Ductile dicing of $LiNbO_3$ ridge waveguide facets to achieve 0.29 nm surface roughness in single process step

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A single-step ductile dicing process capable of manufacturing optical quality facets in lithium niobate ($LiNbO_3$) ridge waveguides with an average surface roughness of 0.29 nm is reported. This result is comparable with surface roughnesses achieved by lapping and polishing and represents an order of magnitude improvement over the prior state of the art in $LiNbO_3$ waveguide facet dicing.

Introduction: Dicing, a form of mechanical sawing, is commonly used in semiconductor and photonics processing to separate individual die from wafers. In most semiconductor processes where functional elements are accessed from the top of the die, dicing speed is more critical than quality and often performed in a 'brittle' regime where cracks and edge chipping on the order of tens of microns are common. In photonics, optical components are more often accessed (launched) from the side of the die and require a surface roughness of a few nanometres to prevent unwanted loss by scatter. Such roughness is typically achieved by laborious extra stages of lapping and polishing, in which individual components are manually handled through multiple mounting and cleaning steps.

In recent work, we have demonstrated optical quality dicing of micron-order ridge waveguide structures in germanium telluride with a facet roughness of 3.0 nm (Sa) [1]. Here, we present results in lithium niobate ($LiNbO_3$), a popular nonlinear optical material for use in laser wavelength conversion [2–6]. A single-step ductile dicing process was developed to achieve sub-nanometre surface roughness on periodically poled $LiNbO_3$ (PPLN) facets, circumventing the need for lapping and polishing. This represents an order of magnitude improvement in surface roughness over previous publications in the field [5].

Ductile dicing: Ductile mode machining was first reported by Bifano *et al.* [7] in diamond turning of various brittle materials such as silica, silicon, and germanium. Ductile machining removes material via plastic deformation, leaving surfaces with nanometre-scale surface roughness and without cracks or chips. Plastic deformation of a workpiece can only occur if the shear strain applied is below a critical value, which corresponds to a chip size, or certain set of machining parameters [7]. Machining parameters to be optimised include the dicing blade grit size, concentration and bond material, rotational speed, translation speed, depth of cut into the sample, and the type and flow of coolant used. If the dicing parameters exceed the material's plastic limit, then the machining will occur in the brittle regime. The dicing of smooth surfaces in PPLN has been demonstrated by numerous groups [3–6] in the production of ridge waveguides, with a previous best result of 2.82 nm average surface roughness (Sa) [5].

Facet preparation: PPLN waveguides are a popular choice for wavelength conversion due to a high nonlinear coefficient (typical d_{33} of 16 pm/V available from commercial devices) and co-linear propagation of pump and signal wavelengths. Waveguides are commonly fabricated in $LiNbO_3$ via metal diffusion, proton exchange, ion implantation, direct laser writing, or mechanical machining [2–6, 8] processes, to achieve active waveguide regions of $<10 \times 10\ \mu m^2$. Efficient coupling of light into such waveguides requires mode matching, reduction of Fresnel losses, and low facet roughness to reduce scatter. Preparation of PPLN waveguide facets (see Fig. 1) for optical end firing or fibre butt coupling is most commonly achieved via lapping and polishing. Fig. 2*a* shows an example micrograph image of a lapped and polished rib waveguide facet in PPLN, prepared using a Logitech LP50 system with a 3 µm aluminium oxide lapping step on a cast iron plate, followed by a 30 min colloidal silica chemical-mechanical polishing step on a conditioned polyurethane plate. The black dashed line shows the area where surface roughness was measured using a Zemetrics Zescope white light interferometer. Polynomial levelling was applied to each $11 \times 6\ \mu m^2$ area before roughness values were calculated. Fig. 2*b* shows a typical surface metrology result for the polished facet, with an average surface roughness (Sa) of 0.19 nm, RMS surface roughness (Sq) of 0.25 nm, and correlation length of 364 nm (1/e).

