

Large quadratic modulation instability gain in nanophotonic lithium niobate

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Abstract: We exploit quadratic modulation instability in a periodically poled lithium niobate nanophotonic waveguide to achieve broadband optical amplification. A high on-chip gain exceeding 18 dB is obtained with a pump peak power below 1.5 W. © 2024 The Author(s)

Signal amplification is critical for a wide range of optical systems, including communicating [1], sensing [2] and computing[3]. Despite recent advancements, several outstanding challenges persist in developing chip-scale integrated optical amplifiers, particularly regarding operating bandwidth and power efficiency. For instance, while parametric down conversion utilizing strong $\chi^{(2)}$ optical nonlinearity in quasi-phase-matched (QPM) lithium niobate (LN) nanophotonic waveguides can provide significant parametric gain [4], achieving parametric amplification of short-wavelength visible light signal using this approach is difficult due to the need for expensive powerful pump sources in the shorter wavelength visible and UV spectral ranges. Although on-chip parametric amplification based on $\chi^{(3)}$ nonlinearity can amplify signals at shorter wavelengths than the pump via the four-wave mixing process [5, 6], this method necessitates high pump power and offers limited gain per unit length due to the inherently weak nature of $\chi^{(3)}$ nonlinearity. Here, we report a new signal amplification mechanism in QPM LN nanophotonic waveguide: the quadratic modulation instability induced gain. Such a gain mechanism arise from the back-conversion of the second harmonic wave to the fundamental wave in the presence QPM and large group velocity mismatch. Using this approach, we achieve an on-chip gain of 18.83 dB and a high gain per unit length of 31.83 dB/cm with a modest pump peak power of 1.47 W at 1080 nm. The gain spectrum spans 800 nm to 1250 nm, paving the way for amplifying weak visible signals for various integrated quantum photonic applications.

The experimental setup for gain measurement is illustrated in Fig. 1. A 7-GHz-repetition rate, 3-ps pulse train at 1080 nm, generated by an electro-optical frequency comb (Fig. 1a), serves as the pump source. LN nanophotonic waveguides was fabricated from a 600-nm-thick MgO-doped thin-film LN thin film on a 4.7- μm -thick SiO₂ substrate. Quasi-phase matching between the 1080 nm fundamental wave and the 540 nm second harmonic wave is achieved through periodic poling (Fig. 1b), with a poling period of 2.4593 μm and a poling region length of 6 mm.

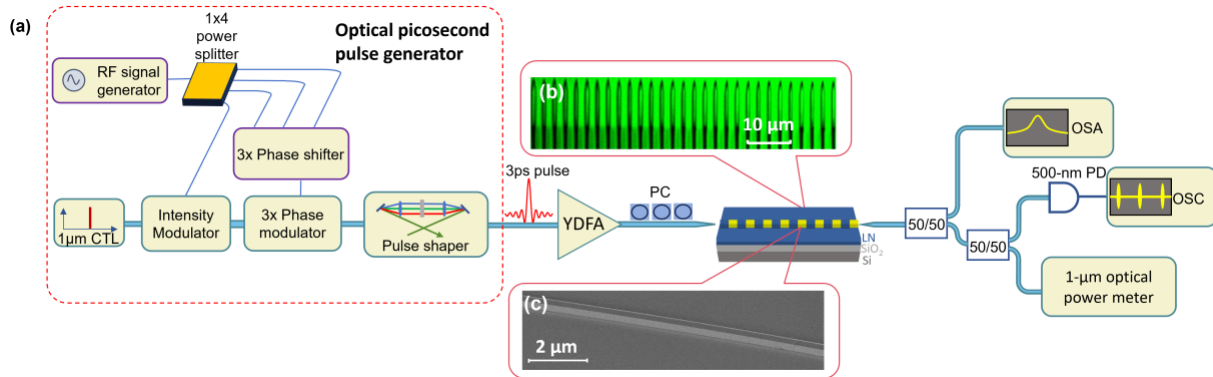


Fig. 1. (a) Electro-optical frequency comb setup. (b) Two photon microscope image and (c) SEM image of the fabricated PPLN waveguide. CTL: continuous tunable laser; YDFA: ytterbium-doped fiber amplifier; PC: polarization controller; OSA: optical spectrum analyzer; OSC: oscilloscope.

First, we perform a numerically simulation by injecting a 3-ps pump pulse into a 6-mm-long periodically poled lithium niobate (PPLN) nanophotonic waveguide and sweeping the average pump power from 0 to 40 mW at the phase matching condition. Fig. 2(a) shows the output power of FH and second harmonic, in which two regimes exist. In Regime (i) (pump power < 5 mW), second-harmonic generation (SHG) process dominates, and no significant gain is observed (Fig. 2(b-i)). In regime (ii), a further increase of the pump power leads to the strong saturation of SH and the energy of SH starts to convert back to the FH. In this regime, strong modulation

instability gain emerges around the FH, and the input noise from 780 nm-1500 nm is amplified by ~ 20 dB at pump power of 40 mW as shown in Fig. 2(b-ii). Next, we experimentally measured the device by inputting 3-ps 1080 nm pulse train into the PPLN waveguide. The output FH and SH power are plotted in Fig. 2(c) as functions of pump power. The device operates in regime (i) when the on-chip pump power is less than 5 mW. We recorded the SH evolution and the output spectrum at 5 mW pump power and show them in Fig. 2(d-i). As can be seen, the SH power continues to grow along the waveguide and no modulation instability gain is observed. As the pump power increases, the device enters regime (ii) and SH back conversion happens. Modulation instability induced gain is obtained from 800 nm to 1250 nm when on chip pump average power increases to 35 mW (corresponding to an on-chip peak power of 1.47 W), as Fig. 2(d-ii) shows. The maximum gain over the gain bandwidth is 18.83 dB, which is translated to a gain per unit length of 31.83 dB/cm.

