MODE-LOCKED PULSED LASER SYSTEM AND METHOD

CROSS REFERENCE TO RELATED APPLICATIONS

This application claims the benefit of U.S. Provisional application serial No. 60/193,287, filed Mar. 30, 2000, entitled "Direct Optical Synthesis and Phase Stabilization of Ultrashort Optical Pulses," by Steven T. Cundiff, Scott A. Diddams, John L. Hall, and David J. Jones, and PCT International Application No. PCT/US01/10554 filed Mar. 29, 2001 entitled "Mode-Locked Pulsed Laser System and Method," by Steven T. Cundiff, Scott A. Diddams, John L. Hall, and David J. Jones. These applications are specifically incorporated by reference herein for all that they disclose and teach.

BACKGROUND

A. Field

The present disclosure pertains generally to lasers and more particularly to ultrafast mode-locked pulsed lasers. In one aspect this disclosure discusses carrier-envelope phase control of femtosecond mode-locked lasers and direct optical frequency synthesis

B. Background

1. Introduction. Progress in femtosecond pulse generation has made it possible to generate optical pulses that are only a few cycles in duration. [See G. Steinmeyer, D. H. Sutter, L. Gallmann, N. Matuschek, U. Keller, Science 286,1507 (1999); M. T. Asaki, C.-P. Huang, D. Garvey, J. Zhou, H. C. Kapteyn, M. M. Murnane, Opt. Lett. 18, 977 (1993); U. Morgner, F. X. Kartner, S. H. Cho, Y. Chen, H. A. Haus, J. G. Fujimoto, E. P. Ippen, V. Scheuer, G. Angelow, T. Tschudi, Opt. Lett. 24, 411 (1999); D. H. Sutter, G. Steinmeyer, L. Gallmann, N. Matuschek, F. Morier-Genoud, U. Keller, V. Scheuer, G. Angelow, T. Tschudi, Opt. Left. 24, 631 (1999)]. This has resulted in rapidly growing interest in controlling the phase of the underlying carrier wave with respect to the envelope. [See G. Steinmeyer, D. H. Sutter, L. Gallmann, N. Matuschek, U. Keller, Science 286,1507 (1999); L. Xu, Ch. Spielmann, A. Poppe, T. Brabec, F. Krausz, T. W. Hansch, Opt. Lett. 21, 2008 (1996); P. Dietrich, F. Krausz, P. B. Corkum, Opt. Lett. 25, 16 (2000); R. J. Jones, J.-C. Diels, J. Jasapara, W. Rudolph, Opt. Commun. 175,409 (2000)]. The "absolute" carrier phase is normally not important in optics; however, for such ultrashort pulses, it can have physical consequences. [See P. Dietrich, F. Krausz, P. B. Corkum, Opt. Lett. 25, 16 (2000); C. G. Durfee, A. Rundquist, S. Backus, C. Heme, M. M. Murname, H. C. Kapteyn, Phys. Rev. Lett. 83, 2187 (1999)]. Concurrently, mode-locked lasers, which generate a train of ultrashort pulses, have become an important tool in precision optical frequency measurement. [See T. Udem, J. Reichert, R. Holzwarth, T. W. Hänsch, Phys. Rev. Lett. 82, 3568 (1999); T. Udem, J. Reichert, R. Holzwarth, T. W. H änsch, Opt. Lett. 24, 881 (1999); J. Reichert, R. Holzwarth, Th. Udem, T. W. Hänsch, Opt. Comm. 172, 59 (1999); S. A. Diddams, D. J. Jones, L.-S. Ma, S. T. Cundiff, J. L. Hall, Opt. Lett. 25, 186 (2000); S. A. Diddams, D. J. Jones, J. Ye, S. T. Cundiff, J. L. Hall, J. K. Ranka, R. S. Windeler, R. Holzwarth, T. Udem, T. W. Häsch, Phys. Rev. Lett. 84, 5102 (2000); Various schemes for using mode-locked lasers in optical frequency metrology were recently discussed in H. R. Telle, G. Steinmeyer, A. E. Dunlop, J. Stenger, D. H. Sutter, U. Keller, Appl. Phys. B 69, 327 (1999)]. There is a close connection between these two apparently disparate topics. This connection has been exploited in accordance with the present invention to develop a frequency domain technique that stabilizes the carrier phase with respect to the pulse envelope. Using the same technique, absolute optical frequency measurements were performed in accordance with the present invention using a single mode-locked laser with the only input being a stable microwave clock.

Mode-locked lasers generate a repetitive train of ultrashort optical pulses by fixing the relative phases of all of the lasing longitudinal modes. [See A. E. Siegman, *Lasers*, (University Science Books, Mill Valley Calif., 1986), p. 1041–1128]. Current mode-locking techniques are effective over such a large bandwidth that the resulting pulses can have a duration of 6 femtoseconds or shorter, i.e., approximately two optical cycles. [See M. T. Asaki, C.-P. Huang, D. Garvey, J. Zhou, H. C. Kapteyn, M. M. Murnane, Opt. Lett. 18, 977 (1993); U. Morgner, F. X. Kärtner, S. H. Cho, Y. Chen, H. A. Haus, J. G. Fujimoto, E. P. Ippen, V. Schenuer, G. Angelow, T. Tschudi, Opt. Lett. 24, 411 (1999); D. H. Sutter, G. Steinmeyer, L. Gallmann, N. Matuschek, F. Morier-Genoud, U. Keller V. Scheuer, G. Angelow, T. Tschudi, Opt. Lett. 24, 631 (1999)]. With such ultrashort pulses, the relative phase between the peak of the pulse envelope and the underlying electric-field carrier wave becomes relevant. In general, this phase is not constant from pulse-to-pulse because the group and phase velocities differ inside the laser cavity (see FIG. **7**A). To date, techniques of phase control of femtosecond pulses have employed time domain methods. [See L. Xu, Ch. Spielmann, A. Poppe, T. Brabec, F. Krausz, T. W. Hänsch, Opt. Lett. 21, 2008 (1996)]. However, these techniques have not utilized active feedback, and rapid dephasing occurs because of pulse energy fluctuations and other perturbations inside the cavity. Active control of the relative carrier-envelope phase prepares a stable pulse-to-pulse phase relationship, as presented below, and will dramatically impact extreme nonlinear optics.

At the present, measurement of frequencies into the microwave regime (tens of gigahertz) is straightforward thanks to the availability of high frequency counters and synthesizers. Historically, this has not always been the case, with direct measurement being restricted to low frequencies. The current capability arose because an array of techniques was developed to make measurement of higher frequencies possible. [See G. E. Sterling and R. B. Monroe, *The Radio Manual* (Van Nostrand, New York, 1950)]. These techniques typically rely on heterodyning to produce an easily measured frequency difference (zero-beating being the limit). The difficulty lay in producing an accurately known frequency to beat an unknown frequency against.

Measurement of optical frequencies (hundreds of terahertz) has been in a similar primitive state until recently. This is because only few "known" frequencies have been available and it has been difficult to bridge the gap between a known frequency and an arbitrary unknown frequency of the gap exceeds tens of gigahertz (about 0.01% of the optical frequency). Furthermore, establishing known optical frequencies was itself difficult because an absolute measurement of frequency must be based on the time unit "second", which is defined in terms of the microwave frequency of a hyperfine transition of the cesium atom. This requires a complex "clockwork" to connect optical frequencies to those in the microwave region.

Optical frequencies have been used in measurement science since shortly after the invention of lasers. Comparison of a laser's frequency of $\sim 5\times 10^{14}$ Hz with its