Characterizing a Ti:Sapphire laser in CW and mode locked operation

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March 18, 2014

We pumped a Ti:Sa laser with a frequency-doubled Nd:YAG laser at 532nm and operated it in CW mode with a broad tunable range of 750nm to 900nm. Tunable range decreased with decreasing pump power. Then, we mode locked the Ti:Sa around 800nm whiles using a translating Michelson interferometer to characterize the pulse train. We produced 160fs pulses with a time-bandwidth product of 0.84, roughly twice above the transform limited value for Gaussians. Finally, insertion of a 10cm fused silica rod further increased dispersion, resulting in 234fs pulses with a time-bandwidth product of 1.20.

Ti:Sa laser and application to mode locking. The Ti:Sa laser has a sapphire Al_2O_3 gain medium embedded with Ti^{3+} ions. In the crystal field, Ti^{3+} has a broad emission spectrum spanning roughly from 650nm to 900nm (fig 1). Its absorption spectrum spans from 400nm to 600nm, with minimal overlap with emission. Therefore, the Ti:Sa laser has a broad gain spectrum and thus can be wavelength tuned over a wide range, enabling it to replace tunable dye lasers in many applications.

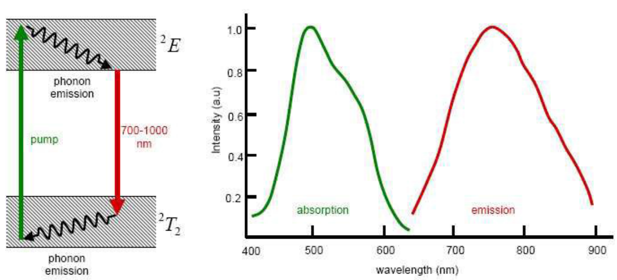

Fig 1 Absorption and emission in Ti:Sa

Here, we first characterized a Tsunami Ti:Sa laser in CW and then mode locked it. Mode locking produces a train of short pulses on the order of ps or even fs. In the frequency domain, such pulses encompass a frequency comb and are useful for probing material properties. Mode locking thus requires a broad BW, which is provided by the Ti:Sa. To achieve mode locking, we also modulated the cavity through an AOM and controlled the dispersion via a prism system.

Wavelength tunable CW mode operation. The Ti:Sa crystal is pumped by a frequency-doubled 532nm Nd:YAG laser, which is in turn pumped by diode bars. The Nd:YAG laser natively produces 1064nm radiation which undergoes second harmonic generation (SHG) inside an intra-cavity nonlinear crystal. The nonlinear crystal has a considerable $\chi^{(2)}$ term in the Taylor expansion of its nonlinear polarization which leads to frequency doubling.

We may control the lasing wavelength by adjusting position of a slit next to the dispersive prism. The output is proportional to the number above threshold. The threshold is in turn proportional to

$$\frac{\alpha_0 - \frac{1}{L}\ln R_1 R_2}{\gamma}$$

Where α_0 is the material loss, R_i the mirror reflectivities, and γ the gain. At a pump power of 5W, we're able to lase from roughly 750nm to 950nm, with a considerable FWHM of 140nm (fig 2). Peak is around 800nm. As we lower our pump to 4W, we're no longer able to lase at fringe frequencies where the gain is now too low. The output power for the remaining lasing wavelengths lowers as our number above threshold decreases.

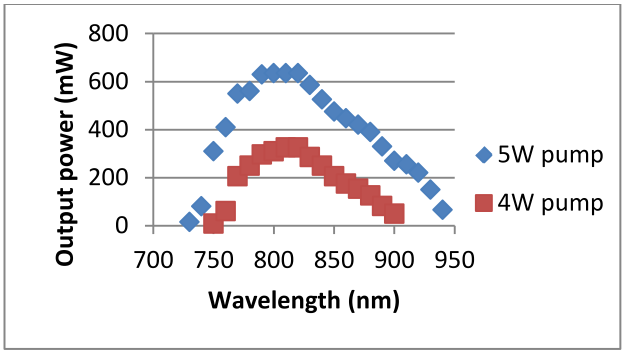

Fig 2 Wavelength tunable laser output

At our peak wavelength of 800nm, the output power shows the classic threshold linear response vs. pump power

$$P \propto \frac{I}{I_{th}} - 1$$

The threshold current is 3W while the slope efficiency is 31% (fig 3). If we were to repeat this measurement at a wavelength where the gain curve trails off, we would expect to see a higher threshold. However, the slope efficiency won't change as much it's dependent on absorption loss.

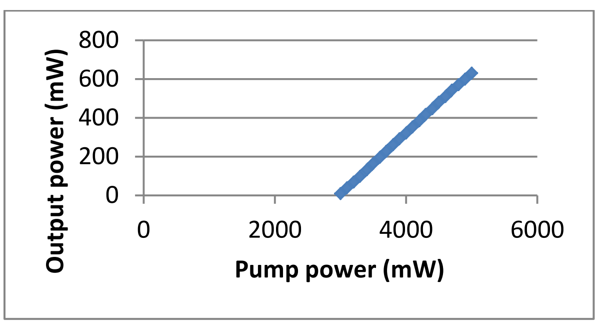

Fig 3 Threshold and slope efficiency

Mode locking. Goal is to generate a train of ultra-short pulses (fig 4).

