6th North American Particle Accel. Conf. (NAPAC2025), Sacramento, CA, USA JACoW Publishing
ISBN: 978-3-95450-261-5 ISSN: 2673-7000 doi: 10.18429/JACoW-NAPAC2025-WEP021

DESIGN OF AN OPTICAL AMPLIFIER FOR AMPLIFIED OSC IN IOTA FACILITY AT Fermilab*

A. Mondal†, J. Ruan, J. Jarvis
Fermi National Accelerator Laboratory, Batavia, IL, USA

Abstract

Optical stochastic cooling (OSC) is a cutting-edge beam cooling technology that enables high-bandwidth cooling and control of the phase space of particle beams. It has recently been successfully, experimentally, demonstrated in Fermilab's IOTA storage ring, marking a major step forward in beam cooling. One promising way to boost OSC performance is by adding a high-gain optical amplifier. However, this amplifier must be carefully designed to meet the specific constraints of the OSC system. A major challenge lies in the limited optical delay, which is just 6 mm for the case of IOTA and restricts us to use a short-length gain medium. Additionally, IOTA's high repetition rate and the relatively long bunch length, limits the peak power available for the pump laser without damaging the crystal, which is crucial for achieving strong nonlinear gain. Furthermore, it's essential to preserve the phase coherence of the OSC radiation during amplification, which further complicates the amplifier design. This report details a specialized amplifier setup that addresses these challenges, includes simulations of the integrated system, and summarizes the latest experimental progress and results.

INTRODUCTION

Since the proposal of optical stochastic cooling (OSC) in early ninties it is regarded as a superior beam cooling technology to control the phase-space density of particle beams due to its much wider optical bandwidth comparing to the conventional stochastic method [1, 2]. OSC has recently been experimentally demonstrated, establishing it as a powerful beam manipulation technique capable of cooling, heating, and controlling both ensembles and single particles [3]. With the core physics validated, current efforts at the Integrable Optics Test Accelerator (IOTA) are focused on advancing OSC performance through the implementation of an optical amplifier to enhance radiation from the pick-up undulator [4]. We explore the use of an optical parametric amplifier (OPA) for this purpose, leveraging its high gain and broad tunability across the visible to mid-infrared (MIR) spectrum [5]. A typical OPA consists of a high-power pump laser and a nonlinear crystal, which is transparent to both pump and signal frequencies, ensuring minimal absorption and thermal load. The amplification is parametric, involving virtual transitions and no net energy exchange with the crystal, enabling efficient power scaling without heat accumulation. To achieve amplification, both energy and momentum (phase-matching) conservation must be satisfied. The process generates an idler wave at frequency $\omega_i = \omega_p - \omega_s$ as required by $\hbar(\omega_p - \omega_s - \omega_i) = 0$ [5, 6]. The gain scales hyperbolically with the product of crystal length and pump amplitude [5]. The pump intensity we can use for the process is limited by the thermal damage threshold occurring due to the small linear absorption of the pump in the crystal. In our experiment, the length of the crystal is limited by the delay budget created by sending the electron beam via a bypass between the pick-up and kicker undulators [3]. In the current IOTA configuration, we estimated a delay budget around 6 mm within which all optical components including dichroic coupling mirrors, delay-adjustment plates, and a relay telescope must be accommodated. A critical requirement for OSC is the preservation of the undulator radiation's phase throughout amplification and transport. The relay optics should ensure a $\pm I$ transfer matrix while suppressing depth-of-field effects. In this work, we demonstrate a design achieving up to 40 dB amplification under these constraints, maintaining the phase integrity essential for OSC functionality.

THEORY

Initial design studies for the amplified OSC system were performed in Synchrotron Radiation Workshop (SRW) [3]. Based on available nonlinear crystals and commercially viable pump lasers, we selected undulator parameters that yield broadband radiation centered at 2.1 µm with a FWHM of 1.6 µm. For amplification, we used a periodically poled lithium niobate (PPLN) crystal for its high nonlinear coefficient and large acceptance bandwidth [7]. Pumped by a high-energy, narrowband laser at 1.064 µm. The amplification process was modeled using coupled-wave equations for difference-frequency generation (DFG), assuming low pump depletion and slowly varying envelopes. The signal (A_s) and idler (A_i) field amplitudes evolve as

