Deliverable Report

Deliverable No: 2.4

Deliverable Title: Special-purpose laser source for high clock rate pulsed squeezing

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Project title: European Photonic Quantum Computer

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Deliverable table

Deliverable no.	2.4
Deliverable name	Special-purpose laser source for high clock rate pulsed squeezing
WP no.	2
Type	DEM — Demonstrator, pilot, prototype
Dissemination level	PU - Public
Delivery date from Annex I	Month 12
Actual delivery date	
Lead beneficiary	NKT PHOTONICS
Name and surname of the scientific representative	Casper Ahl Breum
Email address of the scientific representative	Casper.breum@nktphotonics.com

What was planned *(from Annex I:)*

D2.4: Special-purpose laser source for high clock rate pulsed squeezing [M12]

Target parameters: 1 GHz repetition rate, 100-300 ps pulses (switchable to continuous-wave operation), ~1 W peak power at 775 nm, 100 mW at 1550 nm.

Introduction

The desire for a “special-purpose laser source”, which is to be developed within T2.4, comes from the specific requirements of the quantum computing architecture of the QSQUEEZE machine. The machine will implement the continuous-variable version of the measurement-based quantum computation (CV-MBQC) scheme on a quantum photonic integrated circuit (QPIC) platform. The CV-MBQC scheme uses squeezed vacuum states as its base resource state. These states are notoriously fragile as their unique quantum properties vanish quickly with linear loss and phase noise. In fact, based on the exact protocol and associated error-correction scheme being implemented, one can often calculate explicit thresholds for the squeezing levels required for the protocol to succeed (eg. beat the associated classical limit, show supremacy, supress errors, etc.).

In the QSQUEEZE machine the squeezed vacuum states will be generated by the conventional method of spontaneous parametric down-conversion (SPDC) inside on-chip optical parametric oscillator (OPO) cavities. In the SPDC process a pump photon at frequency 2ω is converting into two signal photons at frequency ω. Even though the noise of the pump field is not coupled to the signal field when generating squeezed vacuum, the noise of the laser source is still relevant is it determines the stability of many auxiliary functions within the QSQUEEZE machine, such as the squeezing level of the signal field when a seed beam is injected as a phase reference, the stability of various interference locks and the effectiveness of the technical noise cancelation during homodyne measurement. To generate and effectively measure the high levels of squeezing required for CV-MBQC it is therefore critical to use a high-quality laser source that is stable and has both low intensity and phase noise.

Besides the noise requirements, the QSQUEEZE machine also requires the pump laser field to be delivered as quasi-CW, ideally top hat shaped, pulses (essentially short pieces of CW light). This requirement is of a more practical nature and stems from the eventual need to use photon counting measurements as part of the CV-MBQC scheme. The specific pulse regime of 100-300ps pulse width and 1GHz repetition rate comes from the QPIC platform. The width must match the bandwidth of the on-chip OPO cavities, and the repetition rate must be fast enough to allow for on-chip delay lines and short-as-possible off-chip delay lines as used for the cluster state generation.

Laser platform

To realize a laser source with the specifications of D2.4 NKT Photonics (NKTP) has opted to build a laser system based on its *Koheras* platform. This platform uses rare-earth doped fiber lasers and amplifiers to provide an industry-leading combination of narrow linewidth, low noise and high power at the 1-2um telecom band while also ensuring industrial reliability and robustness. With frequency conversion these specs are further brough to the visible regime.

The laser system is build using standard and prototype *Koheras* linecard modules that are mounted in a *Koheras* ACOUSTIK to form a compact, rack-mountable and fiber coupled solution. The standard modules of the systems are *Koheras* BASIK to generate a low noise seed at 1550nm, *Koheras* BOOSTIK as amplifiers and *Koheras* HARMONIK to facilitate the frequency conversion of 1550nm to 775nm. The system is named the “QSQUEEZE Laser System” and is pictured in fig. 1.

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Fig. 1 Picture of the current (11-12-2024) assembly status of QSQUEEZE Laser System.

What has been done

- NKTP has designed, build and tested a prototype laser system that delivers a main 775nm fiber coupled output that can be switched between CW and pulsed operation, and two fiber coupled tap outputs at 1550nm, one CW and one pulsed.

- Significant development time was used on building and testing a setup for the flexible generation (down to 100ps width and up to 1GHz repetition rate) and characterization (amplitude, rise/fall time, width, timing jitter) of optical pulses at both 1550nm and 775nm.

- Developing the integrating of the necessary components of the pulse generation setup into the *Koheras* platform.

