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## PAPER

# Characterisation of fabrication inhomogeneities in Ti:LiNbO<sub>3</sub> waveguides

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**Abstract**

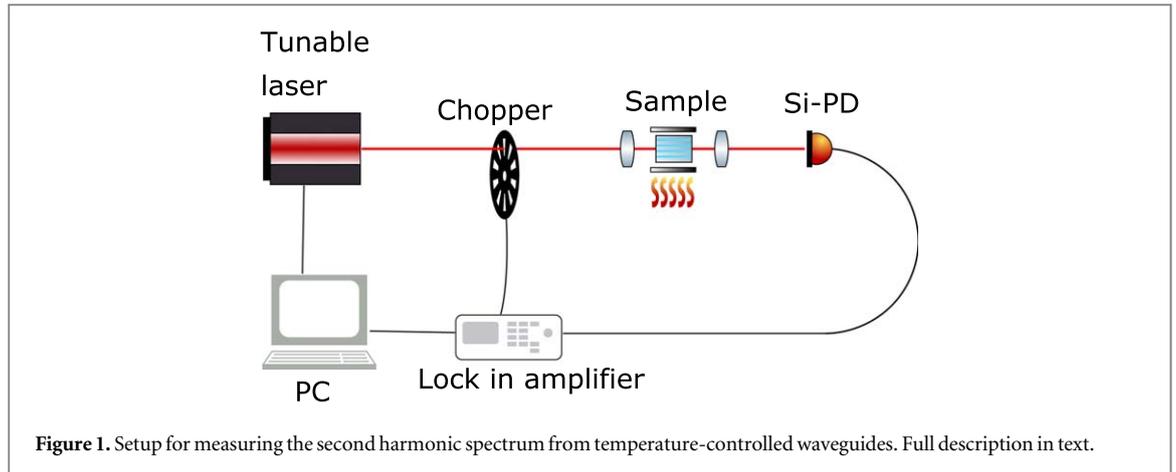
Nonlinear processes in integrated, guiding systems are fundamental for both classical and quantum experiments. Integrated components allow for compact, modular and stable light-processing systems and as such their use in real-world systems continues to expand. In order to use these devices in the most demanding applications, where efficiency and/or spectral performance are critical, it is important that the devices are fully optimised. In order to achieve these optimisations, it is first necessary to gain a thorough understanding of current fabrication limits and their impact on the devices' final performance. In this paper we investigate the current fabrication limits of titanium indiffused lithium niobate waveguides produced using a masked photolithographic method. By dicing a long ( $\sim 8$  cm) sample into smaller pieces and recording the resulting phase matching spectra, the fabrication error present in the UV photolithographic process is characterised. The retrieved imperfections fit well with theoretical expectations and from the measured imperfection profile it is shown that one can directly reconstruct the original distorted phase matching spectrum. Therefore, our measurements directly quantify the intrinsic limitations of the current standard UV photolithographically produced titanium-indiffused lithium niobate waveguides.

**1. Introduction**

Guiding systems fabricated in nonlinear materials are employed in a wide variety of contexts for both classical and quantum applications. In comparison to bulk systems, guiding systems provide simple integration into fibre networks and provide a tighter spatial mode confinement, which generally strengthens the nonlinear interaction. Such systems are already in use in a myriad of classical applications, for example in second harmonic and sum frequency generation (SHG/SFG) to efficiently produce light in spectral ranges otherwise inaccessible [1–3]. More recently these systems are also finding applications in quantum systems, for example in generation and manipulation of quantum states [4–8].

While waveguiding systems offer many advantages, these systems also generally exhibit higher losses and are much more sensitive to device imperfections, when compared to their bulk counterparts. It is known that small device imperfections can dramatically reduce device performance [9–16]. For this reason, it is critical to assess the limits of the current fabrication technology to identify the classes of nonlinear processes physically achievable and to devise strategies to overcome such limitations.