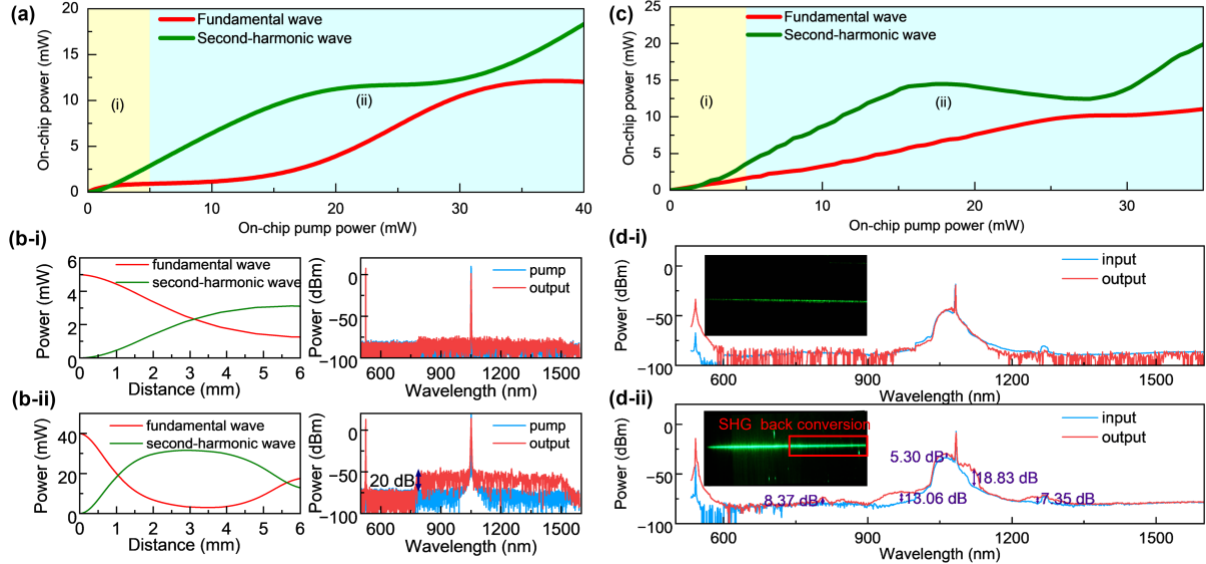


Fig. 2. (a) Simulated output FH and SH power as a function of pump average power. (b) Simulated power evolution (left) and output spectra (right) for regime (i) and (ii). (c) Measured output power of FH and SH as a function of pump average power. (d) Measured spectra for regime (i) and (ii). Insets: Optical microscope images of SH evolution along the waveguide with and without back conversion.

We further examine the gain performance as a function of phase mismatch by tuning the pump wavelength from 1078 nm to 1086 nm while maintaining a constant average pump power of 35 mW. Figure 3(a) shows the maximum gain at each detuned wavelength. We display the input and output spectra for phase matching and a 3.5-nm detuning in Figures 3(b) and 3(c), respectively. The results indicate the highest gain occurs at the phase-matching wavelength, with a significant reduction in gain as the pump wavelength is detuned from phase-matching condition. This behavior confirms the modulation instability gain is predominantly governed by $\chi^{(2)}$ nonlinearity.

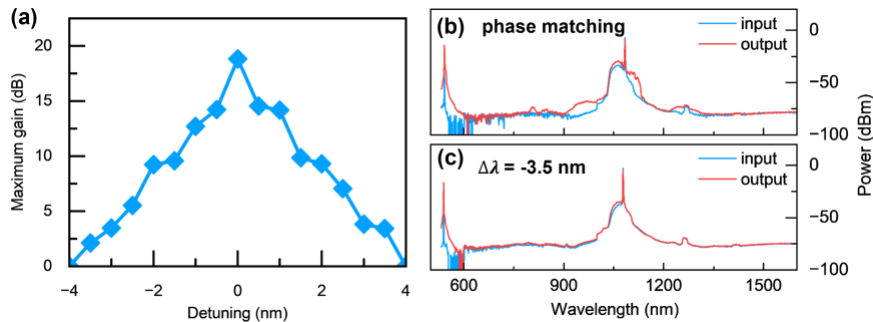


Fig. 3. (a) Measured maximum gain as a function of pump wavelength detuning from the phase matching condition. (b) Output spectrum in phase matching case. (c) Output spectrum when pump wavelength detuning is -3.5 nm.

In summary, we have demonstrated large quadratic modulation instability gain in LN nanophotonics, achieving a large gain per unit length of 31.83 dB/cm and a large gain bandwidth of 450 nm with a pump peak power of less than 1.5 W. Notably, this gain mechanism can be extended to the visible spectral range, which is challenging to access with other parametric amplification mechanisms in integrated photonics.

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