$$\frac{dA_s}{dz} = \frac{2j\omega_s^2 d_{\mathrm{eff}}}{k_s c^2} A_p A_i^* e^{j\Delta kz}, \quad \frac{dA_i}{dz} = \frac{2j\omega_i^2 d_{\mathrm{eff}}}{k_i c^2} A_p A_s^* e^{j\Delta kz}, \tag{1}$$

where A_n and ω_n ($n = p, s, i$) are the complex amplitudes and angular frequencies of the pump, signal, and idler, respectively. The phase mismatch is $\Delta k = k_p - k_s - k_i$, d_{eff} is the effective nonlinear coefficient, and c is the speed of light in vacuum. In quasi-phase-matching, the spontaneous polarization of PPLN is periodically inverted to achieve first-order, type zero phase-matching. This modifies the mismatch as $\Delta k = k_p - k_s - k_i - 2\pi/\Lambda$, where Λ is the poling period.

* Work supported by Fermi Forward Discovery Group, LLC under Contract No.89243024CSC000002 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics.
† amondal@fnal.gov

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Figure 1 shows the simulated gain spectrum as a function of Λ and temperature.

This operating point corresponds to degeneracy, where signal and idler wavelengths are equal [7, 8]. While this yields high gain across a broad bandwidth, it introduces phase sensitivity [7,8]. To explore this, we computed gain as a function of pump phase ϕ_p for various signal wavelengths (Fig. 2).

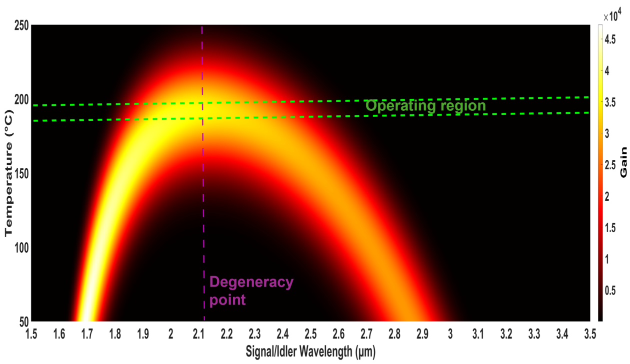

Figure 1: Simulated parametric gain vs. crystal temperature for $\Lambda = 31.59$ µm, with pump wavelength 1.064 µm, pump intensity $I_p = 1.2\,\mathrm{GW/cm^2}$. Maximum gain occurs at 192 °C (at degeneracy).

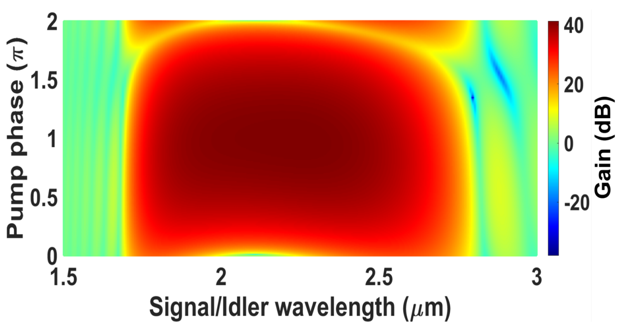

Figure 2: Gain vs. pump phase ϕ_p for different signal wavelengths. Maximum gain occurs when $\Delta\phi = \phi_p - \phi_s - \phi_i = \pi$.

Maximum gain is achieved when $\phi_p = \phi_s + \phi_i + \pi$. In contrast, when $\Delta\phi = 0$, the signal and idler experience attenuation rather than amplification. To further examine the phase dynamics, we simulated signal and idler evolution in the crystal for different ϕ_p at the degenerate wavelength 2.128 µm, assuming initial phases $\phi_{s0} = \phi_{i0} = 0$ (Fig. 3). These results show that $\Delta\phi = \pi$ is the optimal condition for gain without phase distortion when both signal and its complimentary idler is present at the input of the nonlinear crystal. Any self-induced phase drift can degrade OSC performance and must be avoided. Thus, maintaining $\Delta\phi_0 = \pi$ at the crystal entrance is essential. Figure 3(b) shows that the dependence of gain and phase upon the initial pump phase can be removed in the cost of relatively small gain when the input only contains the signal (or idler) at the input.