Despite the importance of these investigations, very little experimental work has been undertaken [14, 15]. In [14], both the amplitude and the phase of a phase matched process in reverse proton exchanged lithium niobate (RPE-LN) waveguides was characterised, allowing the complete determination of the inhomogeneity profile of their waveguides. However, such a scheme is not always possible as it relies on a chirped broadband conversion process to map spatial inhomogeneities to the amplitude and phase of the second harmonic field, which can be characterised using frequency resolved optical gating. In [15], a destructive approach was used to reconstruct the variation of the fabrication parameters of a photonic crystal fibre (PCF). In this method, the



**Figure 1.** Setup for measuring the second harmonic spectrum from temperature-controlled waveguides. Full description in text.

sample under analysis is diced into smaller sections and the phase matching of each section is used to infer the local properties of the system.

In this paper, the dicing technique is used to retrieve the fabrication errors of titanium indiffused lithium niobate (Ti:LN) waveguides. An 83 mm long sample is diced down into  $\sim 10$  mm long pieces, whose individual phase matching spectra, as well as the phase matching profile of intermediate lengths, are characterised. The shift of the phase matching spectrum along the waveguide is mapped and used to retrieve the phase matching variation. We briefly ensure that the measured phase matching variations are reasonable by determining the error in the waveguide width that would correspond to the measured values. Finally, from the measured waveguide inhomogeneities, we are able to reconstruct the original phase matching of the sample.

## 2. Experiment

The system under investigation is a set of seven 83 mm long nonlinear waveguides fabricated by in-diffusing Ti ions in a z-cut LiNbO<sub>3</sub> crystal, as described in [17]. The waveguides are designed to be single-mode in the telecom C band (7  $\mu\text{m}$  in width) and are periodically poled with a period  $\Lambda = 16.8 \mu\text{m}$ . This allows a type 0,  $ee \rightarrow e$  degenerate SHG process pumped at 1 528.4 nm at room temperature.

The nonlinear process is completely determined by the phase mismatch  $\Delta\beta$  of the involved light fields

$$\Delta\beta(z, \lambda) = 2\pi \left( \frac{n_e(z, \lambda/2)}{\lambda/2} - 2 \frac{n_e(z, \lambda)}{\lambda} - \frac{1}{\Lambda} \right), \quad (1)$$

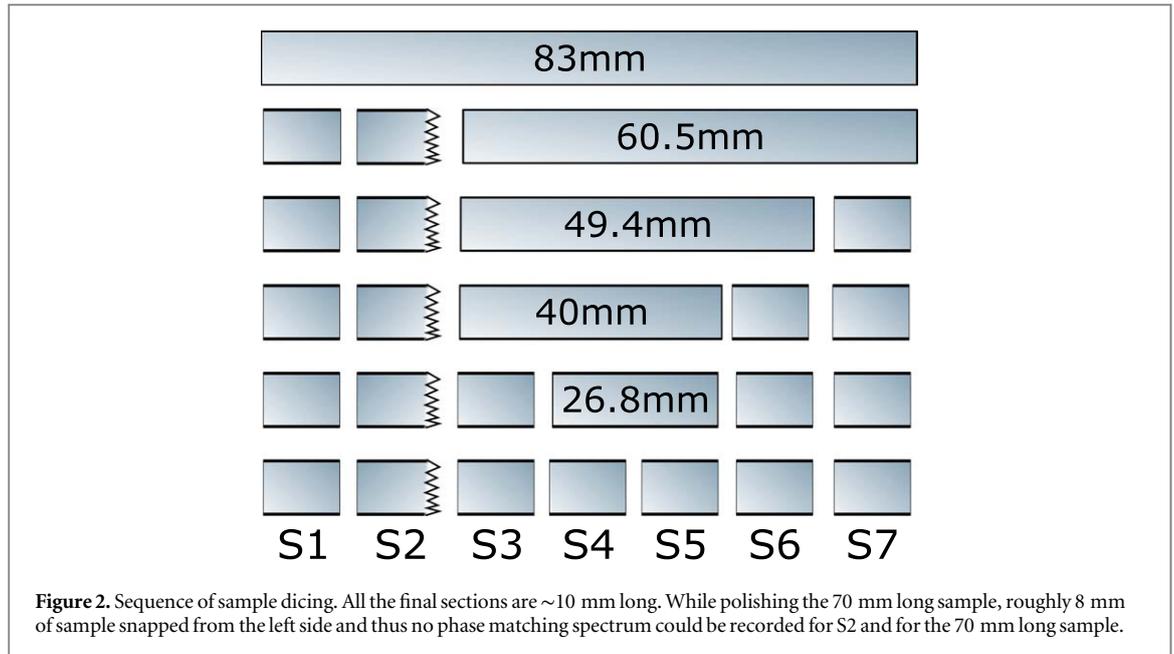
where  $n_e(z, \lambda)$  is the extraordinary refractive index of LiNbO<sub>3</sub> at the position  $z$  and at the pump wavelength  $\lambda$ . We explicitly consider the variation of the refractive index along the propagation axis  $z$  to include the effect of fabrication imperfections, such as inhomogeneities in the waveguide width, depth, operating temperature, poling pattern or a combination thereof.

