Investigation of the fabrication consistency of lithium niobate ridge waveguides formed by dicing

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Abstract: Efficient optical wavelength conversion in lithium niobate ridge waveguides requires high uniformity, low surface roughness and minimal defects along the ridge length, demanding an ultra-precise and stable fabrication process. Here we present our latest work on grinding lithium niobate ridge waveguides with diamond blades on a commercial dicing saw. This includes investigations into the effect of cut depth, blade form, translation speed and blade thickness.

1. Introduction & Motivation

Machining of brittle crystalline materials is a topic of growing interest in both photonics and quantum technology applications as a route to achieving cm-scale structures with nm-scale roughness in formats that are not easily achievable with etching or cleanroom processing. One such material is lithium niobate, which offers high optical transparency, ferroelectric, and non-linear properties. These make it a popular component for conversion of standard off-the-shelf lasers to specific optical wavelengths for telecommunications, atom and ion traps, entangled photon pair generation, and upconversion imaging.

In recent works, we have demonstrated a ductile machining approach for the fabrication of ridge waveguides in Zn-indiffused periodically poled lithium niobate (PPLN) that enables optical-quality ridges and facets with surface roughness of 0.29 nm Sa in a single pass [1]. These devices enable second harmonic generation (SHG) of 1560 nm to achieve 2.5 W 780 nm at 70% conversion efficiency [2].

A width variation of just 200 nm along a 15 mm long ridge waveguide has been shown to have a critical efficiency reduction [3], with more complex local deviations (chips) leading to severe spectral broadening [4]. To link fabrication tolerances (long-range waveguide uniformity, curvature) to overall performance, we have conducted a comprehensive study of waveguide form variation, including; straightness; width; chipping; and surface roughness correlated with optical frequency conversion performance.

2. Experiment

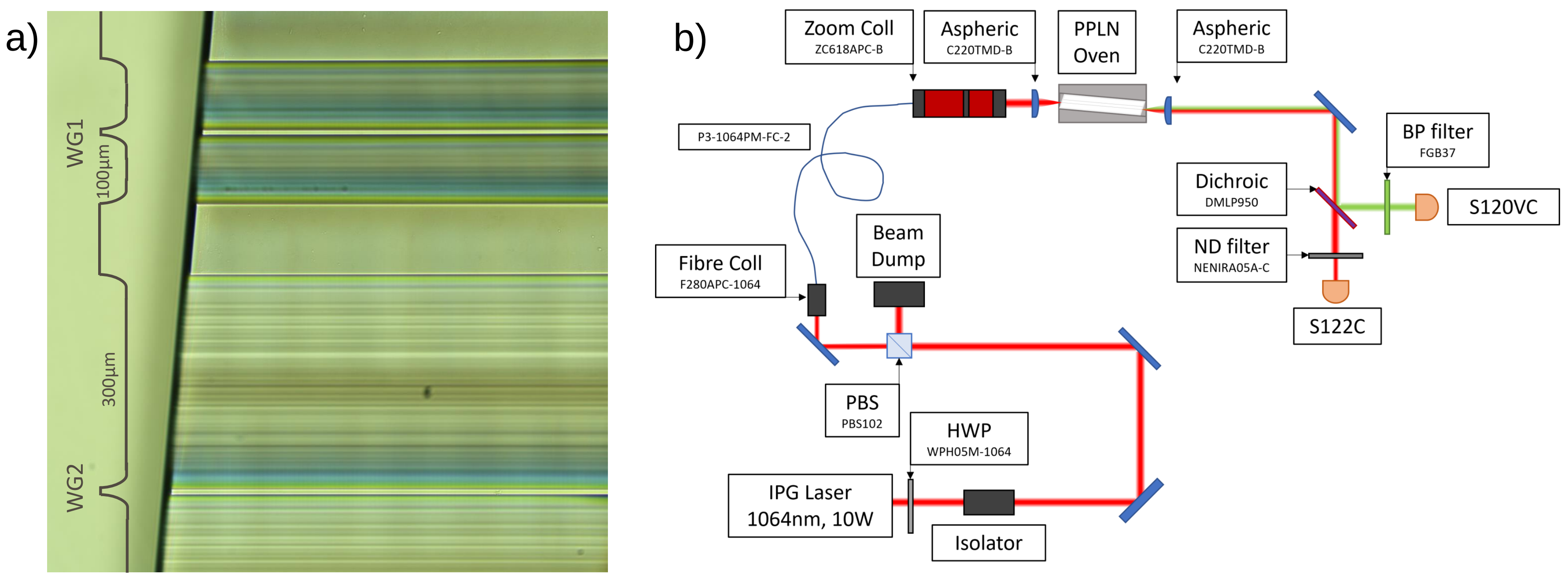

Fig. 1a: Microscope image of ridge waveguides, on the left of the image is a schematic of the geometry. Fig. 1b: Optical experimental arrangement for the phase matching and efficiency measurements.

