

40-Pulse Time-Multiplexed Nanophotonic Optical Parametric Oscillator

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Abstract: We implement a 40-pulse, time-multiplexed optical parametric oscillator in thin-film lithium niobate nanophotonics and demonstrate the independent phase behavior of the pulses in the degenerate and non-degenerate regimes, enabling scalable optical computers and complex simulators. © 2023 The Author(s)

Time-multiplexed systems have become ubiquitous in many subfields of optics, as they offer the ability to create large-scale graphs through the storage of information across distinct temporal bins. As such, they have found applications in areas such as computing, quantum information, and study of topological phenomena [1–3]. Time-multiplexed networks of optical parametric oscillators (OPOs), and specifically OPOs at degeneracy, have been of particular interest due to their ability to approximate the Ising Hamiltonian [4, 5]. Recent advances in thin-film lithium niobate, including demonstrations of extremely high parametric gains [6] and subsequent demonstrations of optical parametric oscillation [7], bring the possibility of achieving such time-multiplexed systems to a chip scale. Here, we demonstrate an on-chip, 40-pulse, time-multiplexed OPO. Through the use of interferometric techniques, we verify the independence of each of the 40 simultaneously oscillating pulses. This work represents a critical milestone in the path towards creating large-scale graphs in an integrated photonic platform.

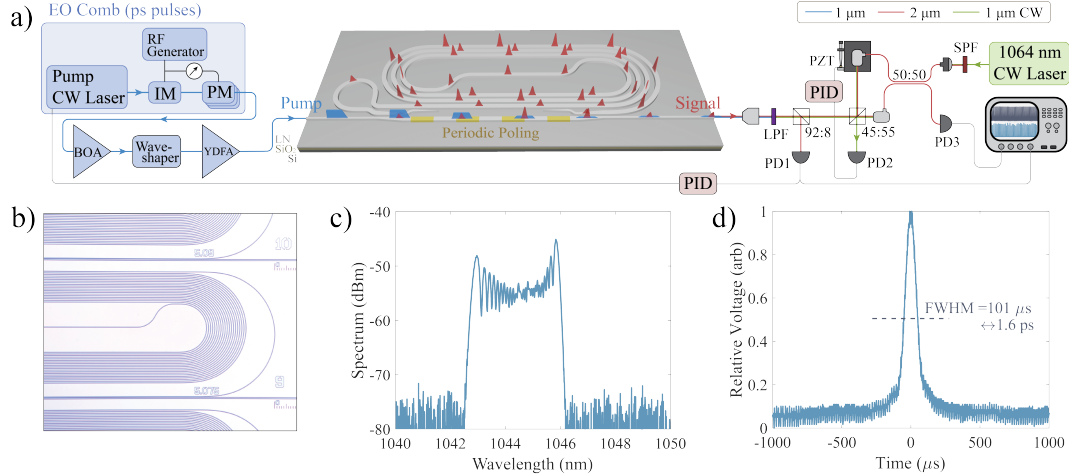


Fig. 1. Experimental setup for measuring the 40-pulse time-multiplexed optical parametric oscillator. (a) An EO comb with a 10-GHz repetition rate is used to pump the on-chip spiral OPO cavity with a 250-MHz free-spectral range, leading to simultaneous oscillation of 40 independent signal pulses. The pump is characterized by its spectrum (b) and intensity autocorrelation (c). (d) Optical microscope image of the fabricated on-chip spiral cavity.

The experimental setup is schematically depicted in Figure 1. We use an electro-optic (EO) comb (Figure 1a, left) with a 10 GHz repetition rate to pump the 250 MHz on-chip optical parametric oscillator such that 40 pulses resonate in the cavity. Following the EO comb generation, our pump preparation includes a booster optical amplifier (BOA), waveshaper, and Ytterbium-doped fiber amplifier (YDFA) for amplification and dispersion compensation. The pump is characterized by its spectrum (Figure 1c) and intensity autocorrelation (Figure 1d), demonstrating over 3 nm of bandwidth around a center wavelength of 1045 nm and an autocorrelation width of 1.6 ps. Periodic poling on the waveguide (Figure 1a, center) provides phase matching between the pump and the signal around 2090 nm. Tapered couplers ensure coupling of the signal to the resonator while allowing the pump to pass through. An optical microscope image highlighting the 53-cm spiral resonator is shown in Figure 1b.