In the case of small refractive index variations, one can approximate variations in the momentum mismatch to be wavelength independent, i.e.  $\Delta\beta(z, \lambda) \approx \Delta\beta_0(\lambda) + \delta\beta(z)$ . In this case, the output intensity spectrum of the SH process is given by [10, 14, 16]

$$I(\lambda) \propto \left| \int_0^L e^{-i\Delta\beta_0(\lambda)z} e^{-i \int_0^z \delta\beta(\xi) d\xi} dz \right|^2 \quad (2)$$

and thus depends on the specific  $\delta\beta(z)$  profile. However, if the waveguide is sufficiently short, the impact of the variations  $\delta\beta(z)$  are not strong enough to appreciably distort the phase matching spectrum, as shown in [16]. They are still expected, however, to affect positioning of the centre of the spectrum. Previous work in this waveguide system has shown that we expect to see nearly ideal phase matching spectra for waveguides shorter than 1 cm in length [16]. Therefore, it should be possible to retrieve the variation of  $\delta\beta(z)$  along the sample by dicing a long sample down to  $\sim 1$  cm long pieces and monitoring the shift in the position (in wavelength) of the phase matching spectrum.

At first, the phase matching spectra of the initial 83 mm long waveguides are measured in the setup illustrated in figure 1. The sample is first stabilised in temperature to around  $25 \text{ }^\circ\text{C} \pm 0.1 \text{ }^\circ\text{C}$  as unwanted temperature shifts are indistinguishable from true waveguide imperfections, since both will act to shift the centre of the phase matching profile. The waveguides are then pumped with approximately 3 mW from a tunable 1550 nm laser (*EXFO Tunics*) and the wavelength of the pump is scanned in 1 pm steps. The generated SH field is



then detected using a Si-PIN photodiode. To increase the signal-to-noise ratio of the measurement the pump field is run through a chopping blade, and the photocurrent from the photodiode is fed into a lock-in amplifier (*Ametek Scientific Instrument 7265*).