This can be enforced by shifting the UR spectrum to one side of the degeneracy line (here we have chosen the higher wavelength side) shown in Fig. 1. To preserve the spatial phase and match the beam transport between the pick-up and kicker undulators, we implemented a four-lens relay telescope that ensures a $+I$ transfer matrix with depth-of-field suppression. The magnification profile across the undulator length is shown in Fig. 4.

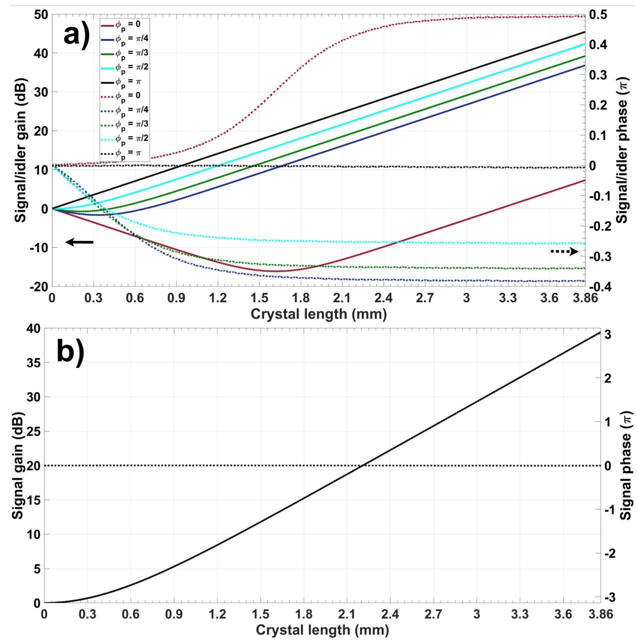

Figure 3: Signal gain and phase evolution through the crystal for various pump phases ϕ_p. a) when signal/idler wavelength span is spread across degeneracy, b) when signal wavelengths are shifted to one side of degeneracy point

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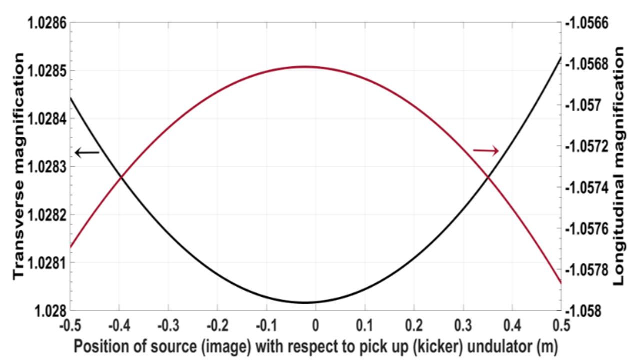

Figure 4: Magnification across the undulators from the relay telescope. The $+I$ transfer and tight focus at the crystal enhance nonlinear gain while preserving phase.

EXPERIMENT

In the actual experiment, the entire amplifier system will operate under vacuum and be coupled to the IOTA accelerator ring. Figure 5 shows a schematic of the experimental

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setup, located along one of the IOTA arms. PU and KU denote the pickup and kicker undulators, respectively. Magnets M1 through M4 form the chicane for particle bypass. Lenses L1 to L4 constitute the telescopic relay system mapping the undulator radiation from PU to KU. Two dichroic mirrors (DCM) couple the pump beam into and out of the nonlinear crystal. The second DCM also serves as a delay plate to adjust the relative timing between the optical path and particle bypass. A lens L focuses the pump beam into the nonlinear crystal (NC), which amplifies the signal from PU.

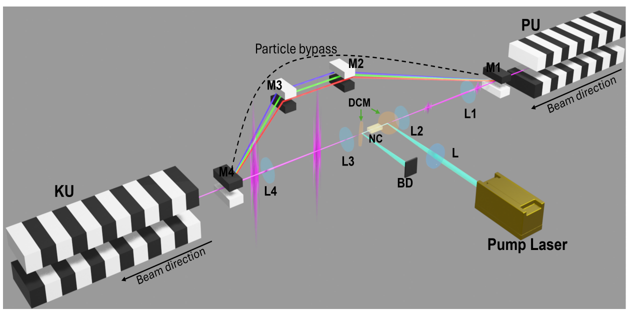

Figure 5: Schematic of the experimental setup at IOTA, illustrating undulators (PU, KU), chicane magnets (M1–M4), lenses (L1–L4), dichroic mirrors (DCM), pump focusing lens (L), and nonlinear crystal (NC).

