Design of Mid-Infrared Supercontinuum Generation in a strip-loaded LNOI Waveguide through lateral leakage engineering

(Student paper)

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We study the lateral leakage of a silicon nitride loaded lithium niobate waveguide in the mid-infrared regime. We then combine lateral leakage and dispersion engineering to numerically demonstrate mid-infrared supercontinuum generation extending from 1200nm to 5000nm.

***Keywords**: Mid infrared, Nonlinear Optics, Lithium Niobate, Lateral Leakage, Supercontinuum Generation*

INTRODUCTION

Mid-infrared (mid-IR, 2-20µm) broadband sources are of great interest in many different fields such as environmental monitoring, bio-imaging and security[1]. Since many molecules have strong vibrational absorption in the mid-IR spectrum regime, mid-IR broadband sources can enable the parallel detection of multiple gas species[2]. Despite the great potential that mid-IR technologies offer, its range of applications is still limited, mostly because of the size and cost of mid-IR sensing devices. Therefore, there is a great need to develop compact and cost effective integrated mid-IR platforms to access these applications. On-chip mid-IR supercontinuum generation (SCG) has been demonstrated in several group-IV platforms [3-5]. Great efforts have been devoted by our group to achieve SCG in silicon-germanium on silicon[3] and germanium on silicon waveguides [4].

Lithium niobate (LN), with its large optical transparency window (400nm-5000 nm) and strong electro-optic effect, has been historically widely used in optoelectronics and more recently, for photonic integrated circuits [5][6] . Also, LN is a promising nonlinear material for realizing SCG in the mid-IR regime and second harmonic generation (SHG) in near infrared regime, as it possesses strong second order nonlinearity and moderate third order nonlinearity [7]. Although LN waveguides with strong field confinement can be achieved by directly etching LN thin films [8],the etching of LN has been notoriously difficult [6]. Instead, we use a LN on insulator (LNOI) thin film optically loaded with a strip of silicon nitride (SiN) and we already demonstrated several integrated photonic components in this platform.

In this work, we design a SiN loaded LN waveguide through the engineering of lateral leakage in the mid-IR regime. We analyse numerically the generation of mid-IR supercontinuum extending from 1200 to 5000nm and show that the simultaneous presence of second and third order nonlinearities in PPLN can achieve octave spanning supercontinuum and efficient SHG which this creates a pathway for stabilization of our mid-IR sources through the f-2f self-referencing technique within a compact single-waveguide system

DESIGN AND SIMULATIONS

Lateral leakage describes an effect that occurs in a photonic waveguide which was first seen in silicon on insulator rib or ridge waveguide [9] , where the effective refractive index of the optical waveguide mode is a lower than the orthogonally polarized slab mode. Since LN is birefringence material, we found that in LNOI waveguide the effective index of the TE waveguide mode can be lower than the one of the TM slab mode, which will lead to the leakage of the TE waveguide mode. Thus, our first step when designing the waveguide is to achieve low lateral leakage of the waveguide mode in the mid-IR regime.

We calculated the effective refractive index difference between the TE waveguide mode and the TM slab mode for SiN loaded LNOI ridge waveguides (Fig. 1a) as function of the LN film thickness and the wavelength. We chose a SiN thickness dimensions in [10] which is 400nm and SiN waveguide width of 3000nm. We have used an x-cut LNOI substrate where the TE waveguide mode experiences the extraordinary refractive index of LN and TM slab mode experiences the LN ordinary index. Figure 1(b) shows the resulting effective refractive index difference between the

TE waveguide and TM slab mode $\Delta n_{eff} = \Delta n_{eff,TE} - \Delta n_{eff,TM}$. The black line in the map indicates where the effective refractive index difference Δn_{eff} is zero.

