MC2.1 (Invited)
10:30 am – 11:00 am

Gigahertz Femtosecond Lasers for Optical Frequency Metrology

A. Bartels, National Institute of Standards and Technology, Time and Frequency Division, 325 Broadway, Boulder, CO 80305, e-mail: albrecht@boulder.nist.gov

Abstract: Femtosecond lasers with repetition rate around 1-GHz have several advantages for optical frequency metrology. A state-of-the-art review emphasizing the recent development of a 433-MHz Cr:Forsterite laser and a 1-GHz continuum-generating Ti:sapphire oscillator is given.

The idea of using a femtosecond laser as an optical frequency synthesizer has revolutionized our ability to perform absolute measurements of the frequency of light [1]. Furthermore reversing the optical frequency synthesizer principle has allowed the creation of a novel kind of optical atomic clock with a 1-GHz microwave output [2]. Both technologies rely on the fact that a femtosecond laser's optical spectrum constitutes a strictly periodic frequency comb whose optical components $f_n=f_0+n\times f_R$ (n being an integer) are entirely determined by and controllable via the laser's repetition rate, f_R, and an offset from 0 Hz, f_0. In the most common scheme the laser output is broadened to span more than one octave to allow for a f_0-measurement and to increase the available frequency range. The first demonstration of a modelocked laser based optical frequency measurement employed an oscillator with 78 MHz repetition rate [1]. However, since 1999 lasers with higher repetition rates of $\approx$1 GHz have increasingly replaced lasers with the lower repetition rate of $\approx$100 MHz. These higher repetition rate lasers are much better suited for frequency metrology for three reasons: i) They can be made more compact. ii) The required pre-measurement of the to-be-measured frequency, usually done with a wavemeter, requires less resolution. iii) The signal-to-noise ratio of heterodyne beat-signals between a cw-laser and a component of the frequency comb that has been broadened with a microstructure fiber can be $\approx$100 times higher than with a $\approx$100-MHz system.

The standard ring-cavities for the realization of repetition rates up to 3.5 GHz are sketched in Fig. 1. They comprise the concave mirrors M1 and M2, the flat mirrors M3-5 and the output coupler OC (usually 1-3% transmission). The laser crystal is pumped through lens L (focal length between 30 mm and 50 mm) and also serves as nonlinear Kerr-medium to allow for passive mode-locking. To ensure tight focusing, M1 and M2 have very short focal lengths between 15 and 25 mm. Stable femtosecond pulse generation in a resonator requires a negative net cavity dispersion. Standard methods, like prism sequences, fail to serve this purpose because they require a minimum cavity length of approximately 1 m, inherently impairing repetition rates greater than 300 MHz. Therefore we employ mirrors with a negative dispersive coating at the positions of M1-5. These are either chirped mirrors or Gires-Tournois interferometer mirrors.

Femtosecond Ti:sapphire lasers have been demostrated using the configuration of Fig. 1 with repetition rates between 300 MHz and 3.5 GHz [3]. The cavity in Fig. 1a) is usually used for the highest repetition rates, whereas the one in Fig. 1b) allows the use of longer crystals and achieve more output power. A typical output spectrum is shown in Fig. 2, curve a). The oscillators operate at a pump power as low as 1.3 W, and have demonstrated output power as high as 2.2 W at 10.5 W pump power. Modelocked operation is always unidirectional. While standard oscillators have a central wavelength of $\approx$800 nm, continuously tunable operation with a tuning range between 733 nm and 850 nm has also been demonstrated by insertion of a single prism into the cavity. When operated at 1 GHz repetition rate, the laser output can broadenend to span an octave in microstructure fibers and can readily serve as optical frequency synthesizers.

Extending the concept to the infrared, we have recently used Cr^{4+}:Forsterite as gain medium in a cavity equivalent to the one shown in Fig. 1a) [4]. This laser operates at a repetition rate of 433 MHz and delivers approximately 600 mW of output power in mode-locked operation when pumped by 10 W from a

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Yb-doped fiber laser. Operating at a central wavelength of 1260 nm, it delivers pulses of 30 fs duration. Its output spectrum is shown in Fig. 2, curve b). Recent experiments have shown that this laser is as suitable for frequency metrology purposes as a Ti:sapphire laser; it can also be broadened to an octave spanning supercontinuum in nonlinear fibers and beatnotes between the broadened spectrum and cw-lasers are observable.

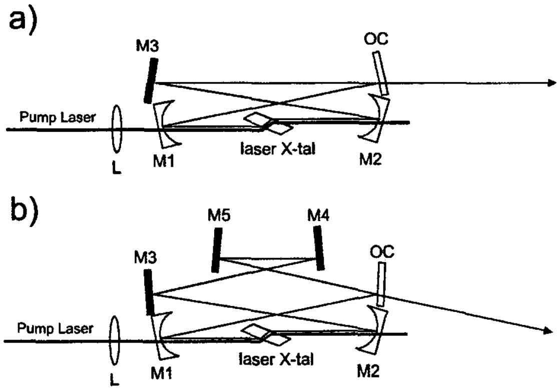

Fig. 1: a) Cavity for repetition rates up to 3.5 GHz. The laser crystal is placed at Brewster's angle between the two concave mirrors M1 and M2. The ring-cavity is completed by mirror M3 and the output coupler OC. Lens L serves to focus the pump laser in the the crystal. b) Cavity equivalent to a) for repetition rates up to 2 GHz but with longer crystal and two extra folding mirrors M4 and M5.

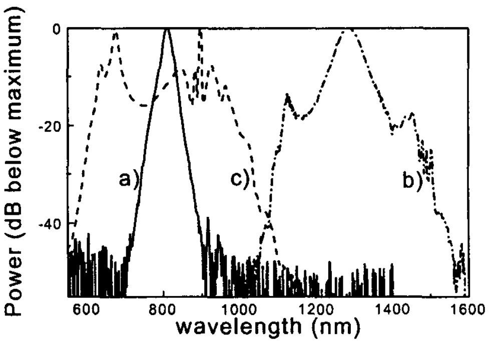

Fig. 2: Curve a (solid line) is a typical spectrum of a 1-GHz Ti:sapphire ring laser, curve b) (dash-dotted line) shows the spectrum of the 433-MHz Cr:Forsterite laser and curve c) (dashed line) shows the output of a broadband Ti:sapphire laser.

While nonlinear fibers, usually microstructured silica fibers, served the purpose of generating a supercontinuum remarkably well in the past, they do exhibit problems regarding long term reliablity. A large step towards a frequency measurement system that operates for days and weeks rather than hours has been taken by the development of a 1-GHz Ti:sapphire laser that spans a broadband continuum directly [5]. Here, in the cavity shown in Fig. 1a) the flat mirror M3 is replaced by a slightly convex mirror that serves to increase the self-gain modulation of the laser due to the Kerr-effect. This change generates shorter pulses and broader spectra in the cavity. The output spectrum of this laser is shown in Fig. 2, curve c). It reaches from 630 nm to 945 nm at 10 dB below its maximum. It allow the detection of its f_0 in a self-referencing technique without the need for external broadening [6]. This system has a remarkable long-term stability in that its f_0 can be measured and phase-locked to a microwave synthesizer for as long as the laser is turned on. Furthermmore a continuous frequency measurement for 14 h has been demonstrated with this laser.

References

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