- Based on feedback from the QSQUEEZE machine partners, NKTP has implemented a hardware modification of the amplifier modules to reduce the RIN below the standard specification.

Results

With the QSQUEEZE Laser System NKTP have successfully generated:

- Stable 775nm pulses with peak powers of **>3W** for pulse regimes between **125-340ps at 0.5-1GHz** (12.5-22.5% duty-cyle) with rise/fall times between **40-70ps**
- **>1W of continuous-wave** 775nm light
- For both pulsed and CW mode the system operates at **>50% conversion efficiency**
- 1550nm tap outputs with >100mW CW and >100mW pulsed peak power.

The main benchmark of D2.4 is shown in fig. 2 as the 775nm output power and conversion efficiency for both CW and pulsed mode as a function of the 1550nm input power. For CW mode power is measured as the average power and for pulsed mode the power is measured as the peak power of the approximate flat top pulse. The peak height is estimated from a calibrated time-resolved measurement of the pulse shape using a fast pulse-optimized photodiode and a 20GHz sampling oscilloscope. The calibration is performed by first measuring a known CW input power, thereby calibrating the scope voltage range to a corresponding optical power range. The pulsed data points of fig. 2 are calculated from the pulse traces shown in fig 3.

From fig. 2 we see that the SHG module performs well in both CW and pulsed mode; the 775nm output power scales linearly with the 1550nm input power and that the conversion efficiency converges to around >50%. As is the case here, we typically see slightly better performance for pulsed conversion compared to CW conversion for this type of system. The exact mechanism behind this behaviour is still under investigation.

In fig 4. we show the effect of doubling the pulse length, while keeping repetition rate and amplifier settings fixed. The 775nm output peak power is roughly halved in response to the approximate doubling in duty cycle from 12.5% to 22.5%. We also note that no degradation of extinction ratio or pules stability is observed between the two pulse regimes.

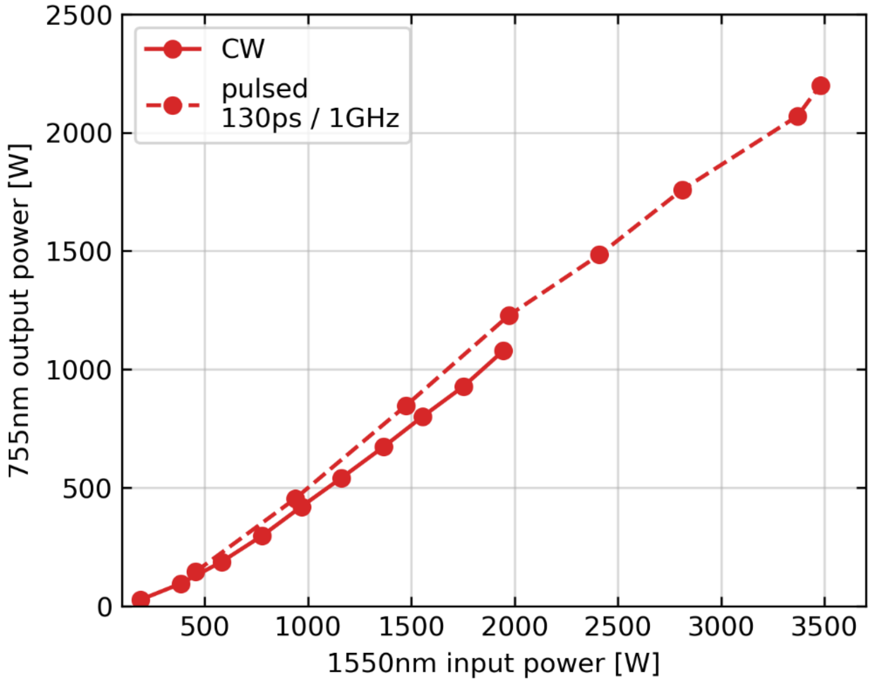

Fig. 2 Performance of the frequency conversion of the QSQUEEZE Laser System for CW (solid) and pulsed (dotted) mode.

