arrived…still no fiber, but both Steve Cundiff and Jinendra. Ranka were patiently navigating the matrix created by legal issues between Lucent and NIST.

Finally, on October 4, 1999 the package arrived and we immediately got to work. Using our 10 fs laser we quickly obtained an octave of bandwidth (Fig. 1). Now to get access the offset frequency of the comb, the spectral components of the continuum at frequency $f$ needed to be optically heterodyned with the components at $2f$. Our first attempt was a single arm interferometer shown in Fig. 2; we simply placed a doubling crystal after the output of the fiber. After working on it for several hours, we recorded the RF spectrum shown in Fig. 1b: we now had access to the offset frequency and it appeared the coherence of the comb was intact.

To improve the spatial, spectral, and temporal overlap we later switched to a Mach-Zender form of the *f*-to-2*f* interferometer, but not before first convincing ourselves that the system really worked and we could make a frequency measurement with it. The optical fiber was

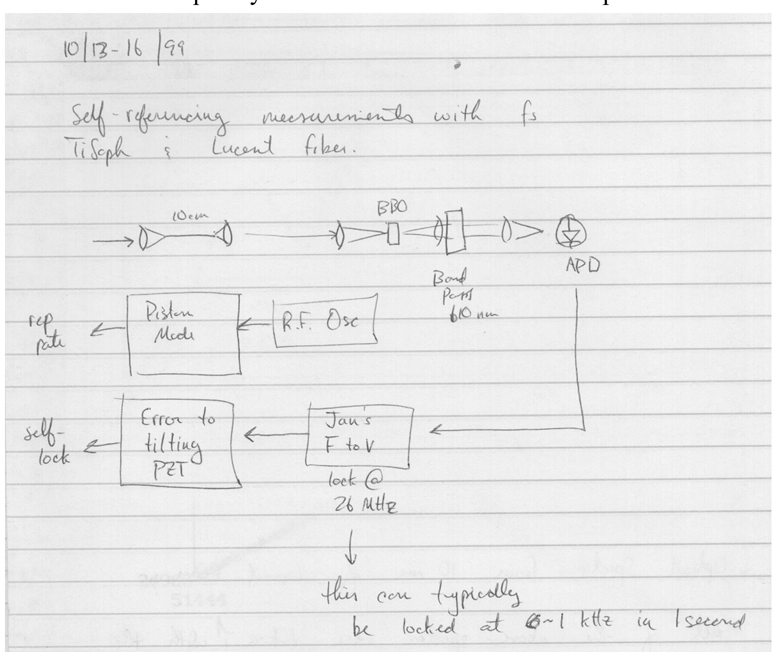


**Figure 2**: (a) Lab book diagram of the initial scheme for measuring and stabilizing $f_0$. A split tube piezo transducer in the linear cavity of the femtosecond laser could be driven in two different modes. The piston mode was used to lock the laser repetition rate, while the tilting mode was used to stabilize $f_0$. The ideas and hardware for the split piezo and its high voltage driver, the avalanche photodiode (APD), and frequency to voltage converter (F to V) all came from Jan

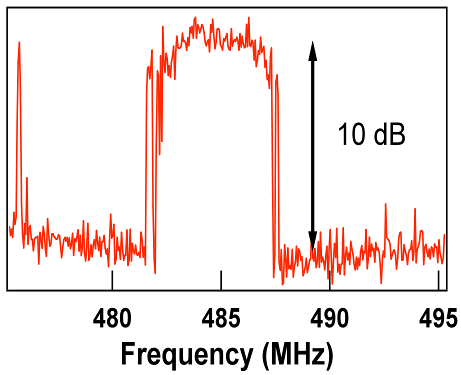


**Figure 3:** On Oct. 16, 1999 we recorded this beat between a tooth of the self-referenced femtocomb (see Fig. 2) and the 2-photon Rb standard at 778 nm.

already in place, connecting Jan's 778-nm Rb 2 photon spectrometer to the octave-spanning, self-referenced femtocomb. As seen if Fig. 2, by the middle of October 1999, Jan had provided a frequency-to-voltage converter that enabled a simple frequency lock of $f_0$ A clean beat was observed, though with a small SNR, between the Rb-referenced laser and the femtocomb (Fig. 3). Combined with the known repetition rate and the offset frequency of the comb, this beat represents the first measurement of an optical frequency with a self-referenced femtosecond laser. At this early stage the uncertainty was at the level of a few hundred kilohertz, but it agreed with the accepted value of the Rb standard, validating the femtocomb approach. Later on that same day, another important tool from Jan's electronics bench—the RF tracking oscillator—could follow this small beat permitting direct counting of optical frequencies.