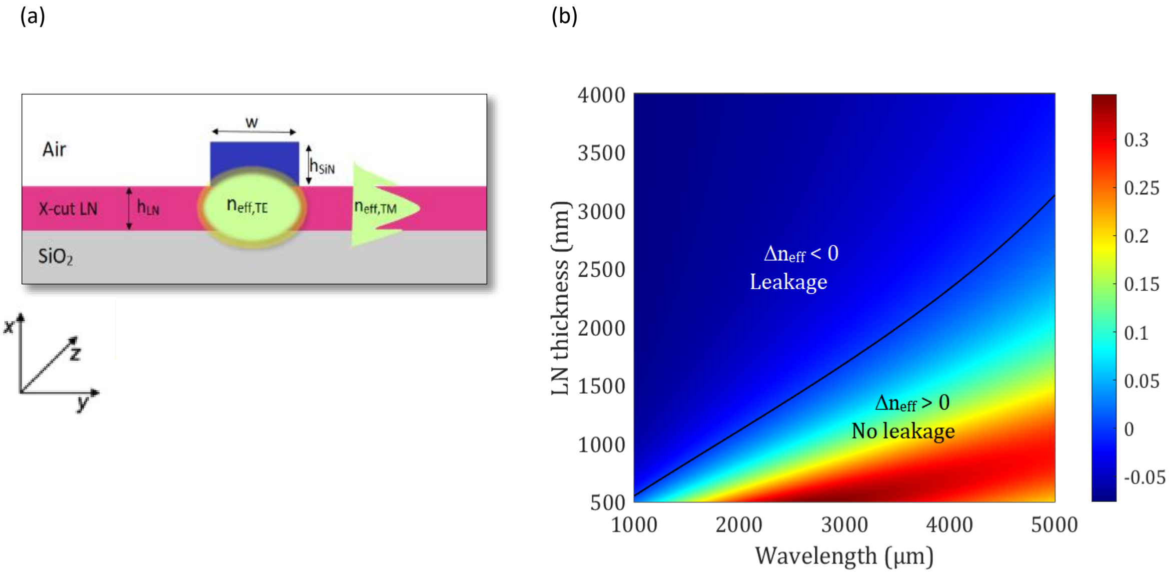

Fig. 1. (a) Illustration of SiN loaded LN waveguide and the modes (b) Calculated effective index difference between TE waveguide mode and the TM slab mode. Waveguide with Δn_{eff}<0 can suffer from lateral leakage

The graph indicates that waveguides with certain LN thickness and operated at wavelengths above the zero line of the effective refractive index difference might lead to a leaky waveguide mode. On the contrary, below the zero line, where the effective refractive index difference is greater than zero, there should not be any leakage of the TE waveguide mode. We observed that by making the LN thickness thinner and thinner, it pushes the leakage wavelength lower and lower. Therefore, for a given LN thickness, some lower wavelengths will suffer from lateral leakage.

Considering these trade-offs, we choose a LN thickness of 600nm which should support modes without leakage down to 1100nm. We now investigate the dispersion required for SCG. The main objective of our dispersion engineering is to achieve low anomalous dispersion to maximize the bandwidth of the SC. We numerically calculate the dispersion of the waveguide using 600nm LN thickness and 400nm SiN thickness. Fig 2(a) shows the simulated results of the dispersion for the TE waveguide mode of three different waveguide widths of 3000nm, 3500nm and 4000nm. Fig. 2(b) shows the integrated dispersion[11] for these different widths for a pump at 2070nm. For each waveguide width, the zero crossing of the integrated dispersion give some prediction of the spectral position of the dispersive wave (DW), hence the dashed black line cross the respective curve between 1200nm-1400nm and 4500-5000nm wavelength.

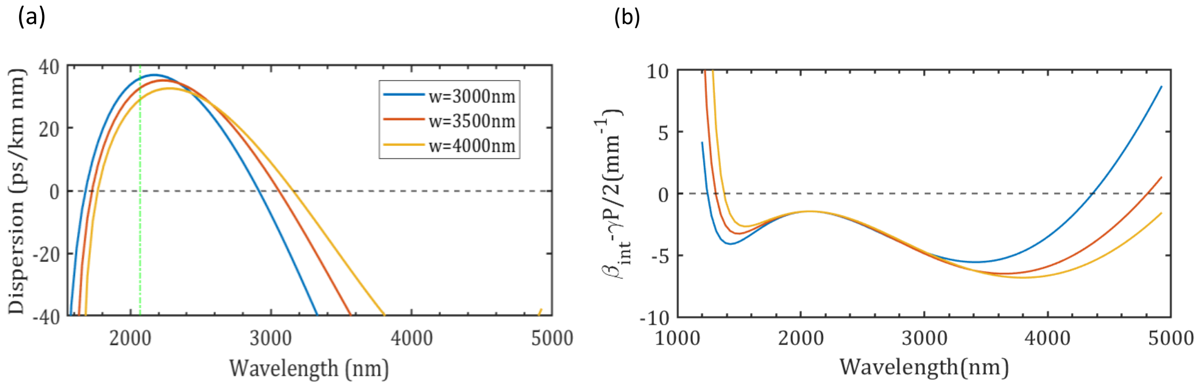

Fig. 2. (a) Simulated Dispersion for selected waveguide widths. (b) Corresponding dispersion operator for a 2070nm pump wavelength

We simulate SCG in a 1 cm long SiN loaded PPLN waveguide with 3000nm width, 600nm LN thickness and 400nm SiN thickness by numerically solving the nonlinear Schrodinger equation using the split step Fourier method. Our model includes second and third order nonlinearity, higher order dispersion, self-steepening and losses. The simulated supercontinuum shows in Fig. 3 is obtained using a pump with an off-the-shelf femtosecond thulium-doped fiber laser (Brevity +, NOVAE) which outputs 90fs pulses at a 20MHz repetition rate[2]. We use 1kW peak power to pump the waveguide at 2070nm in the anomalous dispersion regime. The generated SC extend from 1200nm to 5000nm wavelength. Also, there is a second and third harmonic that appears giving some light all down to 800nm, however the power is -20dB lower than the primary SC light.