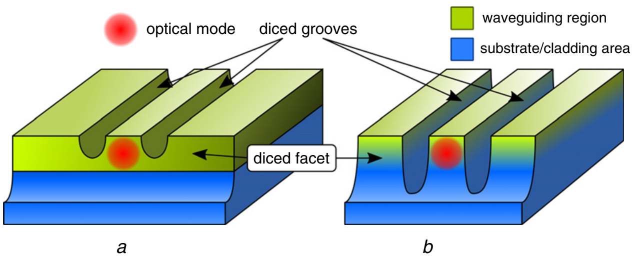

Fig. 1 *PPLN waveguide geometries*
a Rib
b Indiffused ridge showing location of facet produced by ductile dicing

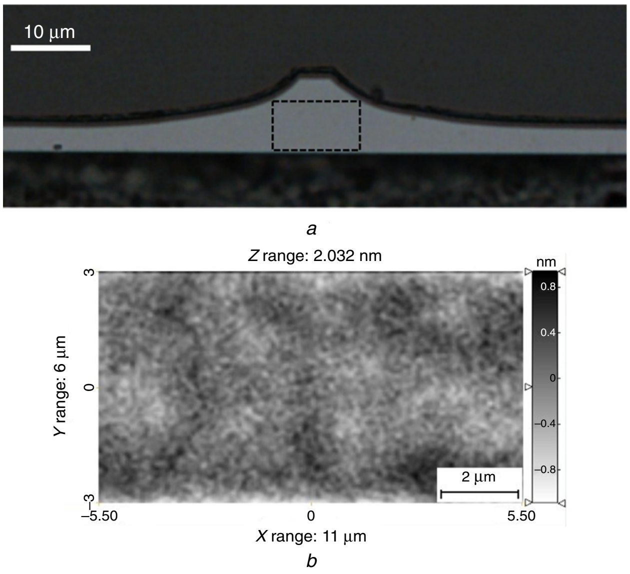

Fig. 2 *Lapped and polished rib PPLN waveguide*
a Micrograph of polished $LiNbO_3$ waveguide facet
b Surface metrology taken within black dashed area, from which average surface roughness of 0.19 nm (Sa) is calculated

Ductile dicing of PPLN waveguide facets was investigated for both epoxy resin- and nickel-bonded diamond impregnated blades to demonstrate the differences in achievable surface roughness and edge chipping. Experiments were performed on a Disco DAD3430 dicing machine equipped with an air bearing slide way and linear position encoders. The DAD3430 having positional accuracies of 1.5 and 1 µm in X and Z axes, respectively. Although a broad range of machine parameters were tested, the dicing parameters used to achieve sub-nanometre surface roughness with both blade types were a blade rotational speed of 20 krpm, a 60 µm depth of cut, and a translation speed of 0.1 mms^{-1}.

The micrograph in Fig. 3*a* shows a PPLN ridge waveguide facet machined using a Disco P1A resin-bonded blade with a grit size of SD6000. Fig. 3*b* is the corresponding surface metrology taken within the area indicated by the black dashed line, from which the calculated surface roughness was an Sa of 0.54 nm, Sq of 0.75 nm, and a correlation length of 320 nm.

Similarly, the micrograph of Fig. 4*a* shows a PPLN rib waveguide facet machined using a Disco Z09 nickel-bonded blade with a grit size of SD5000. Fig. 4*b* is the corresponding surface metrology taken within the area indicated by the black dashed line, from which the calculated surface roughness was an Sa of 0.29 nm, Sq of 0.46 nm, and a correlation length of 320 nm.

Comparing micrographs of the three techniques it is clear that the surfaces generated are similar, especially in terms of surface texture. Fig. 3*b* features some anisotropy on the diced facet, which is visible as horizontal indentations left by the diamonds within the blade and evidenced by a higher Sa. The metrology plots of Figs. 2*b* and 4*b* both show isotropic surface textures and hence have similar roughness values, demonstrating a comparable (<0.3 nm) Sa result between polished and diced facets.

