DEVELOPMENT OF A SINGLE-PASS AMPLIFIER FOR AN OPTICAL STOCHASTIC COOLING PROOF-OF-PRINCIPLE EXPERIMENT AT FERMILAB'S * IOTA FACILITY

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Abstract

Optical stochastic cooling (OSC) is a method of beam cooling which is expected to provide cooling rates orders of magnitude larger than ordinary stochastic cooling. Light from an undulator (the pickup) is amplified and fed back onto the particle beam via another undulator (the kicker). Fermilab is currently exploring a possible proof-of-principle experiment of the OSC at the integrable-optics test accelerator (IOTA) ring. To implement effective OSC a good correction of phase distortions in the entire band of the optical amplifier is required. In this contribution we present progress in experimental characterization of phase distortions associated to a Titanium Sapphire crystal laser-gain medium (a possible candidate gain medium for the OSC experiment to be performed at IOTA). We also discuss a possible option for a mid-IR amplifier.

INTRODUCTION

An Optical Stochastic Cooling experiment (OSC) is planned to take place at the Advanced Superconducting Test Accelerator (ASTA) in the Integrable Optics Test Accelerator (IOTA) ring at Fermilab [1]. OSC is a beam cooling technique capable of providing damping rates orders of magnitude larger than the conventional and widely implemented microwave stochastic cooling. In OSC a particle passes through an undulator (the pickup) and radiates; see Fig. 1. This radiation is amplified while the particle is delayed via a magnetic chicane. The particle and amplified radiation then meet in a second undulator (the kicker) with a relative phase in such a way to provide a corrective longitudinal kick [2] [3].

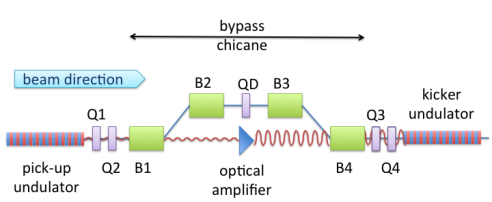

Figure 1: Schematics of the OSC insertion. The labels "Qx", "Bx" respectively correspond to quadrupole and dipole bending magnets.

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The chicane is only capable of providing a few millimeters of delay and thus puts a serious constraint on the optical amplifier (OA) design. A single-pass OA was suggested in [4] using Titanium Sapphire (Ti:Sapph) as the gain medium with a center wavelength of 780 nm.

The Cooling rate is inversely proportional to the bandwidth of the system. Since the undulator bandwidth can be made quite large, the system bandwidth is determined by the OA and so a gain material with a large bandwidth is desirable. Ti:Sapph is a promising candidate gain material because it is capable of providing a large amount of gain for a short signal delay over a large bandwidth.

This paper discusses progress made in the development of a single pass OA using Ti:Sapph, specifically steps toward characterizing the possibility of phase distortions in the amplification process. Additionally Cr:ZnSe is suggested as an alternative gain medium.

PHASE MEASUREMENTS

Technique

If a gain material of thickness T and index of refraction n is inserted into one leg of an interferometer, the relative phase of light passing through can be written as

$$\phi = k[\Delta L + Tn(\lambda)] \tag{1}$$

with ΔL being the path length difference between the two legs, $k \equiv \frac{2\pi}{\lambda}$ and λ is the wavelength of the radiation. The path length difference can be written as $\Delta L = C - Tn(\lambda_o)$ with C being a constant and λ_o a fixed wavelength. The index of refraction can also be Taylor expanded around λ_o. Doing so up to second order and inserting the expression for the path length difference into Eq. (1) yields

$$\phi = kT\left[\frac{C}{T} + \frac{dn}{d\lambda}(\lambda - \lambda_o) + \frac{1}{2}\frac{d^2n}{d\lambda^2}(\lambda - \lambda_0)^2\right] \tag{2}$$

Dividing the above expression by kT results in a quadratic equation in $(\lambda - \lambda_o)$. The linear portion of this equation results in a net delay of the optical pulse and thus can be compensated for by the chicane. The non-linear portion results in a modification of the pulse shape and is not able to be compensated by the chicane. It is this coefficient $a = \frac{d^2n}{d\lambda^2}$ that needs to be measured during the amplification process. This is done by measuring the phase as a function of wavelength and performing a least squares fit.