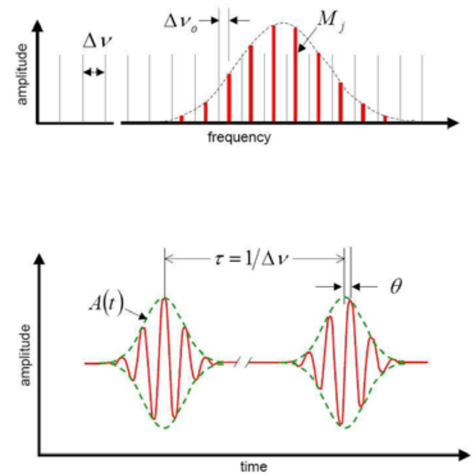

Fig 4 Time and frequency domain representations of mode locking

In the time domain, we have an enveloped sinusoid of frequency $\Delta\nu_0$ repeated at a frequency $\Delta\nu$ (e.g. convolved with a spike train). In the frequency domain, we have harmonic coefficients shifted by $\Delta\nu_0$, spaced $\Delta\nu$ apart, and apodized according to the bandwidth of time domain envelope.

To achieve modelocking, we first modulate the Q of the cavity through an AOM operating at ~80MHz, corresponding to the 1st fundamental of the cavity round trip time. However, the axial modes all see slightly different effective cavity path lengths because of dispersion through air and optical elements. To compensate, we operate a prism system to inject adjustable dispersion so that all the axial modes do add up in phase for mode locking.

Mode locking is both an art and a science. At first, the laser operates in CW, showing a single spike in the spectrum. The prism dispersion must then be manually tuned until (by luck or a fine touch) the spectrum suddenly broadens, indicating that a pulse train is running in the time domain. Now, the laser has mode locked and can maintain mode locking even if we further adjust wavelength and dispersion (which implies hysteresis behavior). We can shorten the pulse by toggling the dispersion to maximize the bandwidth seen on the OSA. We can also change the center wavelength by translating the slit. However, at outlier wavelengths the spectrum may suddenly collapse to a spike, indicating relapse into CW. The mode lock is most stable around 800nm where the Ti:Sa has good gain and bandwidth.

Pulse characteristics. We mode locked the laser at a $\lambda_c = 799.6nm$. The repetition rate of 80MHz can be seen on a scope, but we must resort to a Michelson interferometer to resolve the pulse duration. In such a setup, the beam interferes with itself as a moving mirror changes the length of one interferometer arm. The self interfered signal then impinges on a photodetector. The signal is thus the autocorrelation

$$s(t) \propto \int dt\, [E(t) + E(t-\tau)]^2$$

Where the integration is over the response time of the detector, which is magnitudes slower than optical frequencies.

When pulses of the original output and its delayed copy overlap, we get an enveloped sinusoid (fig. 5). This autocorrelation sinusoid period T' is proportional to the optical period inside the pulse. The $FWHM_t{}'$ of the interferometry envelope relates to the pulse envelope by the same proportionality constant. Hence we may calculate the real $FWHM_t$ pulse duration as

$$FWHM_t = \frac{FWHM_t{}'}{T'}\frac{\lambda}{c} = \frac{4000\mu s}{65.8\mu s}\frac{799.6nm}{3\text{E}8\ m\ s^{-1}} = 162fs$$

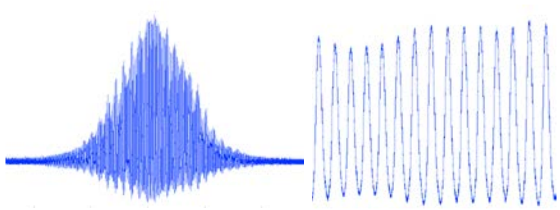

Fig 5 Autocorrelation signal of a pulse (full on left, zoomed in on right)

In the frequency domain, we feed the light pulses into an OSA which shows a broad peak centered at $\lambda_c = 799.6nm$ with a bandwidth $\mathrm{FWHM_f} = 11\mathrm{nm}$, or

$$\left(\frac{1}{\lambda_{low}} - \frac{1}{\lambda_{high}}\right)c = \left(\frac{1}{794.1nm} - \frac{1}{805.1nm}\right)3\text{E}8\ m\ s^{-1} = 5.16THz$$

We can calculate a dimensionless time-bandwidth product as

$$\mathrm{FWHM_f}\ \mathrm{FWHM_t} = 0.836$$

The product has a lower bound which is analogous to uncertainty principle bound. (If we used the standard deviations σ (instead of the conventional FWHM) of a distribution in the time and frequency domains, the Gaussian attains that lower bound.) For a Gaussian shaped pulse, the product is roughly 0.44 (transform-limited), ~2x smaller than our product. Thus our modes have additional phase distortions.

The product is worsened (increased) as we introduce additional dispersion. To that end, we inserted a 10cm long fused silica rod after the laser output. The frequency BW isn't significantly affected as it's largely dependent on the laser. However, in the time domain, the group velocity dispersion of the glass adds varying phase to the different modes, resulting in a smearing of the pulse. The time-bandwidth product is thus increased to 1.20.

	$\mathrm{FWHM_t}$	$\mathrm{FWHM_f}$	Product
No glass	$162fs$	$5.2THz$	0.84
With glass	$234fs$	$5.2THz$	1.20

Conclusion. The Ti:Sa laser offers wavelength tunable CW operation centered around 800nm with a FWHM exceeding 100nm. Higher pump power enables lasing over a broader range. Combined with cavity modulation (AOM) and dispersion compensation (prisms), the broad gain BW of the Ti:Sa enables mode locking production of ultra-short pulses. We had 160fs pulses which lengthened to 234nm upon introduction of additional dispersion through a glass rod. The coherent addition of modes (hence mode locking) thus hinges upon good dispersion compensation.

References

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