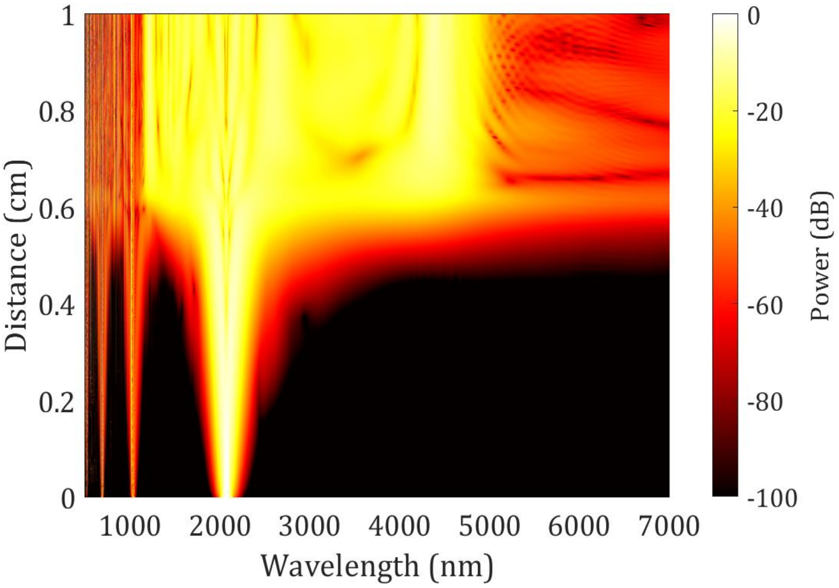

Fig. 3. Simulated spectral pulse evolution along the waveguide length for a peak power of 1kW.

CONCLUSION

In conclusion, we numerically demonstrated mid-IR SC generation in a strip-loaded LNOI waveguide. We designed the waveguide to support mode without leakage and to generate a broadband spectrum for spectroscopy applications. Finally, the generated SHG can enable the stabilization of our mid-IR sources through the f-2f self-referencing technique.

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References

[1] R. Soref, *Mid-infrared photonics in silicon and germanium*, Nat. Photonics, vol. 4, no. 8, pp. 495–497, 2010

[2] E. Tagkoudi, D. Grassani, F. Yang, C. Herkommer, T. Kippenberg, and C.-S. Brès, *Parallel gas spectroscopy using mid-infrared supercontinuum from a single Si 3 N 4 waveguide* , Opt. Lett., vol. 45, no. 8, pp. 2195, Apr. 2020

[3] M. Sinobad *et al.*, *Mid-infrared octave spanning supercontinuum generation to 85 µm in silicon-germanium waveguides*, Optica, vol. 5, no. 4, p. 360, 2018

[4] A. Della Torre *et al.*, *Mid-infrared supercontinuum generation in a low-loss germanium-on-silicon waveguide,* APL Photonics, vol. 6, no. 1, 2021

[5] A. Boes *et al.*, *Lithium niobate photonics: Unlocking the electromagnetic spectrum*, Science, vol. 379, no. 6627, pp. 1-12, 2023

[6] D. I. Zhu *et al.*, *Integrated photonics on thin-film lithium niobate*, Adv. Opt. Photonics, vol. 13, no2, 2021

[7] M. Garcia-lechuga, J. Siegel, J. Hernandez-rueda, and J. Solis, *Imaging the ultrafast Kerr effect , free carrier generation , relaxation and ablation dynamics of Lithium Niobate irradiated with femtosecond laser pulses*, J. Appl. Phys. vol. 116, pp. 113502, 2014

[8] A. Boes, B. Corcoran, L. Chang, J. Bowers, and A. Mitchell, *Status and Potential of Lithium Niobate on Insulator (LNOI) for Photonic Integrated Circuits*, Laser Photonics Rev. vol. 12, no. 4, pp. 1700256, 2018

[9] M. A. Webster, R. M. Pafchek, A. Mitchell, and T. L. Koch, *Width dependence of inherent TM-mode lateral leakage loss in silicon-on-insulator ridge waveguides*, IEEE Photonics Technol. Lett., vol. 19, no. 6, pp. 429–431, 2007

[10] A. Boes *et al.*, *Improved second harmonic performance in periodically poled LNOI waveguides through engineering of lateral leakage*, Opt. Express, vol. 27, no. 17, p. 23919, 2019

[11] A. Della Torre *et al.*, *Mid-infrared supercontinuum generation in a varying dispersion waveguide for multi-species gas spectroscopy*, IEEE J. Sel. Top. Quantum Electron., vol. , pp. 1–10, 2022