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**PICOSECOND AND FEMTOSECOND Ti: SAPPHIRE LASERS**

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**Abstract:** We present some results about the generation of pulses in Ti:Sapphire. Active and passive mode-locking techniques have been studied yielding the production of picosecond and femtosecond pulses when an intracavity group velocity dispersion compensation (prisms) is used. Pulses as short as 75 fs have been obtained and we show that the temporal profile is close to a gaussian.

Since its first lasing demonstration by Moulton et al. in the beginning of the 80's [1], the Titanium Sapphire ( $\text{Ti}^{3+}:\text{Al}_2\text{O}_3$ ) has proved to be a very attractive near infrared laser materials. This crystal combines a large fluorescence bandwidth (from 650 nm to 1100 nm) which is more important than the infrared dyes and a high saturation fluence ( $1 \text{ J/cm}^2$ ). Moreover its absorption bandwidth in the blue-green region (400-600 nm) allows it to be pumped by cw Argon ion or pulsed Nd-Yag (SHG) lasers. Its large fluorescence bandwidth has been exploited to produce ultrashort pulses by using several mode-locking techniques (active or passive).

We report here some results we have obtained first with an actively mode-locked Ti:Sapphire laser that used an acousto-optic mode-locker to produce the pulses. With an intracavity group velocity dispersion (GVD) compensation this laser produces subpicosecond pulses. We then have studied a passively mode-locked Ti:Sapphire laser by using a saturable absorber and that produces sub-100fs pulses when an intracavity GVD compensation is used.

The easier solution to generate pulses with a laser is the active-mode-locking. So we have started our study on pulsed Ti:Sapphire by developing an actively mode-locked laser [2,3]. The cavity is very classical : it is a four mirror linear astigmatically compensated cavity (Figure 1). The concave mirrors  $M_2$  and  $M_3$  have a 100 mm radius of curvature and are used off axis in order to compensate the astigmatism introduced by the Brewster angle cut crystal. The pump beam is focused on the crystal with a 100 mm focal length lens. With 6 watts of pump power we obtained 250 mW average power at 125 MHz.

Pulse duration is measured by using a standard noncollinear second-harmonic-generation autocorrelator with a KDP as the doubling crystal. Spectra are recorded using a spectrometer coupled with a photodiode array. The RF power injected in the mode-locker was around 2 Watts.

Due to the large fluorescence bandwidth of the Ti:Sapphire we expected to produce very short pulses. But in fact it was impossible to produce pulses shorter than 30 ps when one wants to have very stable pulses. By changing slightly the cavity length of the laser in order to mismatch the frequency given the cavity round trip from the frequency of the mode-locker, it was possible to obtain pulses around 10 ps. But in that case the laser operated in a Q-switched regime and the stability and the repeatability of the performances were poor. By looking at the spectrum of the 30 ps pulses we observed that the pulses were not limited by the Fourier transform. In fact the time bandwidth product was 10 times the theory. That means that the pulses exhibited a strong chirp.

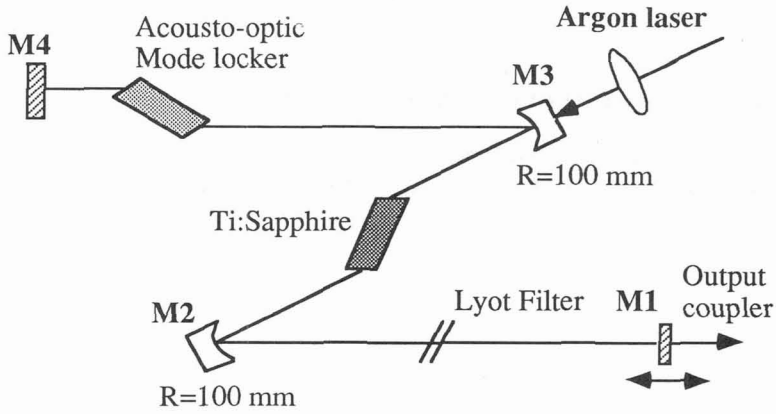


Figure 1 : Schematic of the actively mode-locked Ti:Sapphire laser.

In order to avoid such a chirp and to produce shorter pulses, we have inserted in the cavity a system of two high index prisms ( $n=1.76$  at 800 nm) that introduces a negative GVD. This negative dispersion will compensate the positive dispersion of the Ti:Sapphire rod and the acousto-optic crystal. The figure 2 shows the dispersion compensated cavity with the prisms. We also removed the Lyot filter and used a slit after the second prisms to control the laser wavelength.