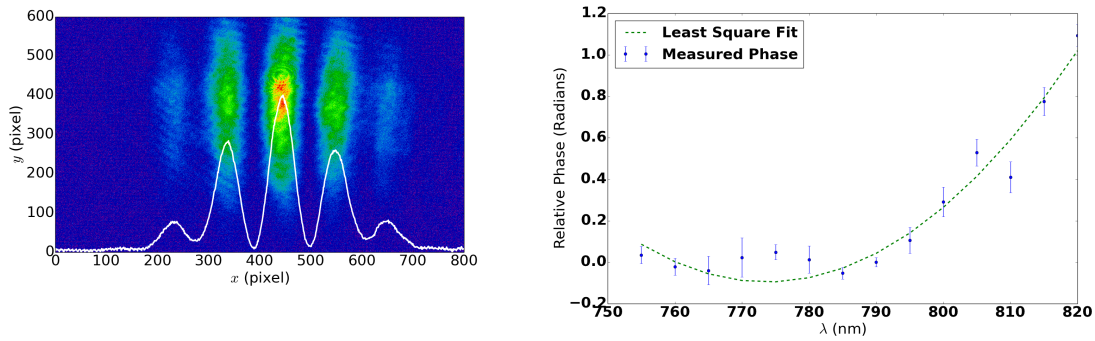

Figure 2: Left: An example interference pattern and its projection along the horizontal axis. Right: The relative phase as a function of wavelength.

The wavelength dependence of the index of refraction is well known from the empirical Sellmeier Equation

$$n^2 - 1 = \frac{B_1\lambda^2}{\lambda^2 - \lambda_1^2} + \frac{B_2\lambda^2}{\lambda^2 - \lambda_2^2} + \frac{B_3\lambda^2}{\lambda^2 - \lambda_3^2} \tag{3}$$

with B_i and λ_i are known constants. With the Sellmeier equation the a coefficient can be calculated when no amplification is present and used to corroborate our results. The Coefficients for Ti:Sapphire are given in Table 1.

Table 1: Sellmeier Coefficients for Ti:Sapph [5]

$B_1 = 1.023798$	$\lambda_1^2 = 0.06144821$
$B_2 = 1.058264$	$\lambda_2^2 = 0.1106997$
$B_3 = 5.280792$	$\lambda_3^2 = 17.92656$

Results for Ti:Sapph

A 2-mm thick Ti:Sapph crystal was used for the measurements. A SPECTRA-PHYSICS TSUNAMI mode-locked laser was used to create an interference pattern directly onto a CCD camera (SONY xcd-sx910). Although the measurements were made with the laser in CW mode, the short pulses generated by mode locking helped minimize the distance between the interferometer legs. An interference pattern was recorded from 755-820 nm. To mitigate error introduced by small vibrations observed in the pattern each measurements was repeated 10 times and averaged. A projection of the pattern is taken and the location of the peak is found. A plot of the peak location as a function of wavelength and an example projection are shown in Fig. 2.

The pixel-to-phase calibration can be readily obtained from the peak-to-peak separation in the interference pattern. Then by multiplying the phase by kT and performing a quadratic least squares fit it is found that $a = 0.068 \pm 0.005$ μm^2.

Next we estimate how the phase should depend on λ using the Sellmeier equation for n in Eq. (1). Again multiplying by kT and performing a least squares fit gives $a = 0.070$ μm^2. Note that, although the constant C in Eq. (2) is physically significant, its value does not alter the value of a and so is set to $C = 0$.

Cr:ZnSe AS A CANDIDATE MEDIUM

It has recently been determined that 780 nm may not be the best wavelength to perform OSC because it does not support cooling in a required acceptance of the IOTA ring. Instead a longer wavelength should be used. A potential gain medium is Chromium doped Zinc Selenide (Cr:ZnSe). Table 2 compiles a list of relevant parameters of Cr:ZnSe and Ti:Sapph.[1]

Table 2: Relevant Optical Properties of Ti:Sapph and Cr:ZnSe

Property	**Ti:Sapph**	**Cr:ZnSe**
σ_{Em} cm^2	3.5x10^{-19} [6]	1.3x10^{-18} [7]
σ_p cm^2	5x10^{-20} [6]	5x10^{-19} [7]
τ μs	3.2 [8]	5 [9]
Emission Peak nm	780 [6]	2450 [7]
Absorption Peak nm	500 [6]	1780 [7]
Δf THz	95 [6]	50 [7]
$\frac{dn}{dT} K^{-1}$	1.3x10^{-5} [8]	6.4x10^{-5} [10]
n	1.76 [8]	2.44 [10]

