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# Wavelength swept Ti:sapphire laser

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ABSTRACT

In this study, we demonstrate, for the first time to our knowledge, electronic wavelength sweeping of a continuous wave Ti:sapphire laser using an acousto-optic tunable filter (AOTF). The dependence of the laser output on the sweeping frequency and on the spectral tuning range was investigated. The lasing up to maximum scan rate 11 kHz for 10 nm tuning range and 5 W pump power was achieved. We detected and quantified asymmetry in the output for opposite scan directions. We theoretically characterized the maximum sweeping frequency for swept lasers with AOTFs and confirmed calculated results by measurements.



Tunable lasers are an indispensable tool in various scientific fields. As a result of intense research efforts, different wavelength tuning mechanisms have been reported. However, emerging applications promote the development of new tunable lasers with specific characteristics. In particular, significant attention was attracted to wavelength swept lasers. In the sweeping regime the laser output scans continuously and repeatedly over a wide spectral range. Swept lasers have many applications in fields such as spectroscopy [1] or optical coherence tomography (OCT) [2]. For OCT systems, continuously swept lasers with narrow instantaneous line width and broad spectral tuning range are required to achieve long imaging depth and high axial resolution. The sweeping frequency determines the imaging speed and, therefore, it is highly desirable to have this parameter in the range of tens kHz. Although unprecedented sweep rates of 370 kHz have been demonstrated with Fourier domain mode locking technique [3], conventional slower tuning techniques are still attractive. For example, in line field OCT, in which swept lasers with low sweeping frequencies (few kHz) can be used [4].

Sweeping can be performed mechanically with dispersive elements as diffraction gratings or prisms [5,6]. However, mechanical rotation of these elements or their related mirrors complicates the design and/or induces limited stability and tuning speed. Electronic tuning avoids such imperfections. Particularly, acousto-optic tunable filters (AOTFs) are capable of yielding stable and fast performance. They offer a wide tuning range, high switching speed (in the range of microseconds) and stable operation against vibration (due to non-mechanical structure). AOTFs were used for tuning of dye laser [7], semiconductor lasers [8,9] and pulsed Ti:sapphire laser [10]. The latter one was demonstrated in a random wavelength access regime. In this communication, we report, for the first time to our knowledge, the development of a swept continuous wave (CW) Ti:sapphire laser. Such lasers, operated near 800 nm, where absorption of the light in biological tissues is relatively low, are attractive for implementation in OCT systems and for spectroscopic measurements. We investigated laser sweeping characteristics and influence of the AOTF as a tunable filter on the laser functioning.

We constructed our laser on the basis of a Z-fold linear cavity CW Ti:sapphire laser (Del Mar Photonics). We inserted an AOTF in the cavity, replaced an output coupler with a high reflectivity mirror and performed necessary realignment. The resulting configuration of the swept laser is presented in Fig. 1. The cavity consists of concave mirrors M4, M5 (100 mm radii of curvature) and flat mirrors M6, M7, M8 (highly reflective in the range 720–940 nm). The physical length of the cavity is 1.5 m. The water cooled Brewster-cut Ti:sapphire crystal is 13 mm long with 0.08 wt.% titanium concentration. The pump source used is 532 nm Spectra-Physics Millennia Pro S laser that produces vertically polarized CW optical radiation. The pump beam, after passing a half-wave plate, is directed by the mirrors M1, M2 and M3 to the cavity and is focused into the crystal by the 80 mm focal length lens. Before transformation to tunable operation, with an 8% output coupler and operated in CW mode, the laser had a threshold pump power of 1.15 W and 22% slope efficiency. For sweeping operation, we implemented the non-collinear $TeO_2$ AOTF (TF900-400, Gooch and Housego PLC) with a tuning range of 700–1100 nm. The filter resolution ranges almost linearly from 0.4 nm at 700 nm to 0.6 nm for 870 nm diffracted light wavelength. The cavity is designed in such a way that diffracted light is back-reflected to the AOTF by the mirror M8 and the zero-order output of the AOTF is used as the laser output. Manufacturer specified diffraction efficiency is more than 90%, indicating that more than 90% of the diffracted light is coupled

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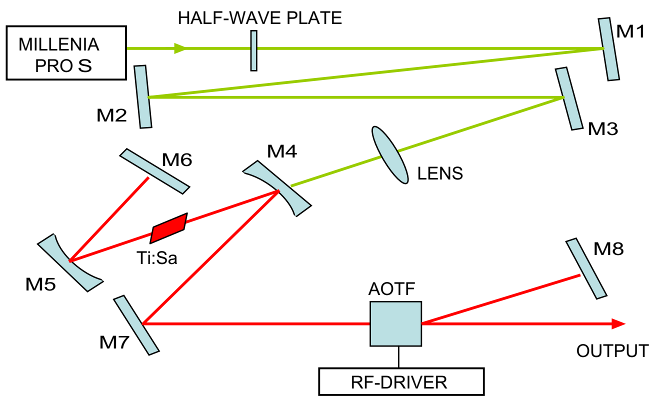