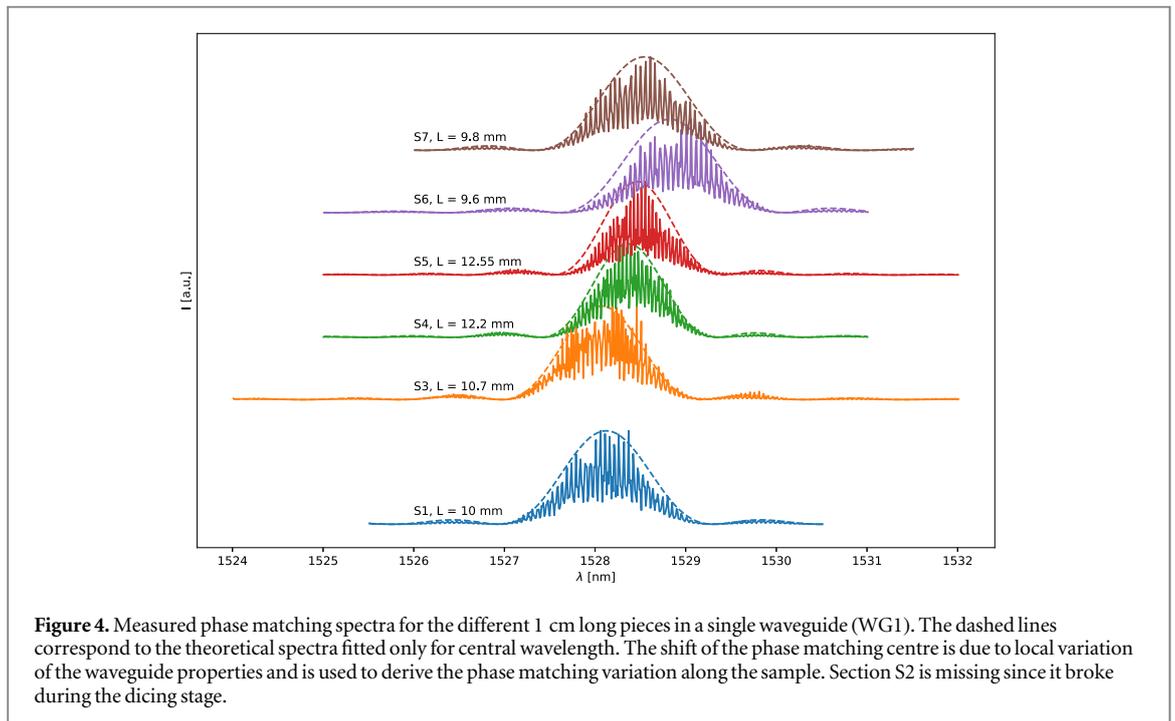
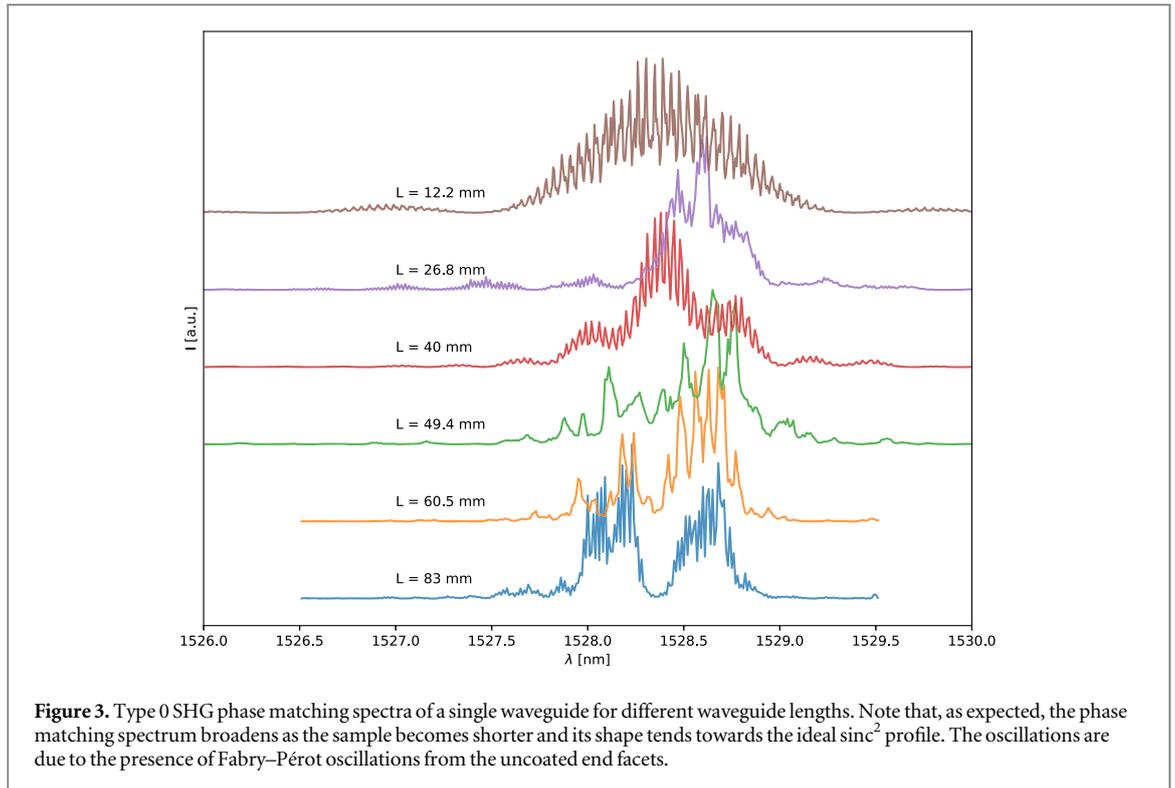
As expected, the spectra of the long waveguides are distorted due to the presence of waveguide inhomogeneities, as can be seen in figure 3. A  $\sim 1$  cm long piece was then cut from one end of the original sample and the resulting surfaces were polished. Similar to the measurement for the original long sample, both resulting lengths were then temperature stabilised and the phase matching spectra of the waveguides in each section were again recorded. This process was repeated until the full sample was finally cut down into 7 pieces of approximately 1 cm long, as shown in figure 2. Note that some of the length is lost in the dicing and polishing of the sample as well as a small piece that was damaged during dicing.