Prior to commissioning the beamline setup, we constructed a tabletop prototype amplifier in our laser laboratory to evaluate OPA performance and the telescopic system. The prototype used a mode-locked Nd:YLF laser producing 12-ps pulses at 5 Hz repetition rate, centered at 1.053 µm. Figure 6 presents a photograph of the prototype. Since the pickup undulator was unavailable, we emulated the synchrotron radiation signal using a 10-mm-long PPLN-based optical parametric generator (OPG). The OPG signal was spectrally filtered to remove the pump and injected into a second 3-mm-long PPLN crystal. Pumping this crystal amplified the signal mimicking the actual OSC conditions. Diagnostics were performed on the amplified output after filtering residual pump light via a dichroic mirror.

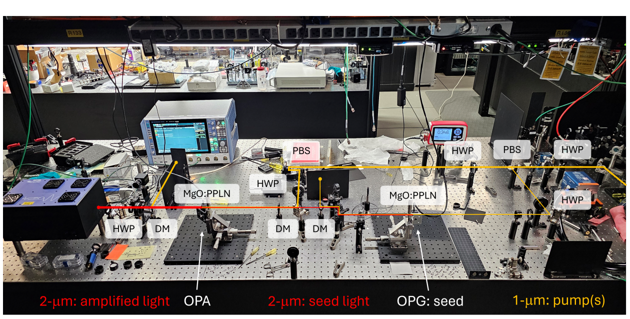

Figure 6: Tabletop prototype OPA setup in the laser laboratory, illustrating the OPG source, amplification stage, and diagnostic components.

We recorded spectra using a MOZZA spectrometer and measured power gain with a photodiode (not shown). Figure 7(a) compares the spectra of the initial OPG signal and the amplified output. Figure 7(b) plots the gain derived from the measurements. Broadband gain of approximately 30 dB was achieved, limited by the 3-mm crystal length compared to the simulated 3.86-mm crystal. The central dip in the gain spectrum likely arises from a phase mismatch, $\Delta\phi = \phi_p - \phi_s - \phi_i \neq \pi$, between pump and signal/idler waves.

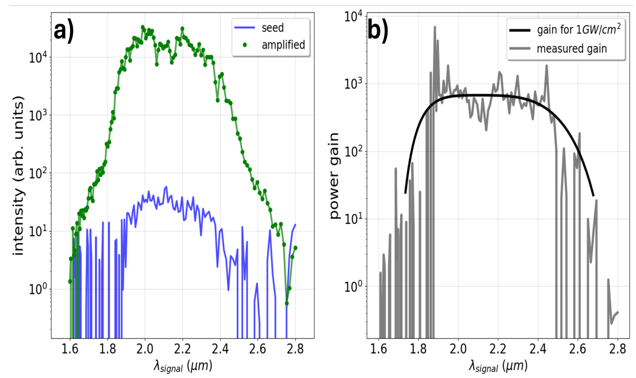

Figure 7: Experimental results: (a) Measured spectra of the OPG signal (blue) and amplified output (green). (b) Calculated gain versus wavelength showing a peak of ~ 30 dB and a central dip attributed to non π phase difference.

CONCLUSION

We have demonstrated a design and tabletop validation of a high-gain, phase-preserving optical parametric amplifier tailored for enhanced optical stochastic cooling at IOTA. Our analysis identified optimal phase-matching conditions near degeneracy, revealing the critical role of input phase alignment to avoid detrimental phase shifts during amplification. The implemented four-lens telescope ensures precise relay of the undulator radiation with minimal depth-of-field effects, maintaining spatial and phase coherence essential for OSC. Experimental tests using a prototype setup verified gain exceeding 30 dB and confirmed the phase sensitivity predicted by theory. These results establish a robust foundation for integrating a compact, high-performance amplifier within the strict optical delay constraints of IOTA, advancing the practical realization of amplified OSC systems.

ACKNOWLEDGMENT

This manuscript has been authored by FermiForward Discovery Group, LLC under Contract No. 89243024CSC000002 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics.

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