**Fig. 1.** Schematic representation of the swept laser with AOTF as tunable element.

back to the cavity. The angle between diffracted-order and 0-order beams is ∼2.6°. The AOTF's diffracted beam pointing stability allows us to avoid the use of the additional optics for keeping the diffracted beam under constant angle [10]. Wavelength sweeping is performed by applying a triangular shaped drive signal from a function generator (Hameg 8030-5) to the voltage controlled oscillator (21039-78-0.25 AMVCO, NEOS Technologies Inc.), which creates an RF-signal with 0.25 W maximum power for acoustic wave excitation. Changes in the frequency of the acoustic waves from 40 MHz to 65 MHz (1.8–8.3 V drive signal) correspond to diffracted wavelengths from 1020 nm to 665 nm, respectively. We distinguish forward and backward scans when the driving signal voltage increases or decreases, respectively. In relation to this, we use the term "sweeping frequency" to describe the periodicity of the waveform which drives the AOTF.

For quantitative characterization of the sweeping dynamics, we considered the influence of the following controllable parameters: spectral tuning range, pump power and sweeping frequency. The averaged output power was measured for a constant spectral tuning range (from 755 nm to 855 nm) as a function of sweeping frequency with 3, 4 and 5 W pump powers. We detected lasing only in a limited range (Fig. 2). The increase of pump power resulted in the increase of the maximum sweeping frequency. At the same time, the minimum sweeping frequency changed slightly. We supposed that presence of the minimum frequency is due to decrease of the AOTF diffraction efficiency for low sweeping rates (more specifically, AOTF tuning range). To verify this, we measured the AOTF's diffraction efficiency with another CW Ti:sapphire laser (Spectra Physics model 3900 S). The laser beam (100 mW power, 800 nm wavelength, instantaneous line width <1 GHz) was directed to the AOTF, which was placed outside the laser cavity. We measured the light intensity in the diffracted-order beam during sweeping operation of the AOTF. The obtained results are presented in Fig. 3. With decreasing sweeping frequency, the diffraction efficiency significantly drops. Furthermore, we observed a slow decrease of the diffraction efficiency for high sweeping frequencies. We suggest that such behavior is due to changes in the effective power of the drive signal for different sweep rates: the diffraction efficiency peaks at a certain RF drive power, deviation from which degrades performance of the AOTF. The stability of the drive signal power in the sweeping regime needs further investigation.

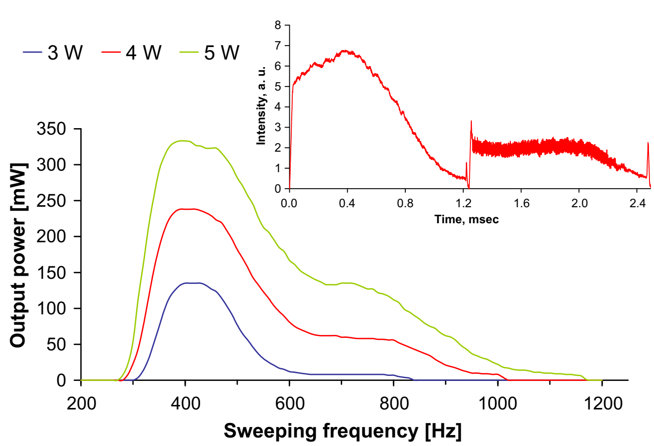


**Fig. 2.** Laser output power versus sweeping frequency for 3, 4 and 5 W pump powers (755–855 nm spectral tuning range). Inset: typical output intensity profiles for backward (from 0 to 1.22 ms) and forward (from 1.22 to 2.44 ms) scans (410 Hz sweeping frequency, 100 nm tuning range). The noisy output for forward scan is due to AOTF induced RF-shift (discussed in the text).

Due to the absence of lasing in the non-sweeping regime, we performed measurements of the instantaneous line width with a variable-delay Michelson interferometer. We measured the coherence length of the laser emission. The line width for backward and forward scans was calculated as 0.2 nm for the 5 W pump power and the 100 nm (750–850 nm) wavelength scan range and the sweeping frequency of 550 Hz. With decrease of the sweeping frequency the line width became narrower for backward scan and wider for forward scan (0.16 nm and 0.24 nm for 400 Hz, respectively).