Theoretical calculations [18] show that, for a given inhomogeneity profile  $\delta\beta(z)$ , the phase matching spectrum becomes less distorted as the length of the waveguide is reduced, since the imperfections become less critical. This behaviour can be appreciated in figure 3, that reports the measured phase matching spectra of a single waveguide as it was gradually cut into shorter and shorter pieces. One can see that the measured spectra gradually approach the ideal  $\text{sinc}^2$  profile as the sample is shortened down to 1 cm. Observing that the transition between a degraded and a clean spectrum occurs for  $L \approx 2$  cm allows the estimation of the maximum phase matching error  $\sigma = \max_z |\delta\beta(z)|$  of the system. From the condition  $\sigma L \leq 10$ , which describes the necessary condition to achieve a good phase matching spectrum [18], we expect the maximum phase matching error  $\sigma$  to be  $\lesssim 500 \text{ m}^{-1}$ .

A more precise value of  $\sigma$  can be determined by measuring the phase matching variation  $\delta\beta(z)$  from the spectra of each 1 cm long piece. Figure 4 shows the measured phase matching profiles for all 1 cm pieces across a single waveguide. For reference, the dashed curve shows the expected  $\text{sinc}^2$  profile fitted only for the central wavelength. The central phase matching wavelength  $\lambda_{\text{pm}}$  is found from the data as the average of the measured wavelengths weighted by the corresponding measured intensities. Since the sample is temperature stabilised, the deviation of  $\lambda_{\text{pm}}$  from the target phase matching wavelength  $\bar{\lambda}_{\text{pm}} = 1528.4 \text{ nm}$  is a measure of the waveguide inhomogeneities  $\delta\beta(z)$ . With the help of equation (1), one can quantify the phase mismatch  $\delta\beta$  with respect to the ideal phase matching for each 1 cm long section.