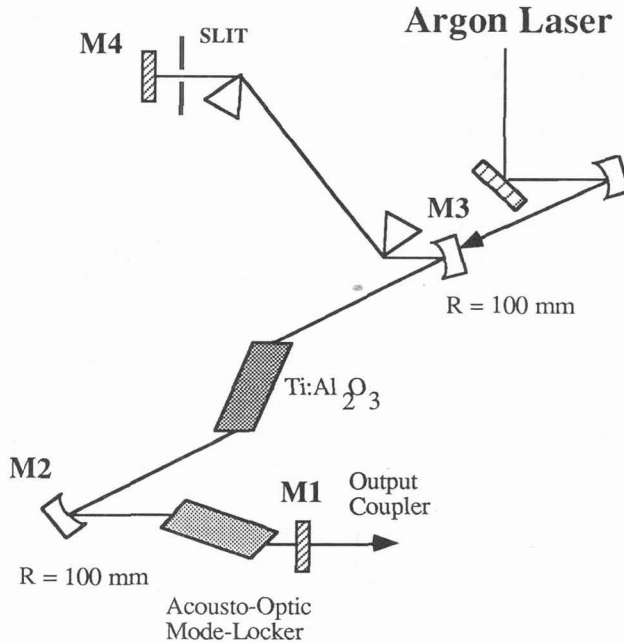


Figure 2 : Schematic of the dispersion compensated actively mode-locked Ti:Sapphire laser.

With this cavity we produced pulses as short as 300 fs at around 790 nm with around the same energy level. In that case the pulses are limited by the Fourier transform and the time-bandwidth  $\Delta t \cdot \Delta \nu = 0.43$  near the theory (0.44) for gaussian pulses. The figure 3 shows the autocorrelation and the spectrum of the pulses we produced. But due to the length of the mode-locker crystal (65 mm) we have to operate with the

prisms separated by 57 cm. We think that is a reason why we did not produce shortest pulses because the high order dispersion of the prisms sequence was too important. We also observed that we could obtain these pulses even with a very low RF power in the mode-locker. Moreover when the laser was producing the pulses it was possible to turn off the RF power in the mode-locker without stopping the pulses emission. But when something disturbed the laser (a dust for example) the laser stopped and did not restarted itself. To start the laser one needed to use the mode-locker. That means that the mode-locker is only for starting the laser and these results have to be correlated to the work of people from the University of Saint Andrews who first observed mode-locking in a Ti-Sapphire without any mode-locker in the cavity [4]. Since that people from Coherent have analysed this behavior and have explain it as Kerr Lens Mode-Locking[5]. In summary they have shown that the mode-locking is due to a change of the cavity spatial mode (due to a lens which appears in the crystal by non linear effect) and the laser only needs a starter which initiates the production of the pulses. The starter can be a mode-locker like in our case but it can also be a moving mirror [6] and also a saturable absorber.

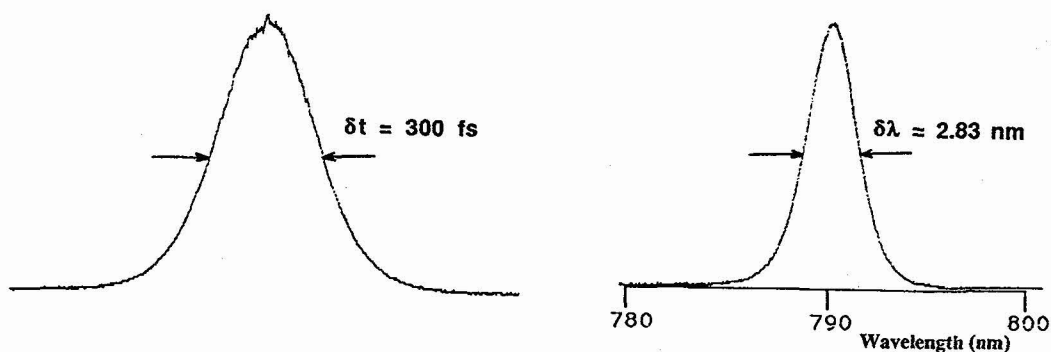


Figure 3 : Autocorrelation trace and spectrum of the pulses produced by the dispersion compensated actively mode-locked Ti:Sapphire laser.

The active mode-locking technique needs a fine adjustment of the cavity length in order to match the frequency injected in the acousto-optic crystal. As we have found that the mode-locker is only used to initiate the pulses, we have try to produce pulses by using a saturable absorber. The figure 4 shows the modified cavity. We removed the mode-locker and added two 50 mm radius of curvature mirrors and a dye jet.