Depending on the pump power and tuning parameters the laser generated pulses or CW output. With increase of the sweeping frequency, we observed transient dynamics from CW to pulse mode operation and back to CW. We explained pulsed behavior by the laser spiking. This process, most pronounced for solid-state lasers, leads to the generation of the regular sequence of peaks (spikes) with few microseconds time separation after switching on or disturbances during operation [11]. The spiking in the solid-state lasers usually damps and leads via relaxation oscillation to the establishment of the CW output. We observed in our laser, due to tuning dynamics, undamped spiking: by tuning the filter we constantly influenced the cavity losses and the establishment of the steady-state conditions was prevented.

Based on a semiconductor laser with a Fabry–Perot filter as tunable element, Huber et al. discussed the limiting factors for swept lasers [12]. The maximum achievable sweep rate is limited by the time constant to build up lasing from the amplified spontaneous emission background, which depends on the laser gain, the pump power, and the cavity round-trip time. For CW solid-state lasers this time constant is large, which means that many round-trips are required to reach threshold. In addition, for our laser, the inelastic scattering of the photons with AOTF's traveling acoustic waves causes a radio-frequency shift (RF-shift) of the circulating radiation [13]. For each cavity round-trip, the light passes the AOTF

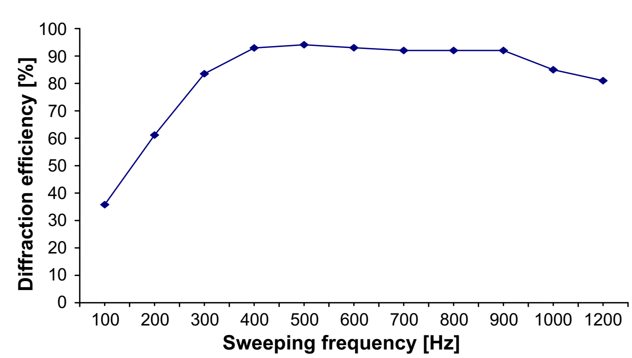


**Fig. 3.** AOTF's diffraction efficiency for different sweeping frequencies. Measurements were made on 800 nm for spectral tuning range 755–855 nm.

twice (in opposite directions). During the reverse pass the frequency shift is not cancelled but accumulated. As a consequence the growing unidirectional (in the frequency domain) RF-shift is induced. This shift can be parallel or opposite to the wavelength scan direction of the AOTF, which results in dissimilar laser output for opposite scans (Fig. 2). During a forward scan, the modes are RF-shifted towards the trailing edge of the AOTF pass band, reducing the available time for lasing build up. Conversely, during a backward scan the directions of movement of RF-shift and trailing edge coincide and the build-up time is longer. Consequently, the threshold pump power for lasing for the forward scan direction is higher than for the backward direction (Fig. 4). We also note that for a constant spectral tuning range the difference in the maximum sweeping frequency for forward and backward scan directions increases from ~20 Hz to ~250 Hz (for pump powers higher than ~2.8 W). We explain this by the wavelength dependence of the gain factor: the high gain near 800 nm promotes the generation to start in this spectral region with smaller number of round-trips and accordingly smaller RF-shift. With increase of the pump power, the laser generation appears in the lower gain regions with larger number of round-trips and, as a consequence, larger RF-shift.

For estimation of the highest accessible sweeping frequency, we use similar approximations as in [12], but with taking into account the additional RF-shift. The maximum sweeping frequency can be described as

$$\nu_{max} = \frac{\Delta\lambda_{AOTF} \pm (n \times \Delta\lambda_{RF})}{2 \times n \times \tau_{rt} \times \Delta\lambda} \qquad (1)$$

where $\Delta\lambda_{AOTF}$ is the AOTF resolution, $n$ is the number of round-trips to reach the lasing threshold from spontaneous emission, $\Delta\lambda_{RF}$ is the RF-shift for one cavity round-trip, $\tau_{rt}$ is the cavity round-trip time and $\Delta\lambda$ is the spectral tuning range. The second term in the numerator represents the influence of the RF-shift with the positive sign for the backward scan and the negative sign for the forward scan (in our case).

From Eq. (1), it is seen that for the attainment of the high sweeping rates the short laser cavity, the high gain, the broad AOTF's band pass and the large RF-shift are required. Eq. (1) also shows that higher sweeping frequencies can be achieved by reduction of the spectral tuning range. To demonstrate this, we measured maximum scan rates for shorter tuning ranges (10, 20, 30, 40, 70 and 100 nm) and compared the results with theoretical predictions. Non-linear least squares fits with the number of round trips as the free running parameter are shown in Fig. 5. Other parameters are listed in the figure caption. This yielded the following values for the number of round trips: $n = 271$ for the forward scan direction; $n = 251$ for the backward scan direction. For the 5 W pump power and 10 nm spectral range (from 795 to 805 nm) the maximum scan frequency for which lasing was detected was highest (8 kHz for the forward scan and 11 kHz for the backward scan) (Fig. 5). On the contrary, for the spectral range of 185 nm (from 725 to 910 nm) the maximum sweeping frequency was only 450 Hz. The increase of the sweeping frequency led to narrowing of the spectral output (due to reduction of the lasing build-up time) (Fig. 6). The minimum sweeping frequency was also tuning range dependent: for wider spectral ranges it is lower, which is a consequence of the fact that the tuning speed (e.g. describing the frequency of the signal applied to the RF-driver, which in turns generates the signal governing the AOTF's diffraction efficiency) is the product of the sweeping frequency and spectral tuning range. To keep the same tuning speed, increase of one parameter leads to the decrease of the other. Although existence of this low limit is not relevant for OCT applications, behavior of the AOTF in sweeping regime of operation needs further investigations.