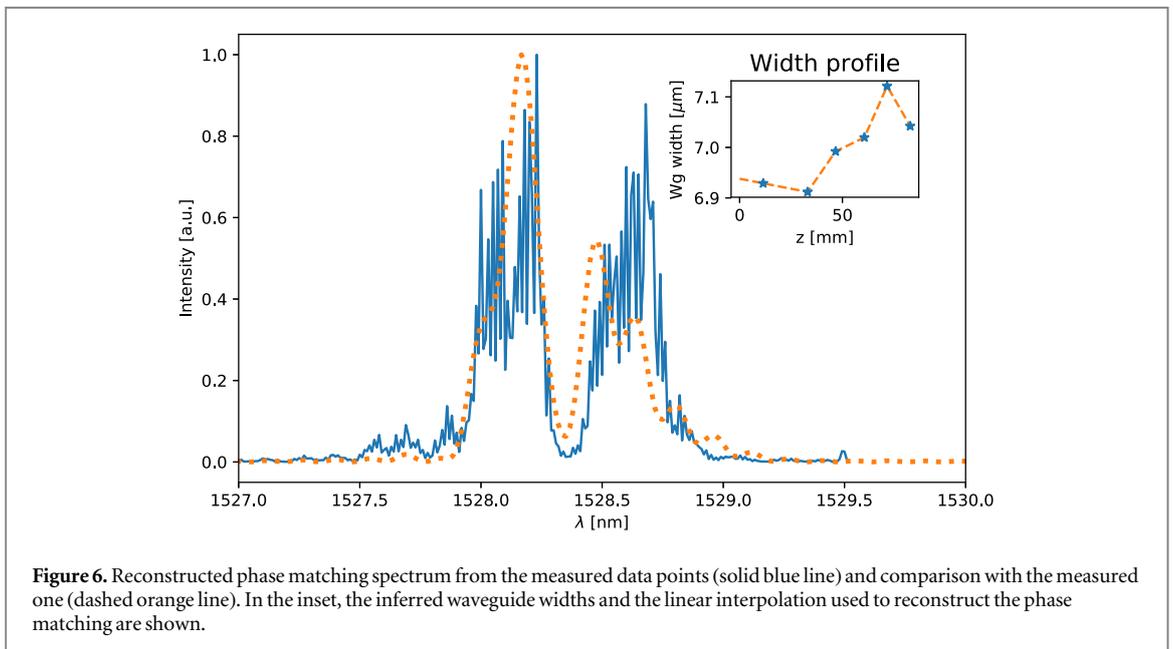
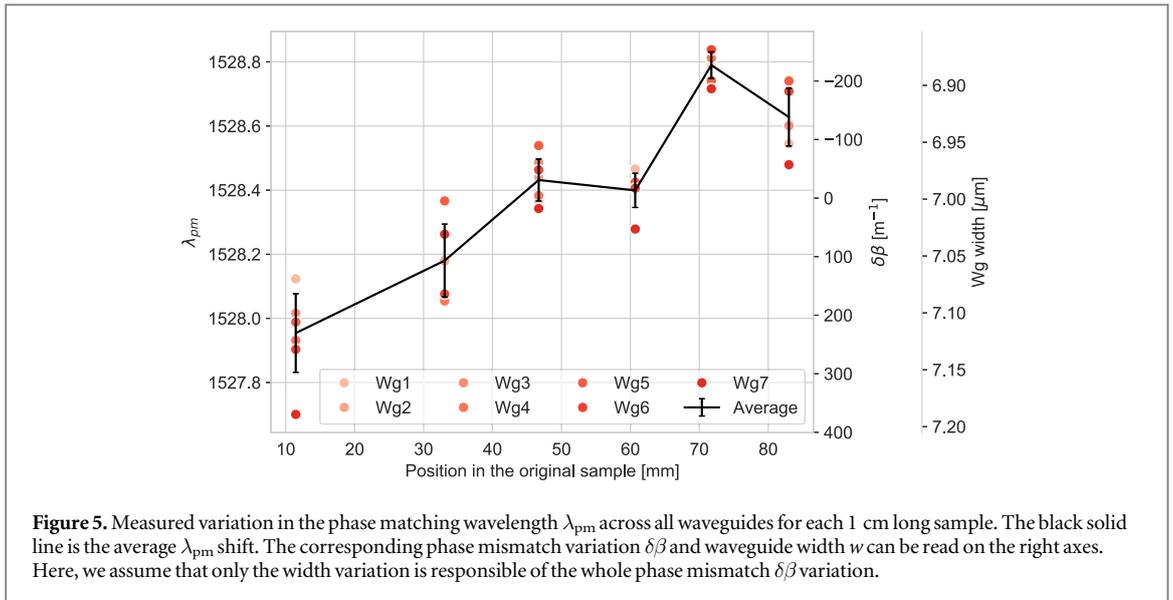
This characterisation is repeated for all remaining waveguides and the central phase matching wavelengths found in the 1 cm samples for all waveguides are shown in figure 5. It is immediately apparent that all the measured waveguides show a similar trend, whereby  $\lambda_{\text{pm}}$  increases along the sample length. Additionally,  $\lambda_{\text{pm}}$  changes quite dramatically between the different sections, with an average maximum variation of 0.6 nm. This corresponds to a  $\sigma$  of  $\sim 442 \text{ m}^{-1}$ , in close agreement with the estimate provided above.

