100 dB/cm broadband optical parametric amplification in dispersion engineered nanophotonic lithium niobate waveguides

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Abstract: We demonstrate phase-sensitive amplification and confirm a gain exceeding 100 dB/cm on a dispersion-engineered thin-film lithium niobate waveguide, using less than 20 pJ of pump energy, and exhibiting a gain bandwidth larger than 600 nm around 2.09 μm.

Amplifiers are essential components for a range of optical systems from sensing [1], to optical computing [2] and communications [3], and obtaining large gains in integrated photonics remains an important challenge. So far, most efforts in integrated photonics using nonlinear mechanisms have focused on four-wave mixing [4] and stimulated Raman [5] and Brillouin [6] scattering, which despite recent advances still suffer from the weak nature of these nonlinearities. On the other hand, semiconductor optical amplifiers are capable of delivering outstanding levels of gain, but are not native to the leading integrated photonic platforms and therefore require further advances in heterogeneous integration [7]. Here we use the quadratic nonlinearity of thin-film periodically poled lithium niobate (PPLN), and dispersion engineering of a nanophotonic waveguide, to design and experimentally demonstrate an optical parametric amplifier (OPA) operating at degeneracy, with gain levels exceeding 100 dB/cm using less than 20 pJ of pump energy, and exhibiting a gain-bandwidth that spans more than 600 nm around 2.09 μm.

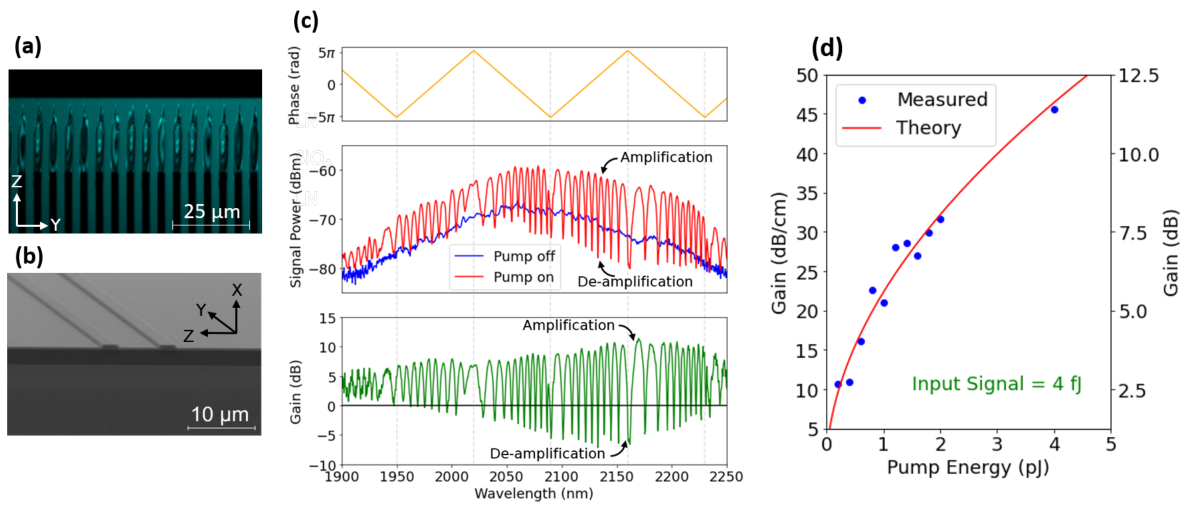

Fig. 1. **Thin-film PPLN waveguides and small-signal gain measurements for a 2.5-mm-long waveguide.** **(a)** Two photon microscope image of the periodically poled thin-film LN. **(b)** SEM image showing two on-chip waveguides after facet polishing. **(c)** Measurement of phase-sensitive amplification. Top: signal phase scanned slowly by a PZT in a delay line. Middle: measured transmitted signal spectrum through the PPLN waveguide with and without the pump. Ripples are due to the phase-sensitive nature of the amplification. Bottom: gain spectrum showing more than 11 dB gain (45 dB/cm). **(d)** Measured small-signal gain versus pump energy along with the theoretical prediction.