**Jan's Vision**

While our rapid success brought much elation and confidence that there really could be a successful union of the ultrafast and ultrastable, Jan was already thinking of other issues, problems and improvements. For example, he recognized that phase-coherent control would be required to take full advantage of the stabilized femtocomb. This was particularly true in the situation where one would want to generate time domain pulses with well-controlled carrier-envelope phase. As we were optimizing the optical setup, Jan was designing and building an all-in one

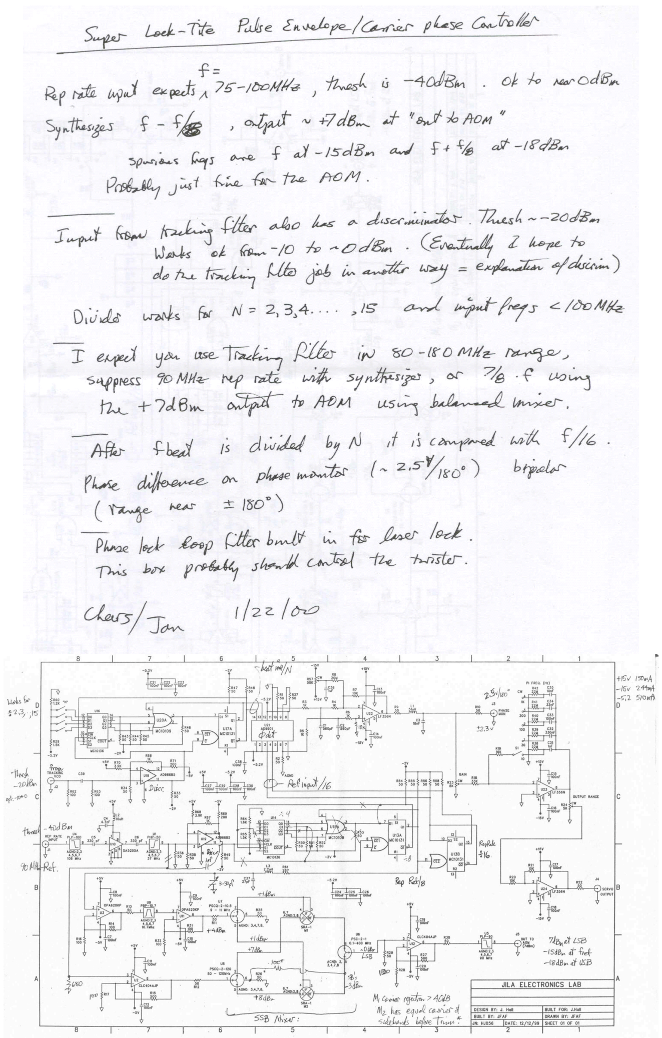


**Figure 4:** The design of the first femtosecond synchronizer

stabilizer for the fs comb's offset frequency ($f_0$)—the single-wide NIM module that ultimately was called the "femtosecond synchronizer". His initial thoughts and the resulting design reproduced from our lab books are shown in Fig. 4. True to its name, the femtosecond synchronizer had a duty of not just stabilizing $f_0$, but locking $f_0$ to a rational fraction of the pulse repetition rate ($f_{rep}$), which enabled the fs laser to generate a pulse train with controllable and definite carrier-envelope phase relation. This capability of the synchronizer would prove critical to demonstrate to the ultrafast community that stabilization of the femtocomb also had significant implications in the time domain.

After many hours of sorting through the prototype (that was of course, quite Jan-esque in appearance) in the student electronics shop, Jan delivered the synchronizer with an adjustable digital frequency divider stage to increase the locking range of $f_0$, an adjustable P-I corner feedback circuit and a means to lock $f_0$ to a rational fraction $f_{rep}$. After a few *in situ* tweaks, the femtosecond synchronizer was successfully commissioned. It provided the control of $f_0$ during a subsequent measurement of the Rb standard, and allowed us to eventually measure this frequency with statistical uncertainty limited only by our local microwave reference [3]. Moreover, a measurement of the phase slip between successive pulses via a nonlinear cross correlation confirmed the carrier-envelope phase coherence and the femtosecond synchronizer enabled us to step this phase over the full $2\pi$ [3].

**Final Thoughts**

Jan's construction of the femtosecond synchronizer is but one example of how he always seemed to have his finger on exactly what is going to be the most critical and important aspect, outcome, or problem of an experiment. And true to his style, he was ready with a solution. Another notable aspect of Jan is his generosity, fairness and openness with scientific ideas and information. While Jan certainly worked hard to make his lab (and for that matter JILA) a center of exciting and groundbreaking results, he generously recognized the contributions made outside his lab. A telling example of his character in this regard is our first publication on frequency measurements of the iodine standard with an octave spanning comb [4]. Once the nonlinear microstructure fiber was introduced at CLEO in 1999, a race ensued to obtain some of this fiber and create a useful octave spanning comb. Because Lucent was not willing to send their fiber out of the country, a sample came to JILA first. As described above, within a matter of weeks we took the necessary steps to make the RF to optical link and control the carrier-envelope offset frequency. When we had completed a few months of measurements and were ready to publish our results, Jan contacted Ted Hänsch and asked if he would like to be a co-author on the paper. This offer was somewhat of a surprise to many of us, but Jan wanted to acknowledge in this first paper that while the experiments were all done at JILA, the inspiring ideas came from Garching. It was Jan's refreshing reminder to us that unified progress towards scientific understanding is ultimately more important than short-term individual glory. Both of us consider ourselves to be very fortunate to have worked alongside Jan during an extremely exciting period of time at JILA; it has positively impacted us immeasurably.

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