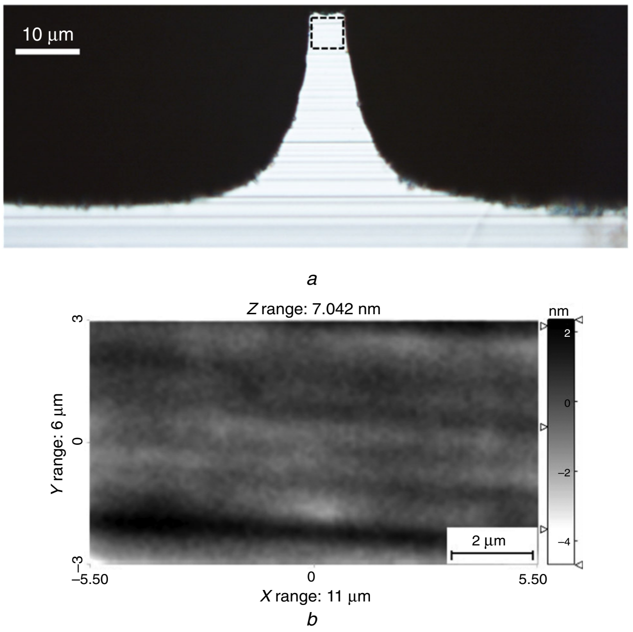

Fig. 3 *Ductile dicing of ridge PPLN waveguide with resin bonded blade*

a Micrograph image of PPLN waveguide facet machined in ductile dicing regime with resin-bonded blade
b Surface metrology taken within black dashed line from which average surface roughness of 0.54 nm (Sa) is calculated

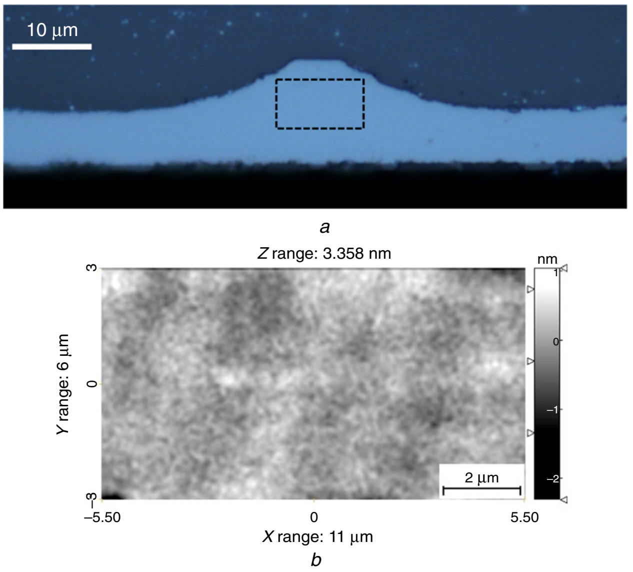

Fig. 4 *Ductile dicing of rib PPLN waveguide with nickel bonded blade*

a Micrograph image of PPLN waveguide facet machined in ductile regime with nickel-bonded blade
b Surface metrology taken within black dashed line from which average surface roughness of 0.29 nm (Sa) is calculated

The previous work carried out by Sun *et al.* demonstrated dicing of a PPLN ridge waveguide facet with a measured Sa of 2.82 nm and Sq of 3.72 nm in a $0.5 \times 0.5\ \mu m^2$ sampled area [5]. Our result, utilising a stabilised ductile dicing recipe and nickel-bonded blade, represents a nine times reduction in average surface roughness (Sa) and an eight times reduction in RMS surface roughness (Sq) from this prior work. Sub-nanometre surface roughness was achieved on our PPLN waveguide facets by careful optimisation of the dicing process to ensure ductile regime machining throughout. The near order of magnitude reduction in surface roughness over prior work is likely enabled by our machining parameter choices and the ultra-precision dicing machine used for these experiments; the DAD3430 is equipped with an air bearing slideway and linear position encoders, which improves control over the machining parameters when compared with the lead screws and rotatory encoders used in typical dicing saws. Careful selection of blade type and the parameters for spindle speed and cut depth also reduces the strain applied to the workpiece during machining, generating smoother surfaces.

Conclusion: We have demonstrated that ductile mode dicing can generate PPLN waveguide facets with <0.3 nm surface roughnesses that are comparable with that of lapping and polishing. Sub-nanometre surface roughnesses have been achieved with both resin- and nickel-bonded blade types using similar dicing routines. Average and RMS surface roughnesses of 0.29 and 0.46 nm have been measured for facets cut with nickel-bonded blades. These results represent a nine times reduction in terms of average surface roughness (Sa) and an eight times reduction in RMS surface roughness (Sq) from previously demonstrated work and represent a viable route to single-step singulation of PPLN waveguide devices from a host wafer without the need for subsequent lapping and polishing.

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One or more of the Figures in this Letter are available in colour online.

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