Three SHG chips consisting of two ridge waveguides were fabricated according to Fig 2a. One ridge waveguide was fabricated with a 300 μm wide blade and the other was fabricated with a 100 μm wide blade, as illustrated in Fig 1a. The rest of the fabrication steps were the same per chip to keep the kerf (machined channel width) as the only control variable.

The waveguides were optically tested using a temperature sweep to obtain the phase matching spectra with the equipment setup in Fig 1b. The optical results are shown in Section 4. Then profiled with a travelling confocal microscope (in-house built) and Coherent Scanning Interferometer (CSI: Zygo ZeGage) to obtain straightness, waveguide width, surface roughness and top-side chipping information, displayed in Sections 5 and 6.

3. Fabrication Steps

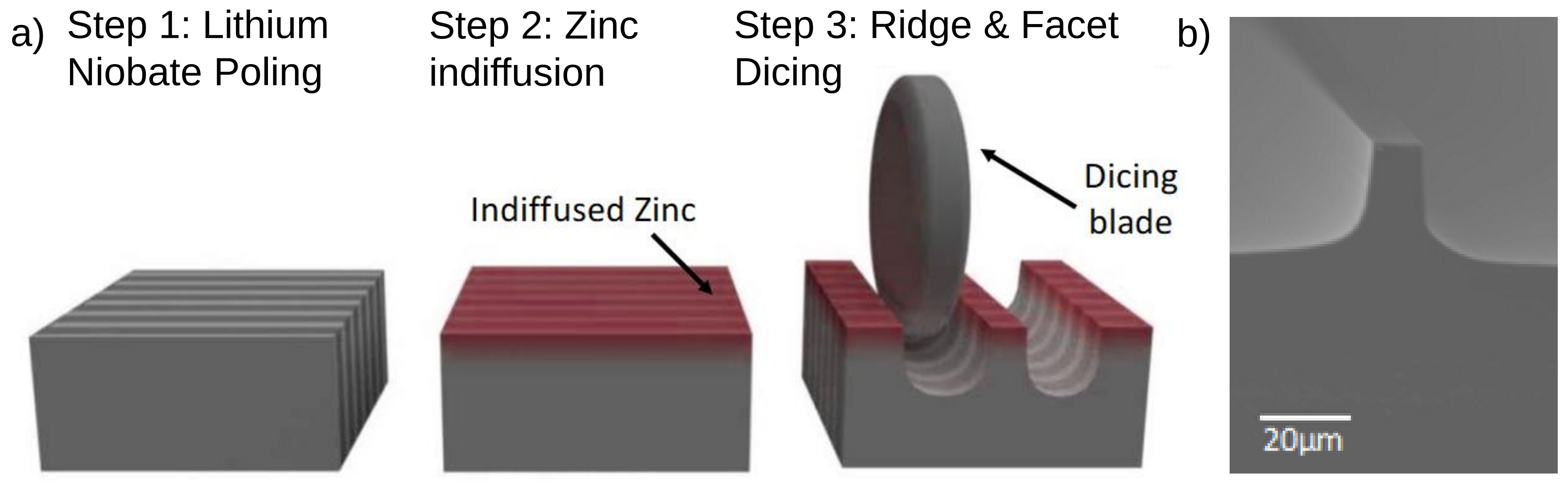

Fig. 2a: Periodically poled lithium niobate ridge waveguide fabrication steps. Fig. 2b: SEM image of a resulting diced waveguide facet and ridge.

Fig 2a. displays the typical lithium niobate second harmonic generation (SHG) ridge waveguide fabrication steps. From left to right, periodic poling provides the wavelength conversion effects, zinc indiffusion forms the planar layer (vertical confinement), and the machined ridge formation provides the lateral waveguide confinement. This results in a narrow, smooth ridge, typically 7-11 μm wide. Facets are formed in a single step, enabling optical quality finish without further post-processing (i.e. polishing), as shown in Fig 2b. For more details, see [1,2].