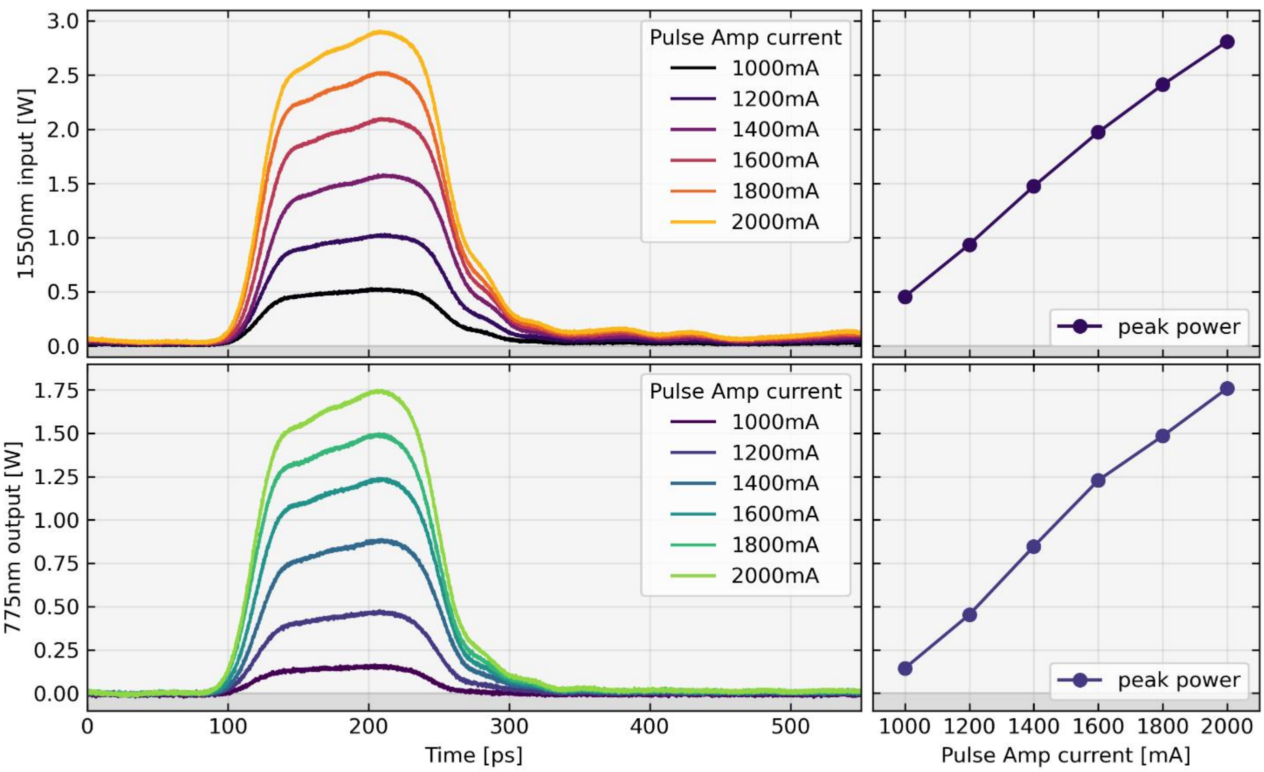

Fig. 3 Temporal pulse shape evolution during amplification (top-left) and frequency conversion (bottom-left). Linear scaling of the peak power with the pump current is observed (right).

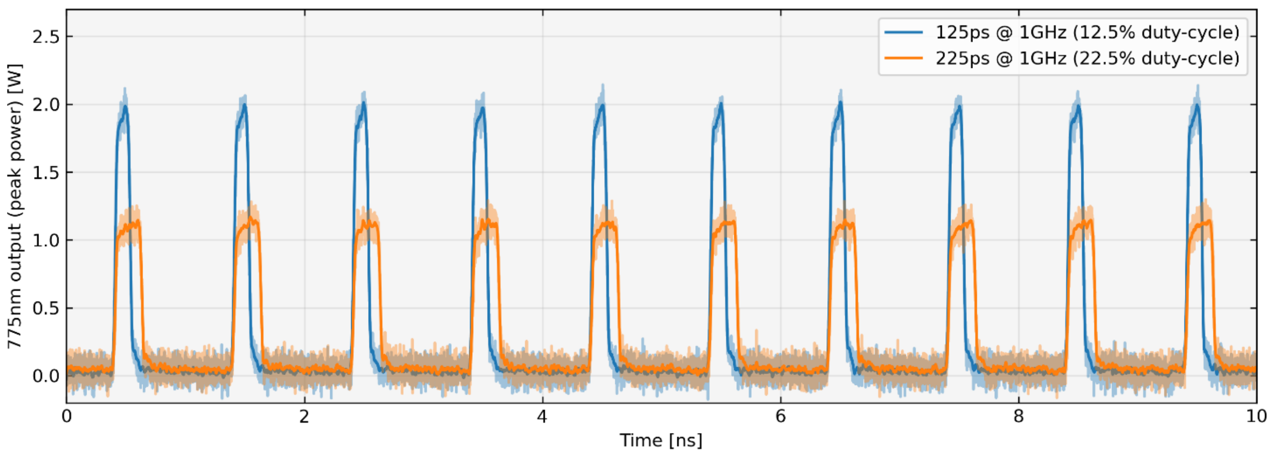

Fig. 4 Time traces of 775nm pulse trains at equal amplification and frequency conversion settings. The effect of approximately doubling the duty-cycle roughly halves the peak power.

