Non-linear Frequency Conversion Waveguides for Quantum Technology

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Abstract: This talk will describe the fabrication of periodically poled lithium niobate non-linear waveguides for the emerging quantum technology industry. It will address the challenges of optical engineering high-efficiency frequency conversion devices for the field and their application.

In the emerging Quantum Technology (QT) industry, optical sources are essential for many of the technology platforms. Be that for controlling atom or ion trap systems, probing vacancy centers in diamonds, or the photon sources for quantum information processing and communication. Quantum technologies often have very different and demanding specifications. As the industry emerges, this list of demands increases to include lower power consumption, greater collection efficiency (lower loss) and increased robustness/stability for commercial deployment.

Frequency conversation via nonlinear optics has played a significant role in quantum optics. Perhaps the most notable application is the generation of entangled photon pairs through spontaneous parametric down-conversion (SPDC). These entangled photon pairs have found wide-ranging applications in quantum communication and quantum information processing. However, non-linear optical processes such as second harmonic generation have also become a mainstay for producing optical sources for controlling matter-based quantum systems such as atom and ion traps for quantum sensing and quantum computing. Frequency conversion has also been found to be applicable in up-conversion detection and remote imaging, where single photon signals in the mid-IR can be converted to energy photons for more efficient and convenient detection. While bulk nonlinear crystals can be used in many of these applications, waveguides are increasingly used due to improved single-pass conversion efficiencies. With optical engineering, these waveguides can be integrated with optical fiber packaging for commercial deployment.

In this presentation, we will discuss the fabrication and development of periodically poled lithium niobate waveguides and their application to various areas of quantum technology. Over the past several years, we have developed a process for manufacturing robust ridge waveguides in magnesium oxide doped periodically poled lithium niobate (MgO:PPLN) wafers. The process uses zinc-diffusion (to provide vertical confinement) and ultra-precision ductile grinding (to provide lateral confinement), see Fig.1. The grinding is achieved by a precision dicing saw and allows us to achieve ridge and facet surface roughness (S_a) of <0.3nm [1]. The process overcomes the challenges of processing lithium niobate, which has proven difficult with conventional microelectronics processing. A scanning electron microscope image of some typical machined MgO:PPLN waveguides is shown in Fig 2.

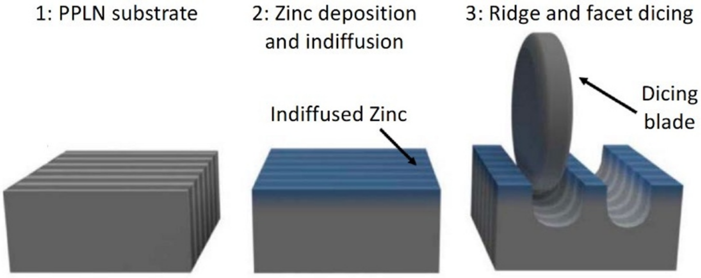

Fig. 1: Lithium niobate waveguide fabrication process, showing the zinc indiffusion and grinding process.

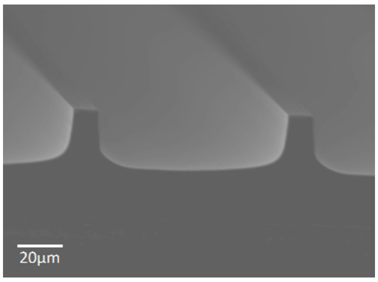

Fig. 2: SEM image of two lithium niobate waveguides

Using this approach, we have demonstrated devices for various applications in the quantum technology industry. We have demonstrated 74% second-harmonic generation (SHG) conversion efficiency for the atom-trap community, generating 2.5W of 780nm [2] for Rb-based gravimetry (see Figure 3). Figure 4 presents the mode profiles of this device, showing how we have engineered the optical modes to maximize the overlap between the pump and second harmonic fields. We have also recently demonstrated an Alexandrite laser and PPLN waveguide combination that enables temperature-tunable UV generation in the 376-386nm range with up to 1.3mW output via third-order SHG [3]. Such devices are of great interest to the quantum technology for ion and atom trapping.

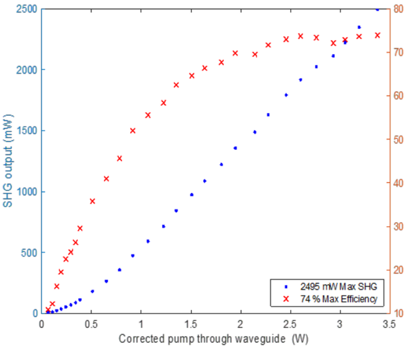

Fig. 3: Second harmonic conversion efficiency (1560 to 780nm) of a PPLN waveguide.