4. Phase Matching Spectra

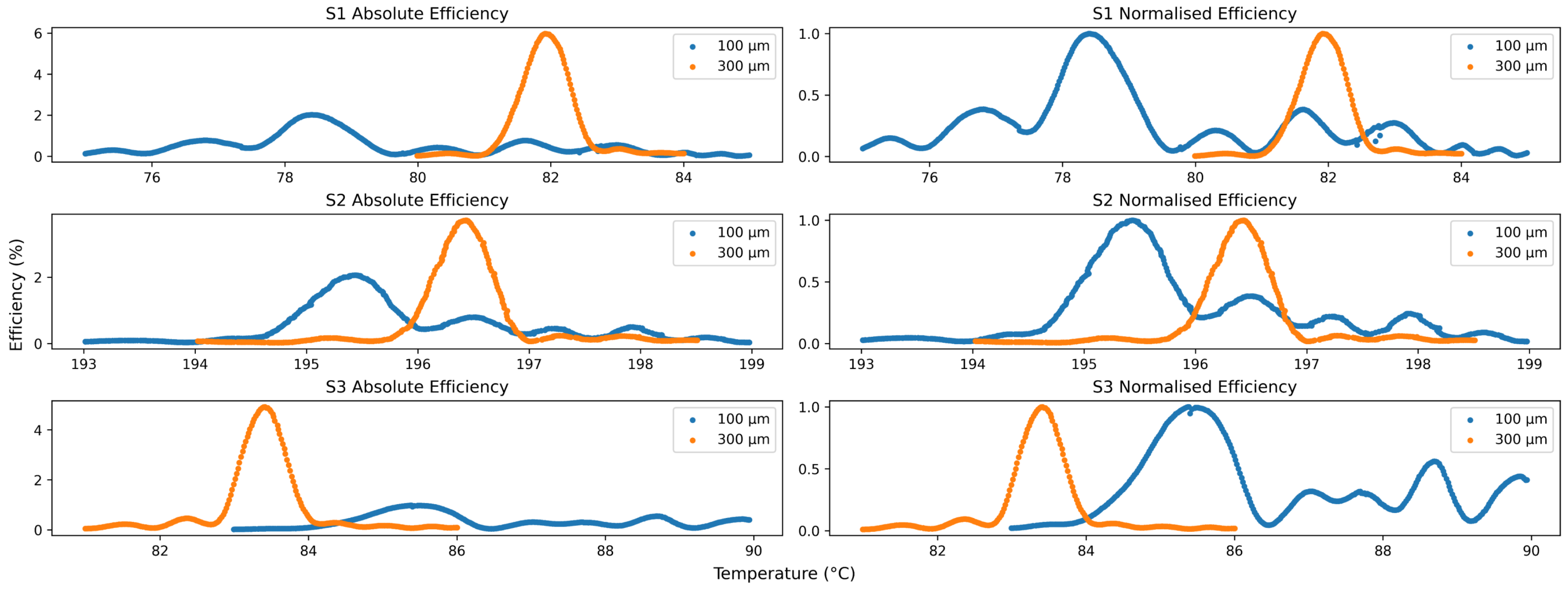

Fig 3. Absolute (left) and normalised (right) phase matching spectra of 3 waveguides each fabricated with 100 μm and 300 μm wide blades

The phase-matching spectra for the sets of waveguides are shown in Fig 3. The data indicates a clear maximum efficiency improvement with the 300 μm wide blade over the 100 μm wide blade, demonstrating an average efficiency improvement of 226%. The nominal spectral shape should have a sinc^2 intensity response, with any deviations from this indicating either width or thickness (from the zinc indiffusion) deviations. The 300 μm kerf machined waveguides consistently have a more uniform sinc^2 profile; this strong correlation indicates that the wider blades achieve more uniform waveguides. Waveguide width variation changes the propagation constant and perturbs the highly sensitive phase-matching condition between the two modes (532 and 1064 nm).