Efficient amplification of broadband pulses requires engineering the waveguide dispersion to provide temporal confinement of the pump and signal pulses, as well as to match their group velocities so they propagate together and maximize their interaction length. We achieve this by engineering the waveguide geometry to minimize the

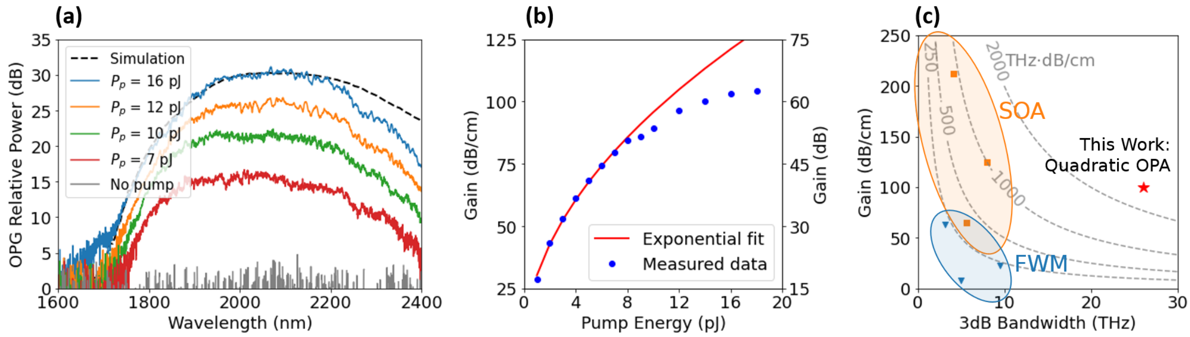

Fig. 2. **Measurements in OPG regime and comparison with other gain mechanisms in integrated photonics. (a)** OPG spectra for different pump energies, along with a simulation result, for a 6-mm-long dispersion-engineered waveguide, showing a 10-dB-gain bandwidth exceeding 600 nm. We use ~100-fs pump pulses centered at 1045 nm and no input signal. **(b)** Parametric gain extracted from OPG measurements showing values exceeding 100 dB/cm. **(c)** Comparison of gain and bandwidth with other on-chip amplification mechanisms.

group velocity dispersion (GVD) at the signal and pump wavelengths as well as the group velocity mismatch (GVM) between both wavelengths. We use a 700-nm-thick, X-cut, MgO-doped, LN thin-film on 2-μm-thick SiO2, and provide quasi-phase matching with periodic poling (Fig. 1a). We pattern the waveguides with e-beam lithography and etch them with Ar^+ plasma. Finally, we polish the waveguide facets to reduce coupling losses (Fig. 1b). We measure the small-signal OPA in a 2.5-mm-long waveguide by injecting 70-fs pump pulses at 1045 nm and 35-fs signal pulses at 2090 nm. We scan the relative phase between the pump and signal by a piezoelectric transducer (PZT) in a delay arm and observe phase-sensitive amplification (Fig. 1c). Figure 1d shows the maximum gain over the signal spectrum as a function of pump energy, for an input signal energy fixed at 4 fJ, along with the theoretical curve. There are no signs of gain saturation at these gain levels suggesting that more gain is available by a further increase in pump energy, which was avoided in the small-signal gain measurements with the 2.5-mm-long waveguide due to potential facet damage.

To measure the maximum bandwidth and unsaturated gain, we used a 6-mm-long device with the same dispersion engineering and without injecting an input signal. When the gain of an OPA is large enough, vacuum fluctuations are amplified to macroscopic levels and the OPA operates as an optical parametric generator (OPG). The measured output spectra for several pump energies are shown in Fig. 2a, along with numerical simulation results based on a nonlinear envelope model that uses a semi-classical description of quantum noise as the input signal. The gain bandwidth at 10 dB below the peak exceeds 600 nm in both experiments and simulations. We use the rate of growth of the OPG power to estimate the corresponding OPA gain (Fig. 2b), and confirm a gain of more than 100 dB/cm with less than 20 pJ of pump energy.

The OPA bandwidth we obtain is significantly broader than those provided by other nonlinear mechanisms (Fig. 2c), and it is controllable through dispersion engineering. Furthermore, this work can be extended to spectral regions that are not easily accessible with other gain mechanisms. The gain per unit length significantly exceeds those reported for cubic nonlinearities and rare-earth-doped waveguides and is comparable to that of SOAs. Currently, the maximum gain per unit length is limited by the maximum pump energy that we coupled to the waveguide, and improving the coupling loss by ~10 dB can lead to a gain of more than 150 dB/cm. Additional enhancements can be achieved through waveguide loss reduction and improving the periodic poling duty cycle, depth, and fidelity. We expect that our results on intense and broadband parametric amplification in integrated photonics can enable new opportunities in on-chip few-cycle nonlinear optics, quantum photonics, optical computing, and beyond.

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