In conclusion, we developed an electronically wavelength swept CW Ti:sapphire laser. We detected and quantified the influence of the AOTF RF-shift. We measured the changes in the AOTF

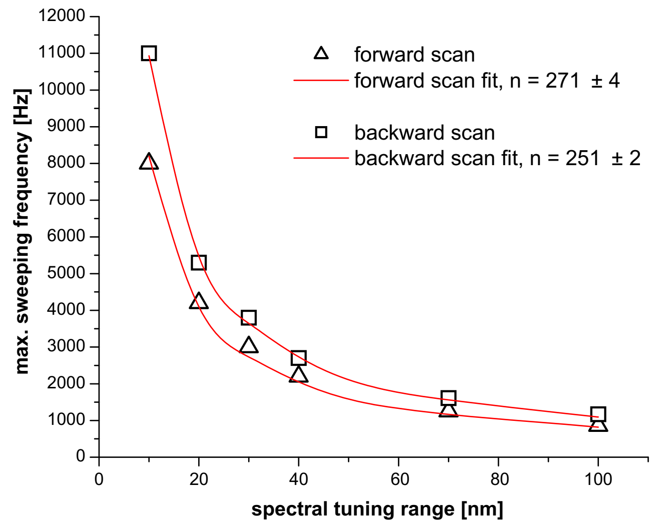


**Fig. 5.** Maximum sweeping frequency versus tuning range for forward and backward scans (5 W pump power). The solid curves show non-linear least squares fits using Eq. (1) with the number of round trips as the free running parameter. The other parameters were fixed at the following values: $\Delta\lambda_{AOTF} = 0.5$ nm; $\Delta\lambda_{RF} = 0.0002$ nm; $\tau_{RT} = 10$ ns.

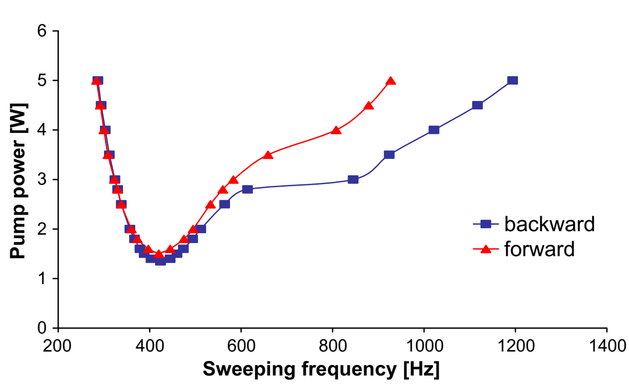


**Fig. 4.** Threshold pump power versus sweeping frequency (755–855 nm tuning range) for forward and backward scans. Lasing was observed only for the pump powers higher than indicated by the curves.

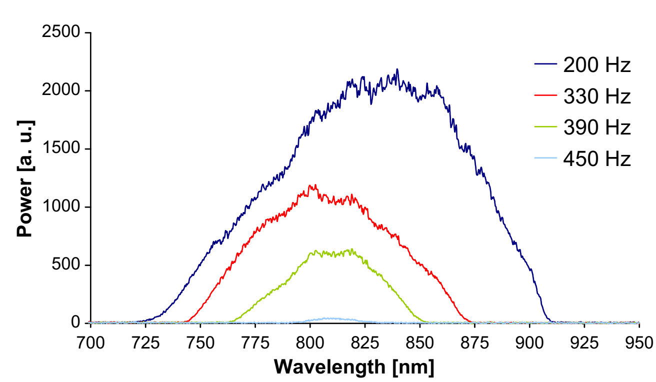


**Fig. 6.** Output spectrums for 5 W pump power, 680–980 nm spectral tuning range and different sweeping frequencies.

diffraction efficiency during sweeping regime of operation. Our results demonstrate that the laser output depends on the tuning parameters. A reduced spectral tuning range allows higher scan rates and vice versa. The instantaneous line width is sweeping frequency dependent. Additionally, forward and backward scan directions are not equal. Such lasers with flexible output characteristics can be useful light sources for different applications, in particular OCT. Depending on the application, appropriate tuning parameters can be chosen.

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