5. Width & Straightness

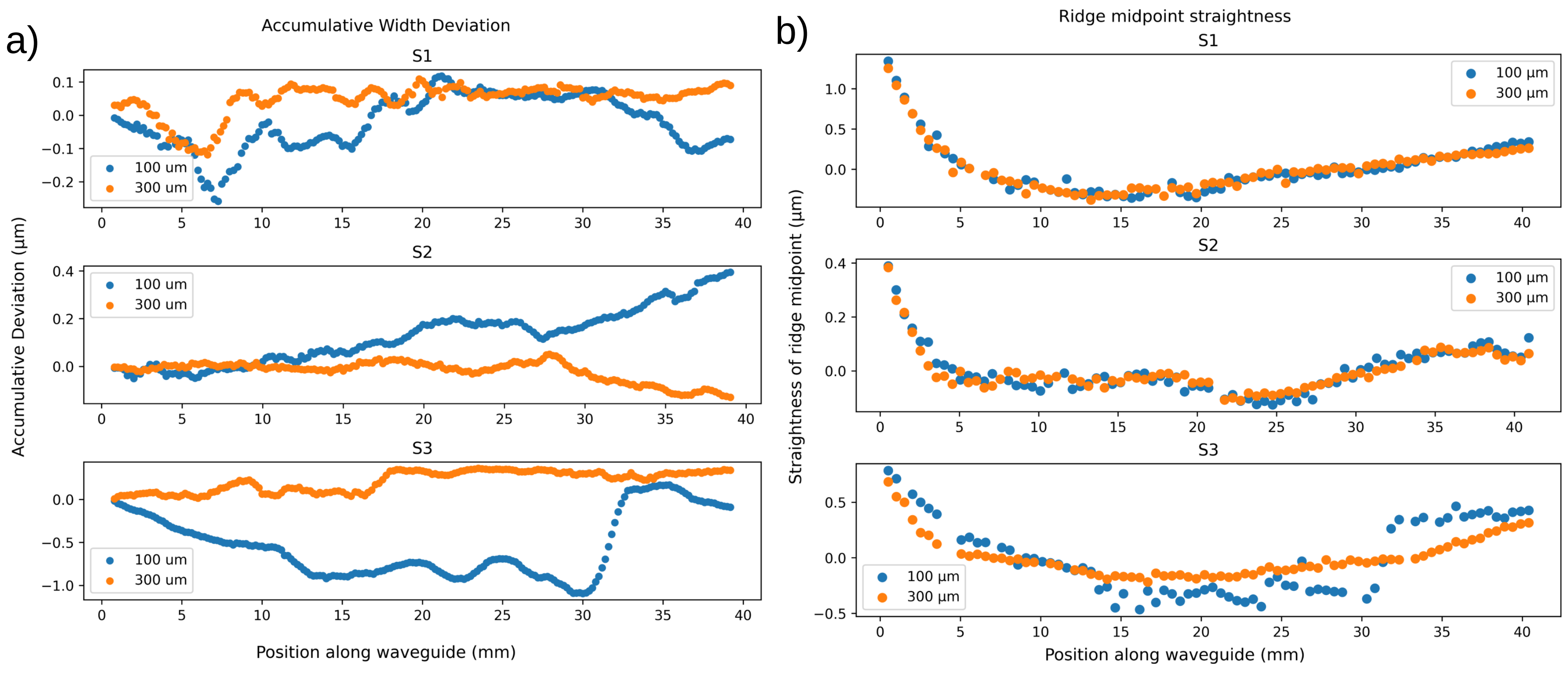

Fig 4: Accumulative width (Fig 4a.) and straightness (Fig 4b.) of the machined ridge waveguides

Fig 4a. shows the accumulative width deviation versus length using data obtained by CSI. This provides a relative quality factor for phase matching. The plots indicate that a significantly worse width consistency is achieved with the 100 μm wide blades versus the 300 μm wide blades. This is likely due to improved stability of the wider blades.

Fig 4b. shows the straightness of the ridges as profiled by a confocal microscope. Both blades provide excellent straightness, often better than the ±1.5 μm specification of our machine. While the straightness achieved with the 300 μm blade is marginally better, this is not expected to cause significant changes to the compared phase matching profiles.

6. Surface Roughness & Chipping

a)

Blade Width (μm)	Surface Roughness Sq (nm)	StdErr (nm)
100	0.2495	0.0011
300	0.2704	0.0006

b)

Blade Width (μm)	Top side Chipping (μm²/μm)	StdErr (μm²/μm)
100	0.063	0.011
300	0.099	0.017

Table 1. Tables showing average surface roughness (Sq) (Table 1a) and average top side chipping area per unit length (Table 1b) of the ridges diced with the 100 μm and 300 μm wide blades.

Table 1a. indicates optical quality surface sidewall roughness is achieved in all of the ridge waveguides; the measured difference between blade widths is marginal. This rules out surface roughness as a factor for the improved optical performance of the wider cuts.

Table 1b. shows the measured the topside chipping per unit length of the ridges. This also indicates a similar result between blades, as expected due to identical blade compositions.

7. Conclusion

We have investigated the effect of dicing blade width on ridge waveguide optical SHG performance and have discovered a significant improvement in both the optical phase matching spectra and the resulting SHG efficiencies with a wider blade. Further investigations have revealed that the uniformity of the machined ridges is significantly improved by increasing the blade width, allowing for more efficient SHG to occur.

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