We now elaborate a simple model of single pass gain amplification to compare the two mediums. Consider a 4-level gain medium such that absorption of a pump photon causes a transition from N_0 to N_3 and amplification occurs from stimulated emission from N_2 to N_1, where N_0 is the ground state and N_i ($i > 0$) are excited ones. If spontaneous emission for N_3 and N_1 happens at a much faster rate than N_2, the input signal intensity I_{so} is sufficiently small, non-radiative transitions are ignored and the pump operates in CW it can be shown that the pump intensity decays through the crystal as

$$I_p = I_{sat} W\left(\frac{I_{po}}{I_{sat}} e^{-\alpha T + \frac{I_{po}}{I_{sat}}}\right). \tag{4}$$

With $I_{sat} \equiv \frac{\sigma_p \tau}{h\nu_p}$, σ_p being the absorption cross section at the pump frequency ν_p, τ is the decay lifetime for N_2,

[1] Emission peak, Absorption peak, Δf are estimated from figures in referenced source [6] [7]. For Cr:ZnSe τ has a dependence on dopant concentration and temperature and so a nominal value is used.

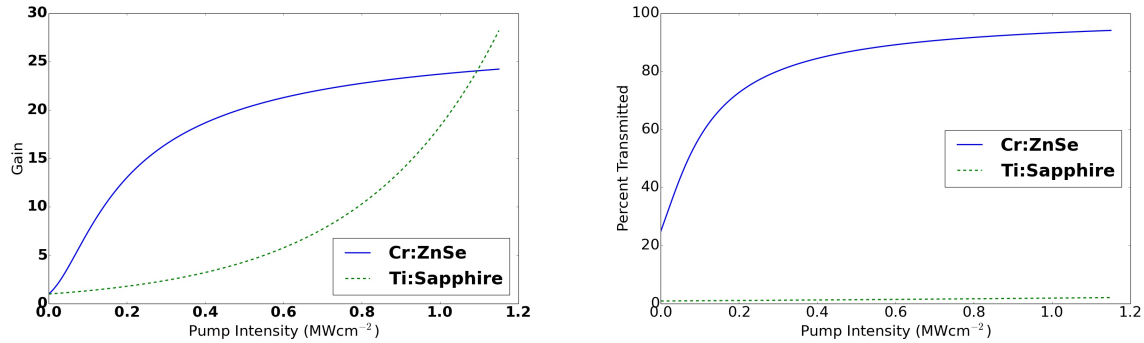

Figure 3: Left:The gain for either a Cr:ZnSe or Ti:Sapph crystal with 2 mm signal delay as a function of intensity. Right: Transmission of pump laser for a CrZnSe and Ti:Sapph crystal.

h is Planck's constant and $\alpha \equiv \sigma_p N_t$ with N_t being the doping concentration. W is the Lambert W Function. For $I_{po} \ll I_{sat}$ Eq. (4) gives exponential decay [11].[2]

From Eq. (4) it can be shown that the small signal intensity is given as

$$I_s = I_{so} e^{\frac{\sigma_{em}\tau}{h\nu_s}(I_{po}-I_p)} \tag{5}$$

To make a comparison of Ti:Sapph and Cr:ZnSe we consider an amplifier with a gain $\frac{I_s}{I_{so}} = 15$. For a fair comparison the total signal delay should be made equal for both crystals. If the chicane is capable of providing 2 mm of the delay for the crystal (not including delay from the necessary focusing lenses) this gives a thickness of 1.4 mm and 2.6 mm for Cr:ZnSe and Ti:Saphh respectively. $N_t = 2.5\text{x}10^{20}$ ions-cm^{-3} is chosen for Ti:Sapph as it is the highest doping that is commercially available. For Cr:ZnSe we choose $N_t = 2.0\text{x}10^{20}$ ions-cm^{-3} although higher doping is possible.