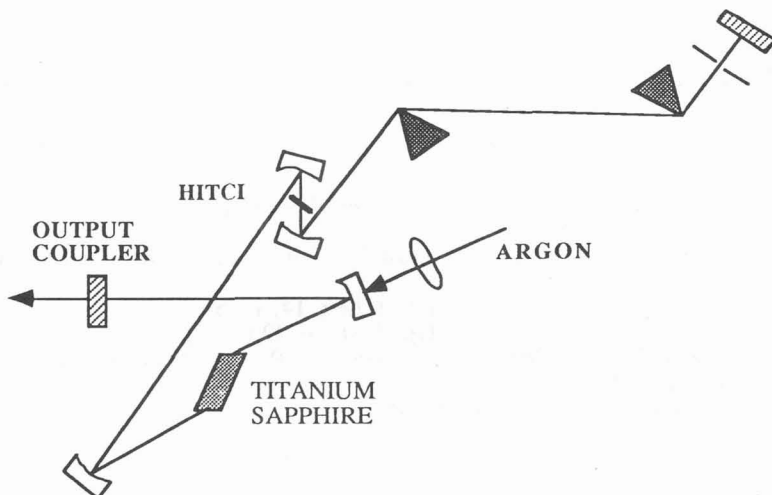


Figure 4 : Schematic of the passively mode-locked Ti:Sapphire laser.

The saturable absorber dye is HITCI with a concentration around  $5 \cdot 10^{-5}$  Mol/l in ethylene glycol corresponding to only a few trail of saturable absorber. The distance between the prisms is reduced to 25 cm because we only have the Ti:Sapphire crystal which introduces positive GVD. In order to control the pulse spectrum we used, like previously, a slit after the second prism. The length of the cavity is 1.5 m corresponding to a 100 MHz repetition rate. With a pump power of 7.5 W on the crystal, we obtained an average power of 250 mW around 807 nm and the threshold was near 5 W. Femtosecond pulses have been obtained for average output power between 100 mW and 250 mW. Below 100 mW, the laser produced large picosecond pulses and above 250 mW, a satellite pulse was observed at around one picosecond from principal pulse. The figure 5a shows the autocorrelation trace of the pulses we have obtained and the fit of the autocorrelation with a gaussian pulse shape. The figure 5b shows the corresponding spectrum of the pulses with also the best fit with a gaussian shape. The spectrum width is 12.5 nm centered at 807 nm. Considering that the best fit of the autocorrelation trace is for a gaussian pulse shape, that the spectrum also fits very well with a gaussian and that the product time-bandwidth  $\Delta\tau \cdot \Delta\nu = 0.435$ , we can deduce that the temporal shape of the pulses produced by our laser is close to a gaussian. The pulse train is very stable (the fluctuations are less than 1 % when the pulse train is recorded with a fast photodiode) and the long term stability is excellent. For example the mode-locked operation has been obtained over more than one week without adjusting (even delicately) any cavity or pump mirror control. We only have to wait the warm-up time of our Argon ion laser, and after this time the laser produced very stable and short pulses.

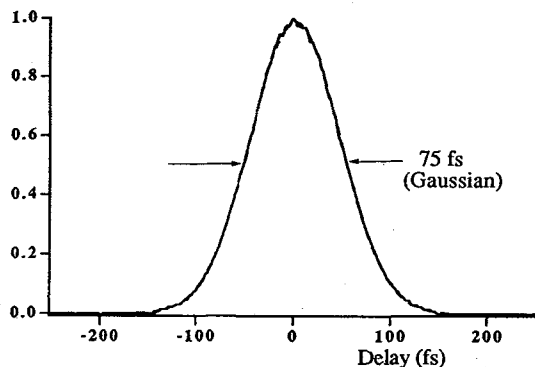


Figure 5a: Autocorrelation trace of the 75 fs pulses (assuming a gaussian pulse shape) obtained.

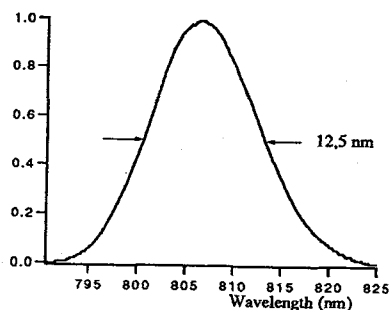


Figure 5b: Corresponding spectrum and its gaussian fit (dashed line) of the 75 fs pulses.

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