Funded by the European Union

Laser noise measurements

As a standard benchmark, we also provide the relative intensity noise (RIN) and frequency noise spectrums of the QSQUEEZE Laser System in fig. 5. The RIN is measured directly with a photodiode and the frequency noise is measured through an imbalanced Mach-Zehnder interferometer. For the RIN spectrum, the effect of the hardware modification is to reduce the noise in the 0.1-100kHz range to below the standard specification. Frequency noise is within the standard specification for the related NKTP products.

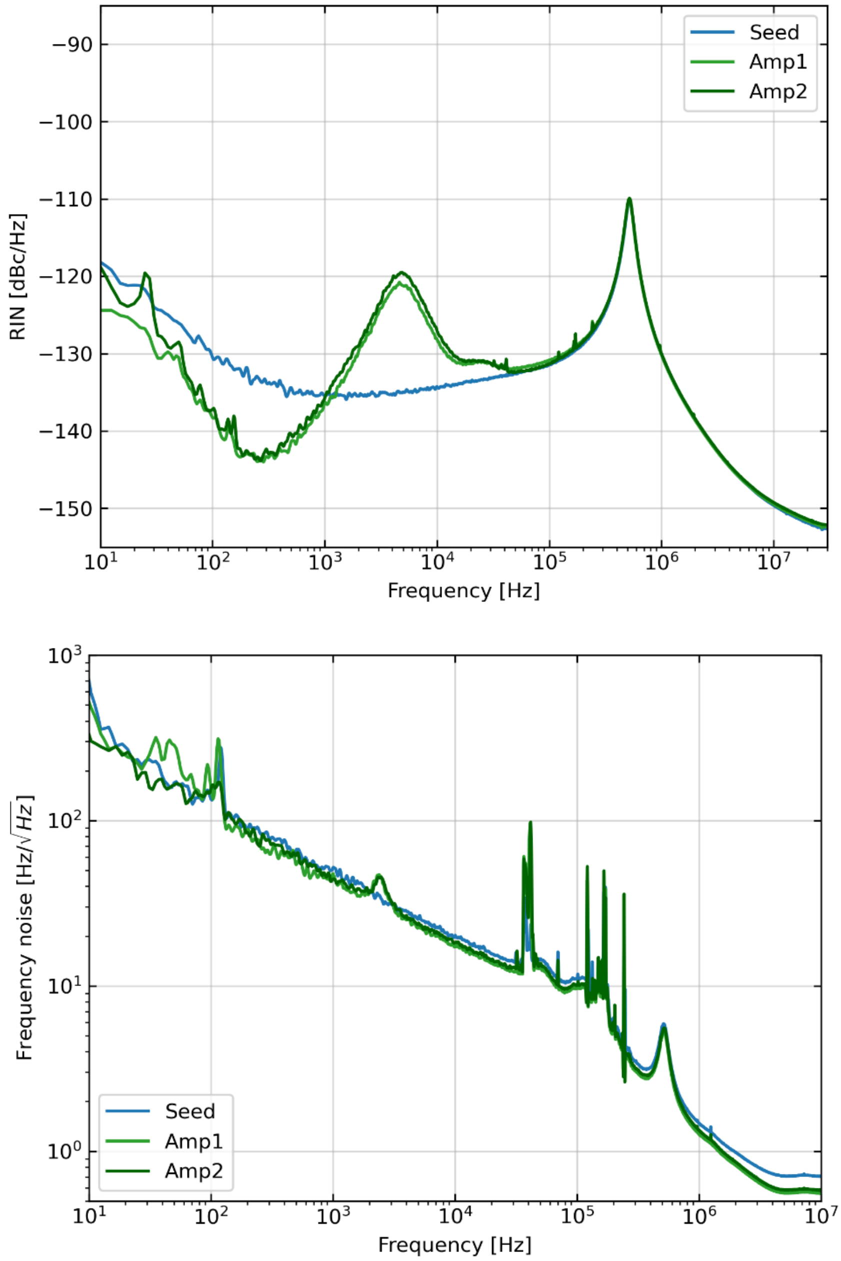

Fig. 5 (Top) RIN spectrum of the seed and amplifier modules. (Bottom) Frequency noise spectrum of the seed and modified amplifier modules.