For pumping Cr:ZnSe an Erbium fiber laser can pump with a power of 15 W at 1570 nm and for Ti:Sapph a diode laser can pump at 532 nm up to 25 W. Figure 3 shows a plot of gain as a function of pump intensity. For a gain of 15 the pump intensity for Cr:ZnSe is 0.25 MW cm^{-2} corresponding to focusing the beam waist to 40 μm. For Ti:Sapp 0.9 MW cm^{-2} is needed, corresponding to a beam waist of 30 μm.

The leveling off of the gain seen for Cr:ZnSe is explained from its relatively low pump saturation intensity which is nearly a factor of 50 less than Ti:Sapph. As the pump intensity increases N_0 becomes depleted and the percent transmission of the pump beam quickly increases as shown in Fig. 3. Transmission from Ti:Sapph shows little dependence at these pump intensities and so essentially decays exponentially in the medium.

Also from Fig. 3 (right) we see that a Ti:Sapph amplifier will not benefit from a longer crystal as the majority of the pump has already been absorbed; Cr:ZnSe on the other hand can benefit tremendously from even slight increases in crystal length.

Furthermore since cooling rate scales as $P^{-1/2}$ and Δf^{-1} [13](where Δf and P are respectively the bandwidth and power of the amplified pulse) in order for Cr:ZnSe to perform as well as Ti:Sapph, assuming the pickup provides the same input signal bandwidth and power, Cr:ZnSe must provide $\sqrt{\frac{\Delta f_{Ti:Sapph}}{\Delta f_{CrZnSe}}} = \sqrt{\frac{95}{50}}$ as much gain to perform equivalently.

One last consideration is the possibility of thermal lensing. One option is cooling the amplifier with liquid nitrogen. However this only reduces dn/dT from 6.4x10^{-5} to 5.1x10^{-5} [10].

[2] A similar derivation for a two level medium can be found in [12].

FUTURE WORK

The next step is to measure the a coefficient during the amplification process with the Ti:Sapph crystal. We have already amplified pulses using as a pump a YAG laser with a frequency doubling crystal (Quanta Ray from Spectra Physics). The pump wavelength was 532 nm with pulse energy of 120 mJ and some focusing.

A pulsed laser is used to avoid complications with cooling; However this makes the amplification transient. To ensure the interference pattern is measured only during amplification a pockel, cell triggered by the pump laser, will be used on the signal pulse. By observing the amplified signal on an oscilloscope a delay unit can be used to choose the time of arrival and the signal length. The arrival time should be when amplification is at a maximum. The signal length should be short enough to have a constant amplitude but long enough to have a well defined frequency.

After the timing has been optimized the measurements and analysis will proceed as before. By repeating this at different pump intensities, a can be measured as a function of gain. We will also begin development of a Cr:ZnSe amplifier and perform similar analysis.

REFERENCES

[1] S. Nagaitsev *et al.*, In *Proc. IPAC'12*, New Orleans, LA, USA, 2012, p. 106.

[2] M.S. Zolotorev, and A.A. Zholents, Phys. Rev. E, **50**, (4), p. 3087 (1994).

[3] A.A. Mikhailichkenko, and M.S. Zolotorev Phys. Rev. Lett. **(71)**, (25), p. 4146 (1993).

[4] V.A. Lebedev *et al.*, In *Proc. NAPAC'13*, Pasadena, CA, USA, 2013, p. 422.

[5] I. H. Malitson. J. Opt. Soc. Am. **52** (12), p. 1377 (1962).

[6] Titan CW CW Ti:Sapphire Laser Operation Manual. Q-Peak Inc.

[7] Tm:Znse /S Series Data sheet. IPG Photonics Inc. (2012).

[8] Ti:Sapphire Crystal. Altechna Inc.

[9] V. E. Kisal *et al.*, In Proc. Advanced Solid-State Photonics, Santa Fe, NM, USA, 2004, p. 367.

[10] H. H. Li. J. Phys. Chem. Ref. Data. **13**, (1), p. 103 (1984).

[11] M. B. Andorf *et al.*, to be presented at the COOL'15 Workshop, Newport News, 2015.

[12] H. Abitan *et al.*, J. Opt. Soc. Am. **47** (29), p. 5354 (2008).

[13] A. Zholents, and M. Zolotorev, In *Proc. PAC'97*, Vancouver, B.C., Canada, 1998, p. 1805.