We characterize the relative phases of the output pulses using an unbalanced (1-pulse delayed) Mach-Zehnder interferometer (MZI) consisting of a 45:55 free-space pellicle beamsplitter and a 50:50 fiber splitter (Figure 1a, right). One of the free-space arms has a delay stage which can be locked using a piezoelectric transducer (PZT) to the signal from a back-propagating CW laser at 1064 nm coupled through one MZI output port and measured on a photodetector (PD2). Using this 100-ps delay, we interfere consecutive pulses in the 10-GHz pulse train. A 1-MHz photodetector (PD3) at the other MZI output measures the average value of these interferences over many pulses. If the phases of the 40 pulses are random and independent of one another, we expect to see a different average interference value for every instance of the OPO. To measure this, we modulate the BOA in the pump preparation setup to carve out 4 μ s pulses at a repetition rate of 10 kHz on top of the 10 GHz comb. This serves to rapidly turn the OPO on and off. We additionally use a 92:8 pellicle at the output of the chip to continuously monitor the MZI input on PD1 for both referencing the measurement and pump stabilization.

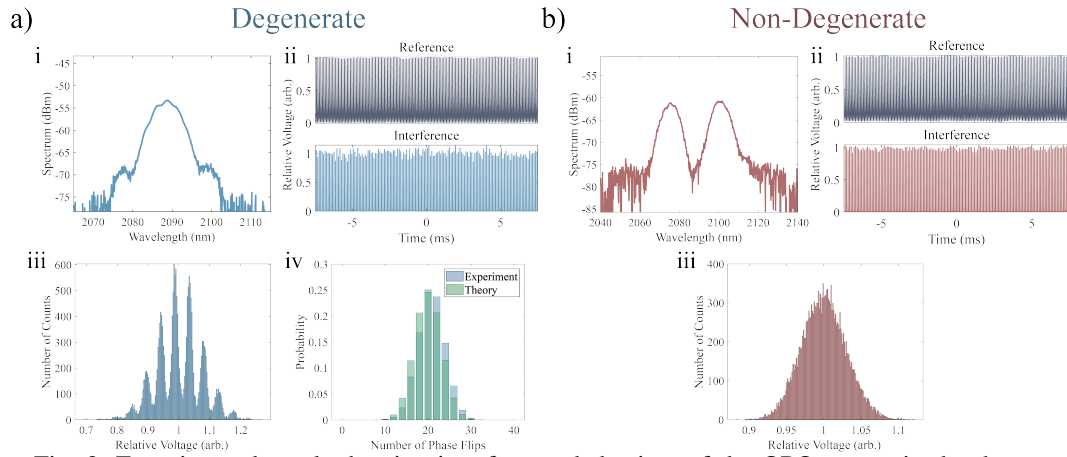


Fig. 2. Experimental result showing interference behaviors of the OPO output in the degenerate (a) and non-degenerate (b) cases. Subfigure (i) shows the spectrum for both. (ii) Sample of the interference time trace data as compared to the reference, measured at the input of the interferometer. (iii) Histogram of peak value measured in each time bin, showing the expected discretization when the OPO is degenerate. (iv) For the degenerate case, comparison with the theoretical probability mass function of the output levels.

Figure 2a shows the experimental results in the case of degeneracy, where oscillation occurs at the half-harmonic of the pump, as confirmed in the measured optical spectrum (i). Here, the OPO is expected to oscillate in only two phase states, 0 or π . With 40 pulses, the average value of the resulting interference should have only 21 possible allowed levels. The probability of each level is given by $\frac{1}{2^{39}} * \binom{40}{N}$, where N is the number of phase flips that occur in the string of 40 pulses. In sub-figure (ii), a sample train of OPO instances is shown. The reference trace collected from the 8:92 splitter allows for post-correction of the measured data to account for intensity noise in the OPO output. The time trace from the interference, shown in the lower panel, shows significantly larger fluctuations than the reference, as expected. A histogram of the interference output over a measurement time of 2 s is shown in (iii). Here, the expected discrete states are clearly observed, indicating that the 40 pulses are in fact behaving as independent, time-multiplexed degenerate OPOs with random binary phases. In addition, we can use the histogram from (iii) to compute a probability mass function and compare it with the theoretical probabilities. The result (iv) shows good agreement between the experiment and theory.

We also measure the case of non-degenerate oscillation, as illustrated in Figure 2b. Here, the optical spectrum indicates distinct signal and idler modes (i). As in the degenerate case, a sample of the time trace data (ii) shows larger fluctuations for the interferences than for the reference measurement. However, unlike the degenerate case, the phase of the non-degenerate OPO is not constrained to discrete levels but can take on any level. Thus, we expect to see a continuous, Gaussian distribution in the histogram, as observed in (iii).

In conclusion, we demonstrate a 40-pulse, time-multiplexed, nanophotonic optical parametric oscillator operating in both the degenerate and non-degenerate regimes. Through measurement of the average interference between consecutive pulses for many instances of the OPO, we have shown the independence of all 40 pulses. This result paves the way for implementing on-chip, optical time-multiplexed systems such as Ising machines

References

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