Using the model presented in [19], one can relate the phase matching shift to a variation of the waveguide properties. We choose to attribute the measured phase matching errors to waveguide width imperfections because previous work in RPE-LN waveguides found this parameter to be the main source of  $\delta\beta(z)$  error [14]. For the waveguides under consideration, a variation of  $\sigma \sim 440 \text{ m}^{-1}$  corresponds to a width inhomogeneity



$\delta w \sim 0.25 \mu\text{m}$ . This result is consistent with AFM measurements on a twin sample, which showed  $\delta w \sim 0.18 \mu\text{m}$ , and gives us confidence that the retrieved  $\sigma$  is physically meaningful.

Finally, it should be possible to reconstruct the original phase matching spectrum given the measured  $\delta w$  profile along the sample. The performance of this reconstruction will of course be limited by the resolution of the measured  $\delta w$  profile and hence only the profile of the full length sample is reconstructed. We interpolate the measured data points with a piecewise linear interpolation to avoid numerical artifacts that are seen to arise from the choice of higher order polynomials fits. Thus, we obtain an approximate waveguide width profile  $w(z)$  and the respective phase mismatch variation  $\delta\beta(z)$ . Equation (2) is then used to calculate the expected phase matching spectrum of the original, full-length sample. In approximately half of cases, the reconstruction of the



phase matching was successful and showed very similar behaviour to the phase matching that was initially measured from the full-length sample. One such reconstruction and the measured phase matching spectrum is shown in figure 6. It is believed that the reconstruction failed in half of cases due to an insufficient spatial resolution for  $\lambda_{pm}$ . Note that, in contrast to previous work in PCF fibres [15], no fitting has been performed to reproduce the measurement of the original sample. This shows that, in most cases, the phase matching properties in Ti:LN waveguide can be considered constant within 1 cm.

### 3. Conclusion

In this paper, the inhomogeneity present in Ti:LN waveguides produced via UV photolithography was characterised by investigating the performance of a type 0 SHG process in these waveguides. The phase matching spectrum of seven waveguides was measured for the full-length sample (83 mm) and for each resulting smaller section as  $\sim 10$  mm long pieces were cut from the ends of the initial sample. The variation in the central phase matching wavelength along the sample was recorded for the 1 cm pieces. From these measurements the variation in the phase matching across the sample were inferred, showing that the maximum phase matching deviation is  $\sigma \leq 440 \text{ m}^{-1}$ . This limits the maximum sample length that ensures an ideal phase matching spectrum for the process under consideration to 2 cm. It was also shown that the measured phase matching

variation along the sample could be used to directly reconstruct the measured, highly distorted phase matching profile of the full-length sample. These results confirm the theoretical model presented in [16, 18], thus verifying the validity of the conclusions presented therein. The measured inhomogeneities in these titanium-indiffused LN waveguides report the current state of the art and provide crucial information that can be used to optimise the design of new samples.

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