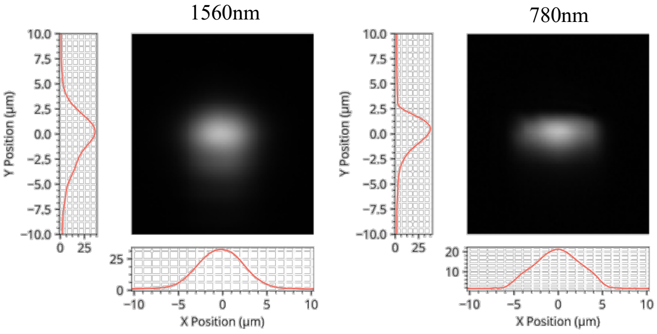

Fig. 4: (left) pump (1560nm) and (right) second harmonic (780nm) optical mode profiles of the non-linear waveguide [2].

In addition to providing optical sources for quantum control, these non-linear waveguides can also provide a source of entangled photons. A recent collaboration has demonstrated a C-band polarization-entangled photon source, producing an entangled photon pair rate of 1.25 gigahertz [4]. Our recent work has also demonstrated conversion from the mid-IR to the silicon detector band, providing a route to convert single or low photon flux signals to a spectral band for efficient, low-cost detection.

In the talk, we will also discuss our results on improving the uniformity of the waveguides to refine device performance and yield. This is especially important for short wavelength applications, where there is a greater sensitivity to the phase-matching criteria. Figure 5 shows the temperature phase-matching curves for two similar waveguides providing second harmonic conversion from 1064nm light to 532nm. The key difference is that the two waveguides are fabricated with 100µm and 300µm wide grinding blades, shown in a) and b), respectively. The nominal waveguide properties of the two devices are very similar, i.e., surface roughness and pump transmission. However, our data shows subtle waveguide width variation, causing the phase-matching response (see Fig 5(a)) to be degraded. Increasing the width of the grinding blade reduces waveguide variation and greatly improves performance, as seen in Fig 5(b).

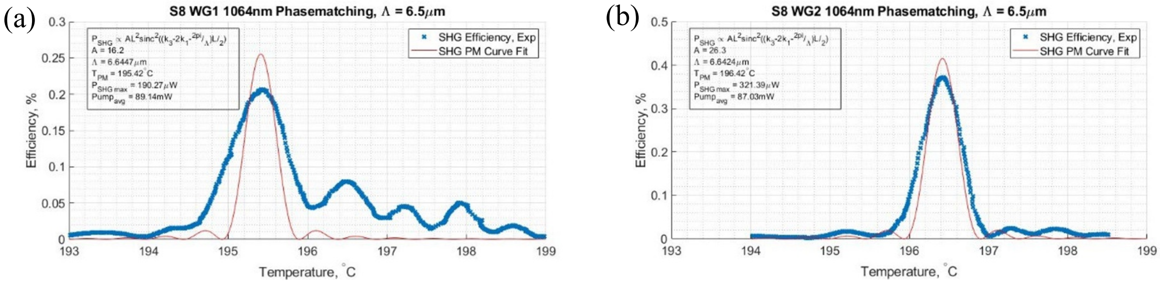

Fig. 5: Lithium niobate waveguide temperature phase-matching plots of two waveguides fabricated with a 100µm wide blade (a) and a 300µm blade (b).

We will present our latest work on developing MgO:PPLN non-linear waveguides for quantum technology applications from the UV to MIR. This will include highlights of the engineering required to optimize the waveguide properties, such as mode matching the pump, SHG and optical fiber to reduce insertion loss and improve the fabrication processes to increase the conversation efficiency.

References

[1] Carpenter, Lewis G., Sam A. Berry, and Corin BE Gawith. "Ductile dicing of $LiNbO_3$ ridge waveguide facets to achieve 0.29 nm surface roughness in single process step." Electronics letters 53.25 (2017): 1672-1674.
[2] Carpenter, Lewis G., Sam A. Berry, Alan C. Gray, James C. Gates, Peter GR Smith, and Corin BE Gawith. "CW demonstration of SHG spectral narrowing in a PPLN waveguide generating 2.5 W at 780 nm." Optics Express 28, no. 15 (2020): 21382-21390.
[3] Tawy, G., Davidson, N. P., Churchill, G., Damzen, M. J., Smith, P. G., Gates, J. C., & Gawith, C. B. Temperature-tunable UV generation using an Alexandrite laser and PPLN waveguides. Optics Express, 31(14), (2023): 22757-22765.
[4] Ndagano, B. I., Pandiyan, K., Wright, L., Smith, R., Anwar, A., Astill, A., ... & McKnight, L. (2024, March). A gigahertz source of polarisation entangled photons enabled by type-0 PPLN waveguides. In Quantum Computing, Communication, and Simulation IV (p. PC129110W). SPIE.