5496–5499 (2000)]. What is the next step? With the stability of the optical frequency comb currently limited by the microwave reference used for phase locking f_{rep}, direct stabilization of comb components based on ultrastable optical references holds great promise. The initial demonstration of precision phase control of the comb shows that a single cw laser (along with its frequency doubled companion output) can stabilize all comb lines (covering one octave of the optical frequency spectrum) to a level of 1 Hz to 100 Hz at 1-s. [See J. Ye, J. L. Hall, and S. A. Diddams, Opt. Lett. 25, 1675 (2000)]. With control orthogonalization, we expect the system will be improved so that every comb line is phase locked to the cw reference below 1 Hz level. Now we can generate a stable microwave frequency directly from a laser stabilized to an optical transition, essentially realizing an optical atomic clock. At the same time, an optical frequency network spanning an entire optical octave (>300 THz) is established, with millions of frequency marks stable at the Hz level repeating every 100 MHz, forming basically an optical frequency synthesizer. The future looks very bright, considering the superior stability (10^{-15} at 1 s) offered by the optical oscillators based on a single mercury ion and cold calcium atoms developed at NIST. [See K. R. Vogel, S. A. Diddams, C. W. Oates, E. A. Curtis, R. J. Rafac, J. C. Pergquist, R. W. Fox, W. D. Lee, and L. Hollberg, submitted for publication, (2000)]. Indeed, within the next few years it will be amusing to witness friendly competitions between the Cs and Rb fountain clocks and various optical clocks based on Hg^+, Ca or another suitable system.

Conclusion. The present invention has demonstrated stabilization of the carrier phase with respect to the pulse envelope of ultrashort pulses produced by a mode-locked laser using a self-referencing technique that does not require any external optical input. The phase can either be locked so every pulse has the identical phase, or made to vary so that every i^{th} pulse has the same phase. In the frequency domain, this means that the broad spectral comb of optical lines have known frequencies, namely a simple (large) multiple of the pulse repetition frequency plus a user-defined offset. This is particularly convenient if the repetition rate of the laser is locked to an accurate microwave or RF clock because then the absolute optical frequencies of the entire comb of lines are known. These results will impact extreme nonlinear optics [C. G. Durfee et al., Phys. Rev. Lett. 83, 2187 (1999); Ch. Spielmann et al., Science 278, 661 (1997)], which is expected to display exquisite sensitivity to electric field of the pulse.

The self-referencing technique also represents a dramatic advance in optical frequency metrology making measurement of absolute optical frequencies possible using a single laser. A mode-locked laser is used which emits a stable train of pulses at repetition rate f_{rep}. Corresponding to the temporal shortness of the pulse, there is a corresponding spectral bandwidth. If the laser spectrum is sufficiently broad, either as directly emitted or utilizing an external broadening device, such that the spectral extremes are separated by a factor of 2 in frequency, the optical spectrum emitted by the laser can be completely determined in terms of rf frequencies. This allows easy comparison to the cesium started, which has heretofore been extremely difficult.

If the laser spectrum does not extend over a factor of two in frequency, but is still significantly broad, for example 28% or more, a modified self-referencing technique can be used. An optical harmonic generator, capable of generating the 4-th harmonic of its input, can be provided with the red end of the spectrum of the laser beam. Another optical harmonic generator, designed to generate another useful harmonic, such as the 3 -rd harmonic, can be provided with the blue end of the spectrum of the laser beam. Either of these beams can be frequency-shifted, either before or after the harmonic generation. The two harmonic beams, one having been shifted, are combined for optical heterodyne detection using a suitable fast photodetector. The detected beat frequency contains the frequency offset of the mode-locked laser system, along with its aliases with the repetition frequency, as well as the repetition frequency and its harmonics. Suitable electronics provide phase-coherent locking of the offset frequency as a rational fraction of the repetition rate. The resultant laser field has two useful properties: 1) the carrier-envelope phase evolves in a deterministic manner from one pulse to the next; 2) the optical spectrum is a comb of harmonics of the repetition frequency as shifted by the (stabilized) offset frequency.

Other combinations of intrinsic optical bandwidth and harmonic multiplications may be used: the principle is to multiply frequencies from the spectral ends of the laser system's bandwidth by different harmonic numbers so as to arrive at the same harmonic frequency (in the uv for the case of visible lasers) which enables heterodyne detection. The rf output is the laser offset frequency. According to the invention, a frequency shifter is used somewhere in this comparison chain to displace the spectral region in which the heterodyne beat appears. Phase knowledge of the repetition rate signal and the frequency offset allows the imposition of useful phase coherence on the laser.

The foregoing description of the invention has been presented for purposes of illustration and description. It is not intended to be exhaustive or to limit the invention to the precise form disclosed, and other modifications and variations may be possible in light of the above teachings. The embodiment was therefore chosen and described in order to best explain the principles of the invention and its practical application to thereby enable others skilled in the art to best utilize the invention in various embodiments and various modifications as are suited to the particular use contemplated. It is intended that the appended claims be construed to include other alternative embodiments of the invention except insofar as limited by the prior art.

What is claimed is:

1. A method of stabilizing the phase of a carrier wave signal with respect to an envelope of the pulses emitted by a mode-locked pulsed laser comprising:

obtaining an optical output from said pulsed laser that has a bandwidth that spans at least one octave;

separating a first frequency output from said optical output having a first frequency;

separating a second frequency output from said optical output, said second frequency output having a second frequency that is twice the frequency of said first frequency;

doubling said-first frequency output of said pulsed laser to produce a frequency doubled first output;

shifting said second frequency output by a predetermined amount to produce a second frequency shifted output;

combining said frequency doubled first output and said second frequency shifted output to obtain a beat frequency signal;

detecting said beat frequency signal;

generating said beat frequency signal to phase coherently stabilize said phase of said carrier wave signal relative to said envelope of said pulsed laser.

2. The method of claim **1** wherein said step of shifting said second frequency output by a predetermined amount to