# Waveguide mode filters fabricated using laser-induced forward transfer

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**Abstract:** Titanium (Ti)-in-diffused lithium niobate waveguide mode filters fabricated using laser-induced forward transfer followed by thermal diffusion are presented. The mode control was achieved by adjusting the separation between adjacent Ti segments thus varying the average value of the refractive index along the length of the in-diffused channel waveguides. The fabrication details, loss measurements and near-field optical characterization of the mode filters are presented. Modeling results regarding the device performance are also discussed.



**OCIS codes:** (140.3390) Laser materials processing; (140.7090) Ultrafast lasers; (230.7370) Waveguides; Laser-Induced Forward Transfer.

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## 1. Introduction

Lithium Niobate (LN) is a very important optical material which is widely used by the photonics industry mainly due to its excellent electro/acousto-optical properties [1]. Channel waveguides, which are at the heart of any photonics circuit, are fabricated in LN by doping it with titanium (Ti) metal using the in-diffusion technique where Ti is locally deposited on a LN substrate using photolithography and lift off methods followed by thermal treatments [2, 3]. This method is suitable for mass production of devices and is compatible with the wafer-scale parallel techniques used in the microelectronics industry. However, for cases that require rapid prototyping of devices more flexible and faster techniques are needed.

In our recent work the laser-induced forward transfer (LIFT) technique was used to deposit segmented Ti metal lines onto LN substrates which produced low loss optical waveguides after thermal diffusion [4]. LIFT is a direct-write technique first demonstrated by Bohandy et al [5, 6] for depositing metals to repair damaged photomasks. Due to its simplicity and flexibility its use was quickly extended to print a variety of metals, semiconductors, dielectrics, ceramics and biomaterials [7-11]. This new approach offers both the flexibility, less stringent experimental conditions and rapid prototyping associated with LIFT, and the large refractive index change, low optical loss and stability of the waveguides associated with the thermal diffusion method. Additionally, printing of multiple diffusion sources in a single shot, from specifically tailored donors and deposition on non-planar substrates are the other advantages offered by this technique. In this paper, we present results of fabrication and optical characterisation of index-tapered waveguides produced by this method by adjusting the density of adjacent titanium segments during the LIFT process that defines the average refractive index which light experiences in different sections of the waveguide. We demonstrate here the use of such a refractive index tapered waveguide as a mode filter thereby taking this technique into a new realm of fabricating custom-made complex refractive index profiles and photonic devices.

## 2. Experiments

The fabrication of tapered waveguides using LIFT was a two-step process. Firstly, a linear arrangement of Ti metal segments was printed on top of LN substrates using the LIFT technique as shown in fig. 1. The LIFT samples were prepared by depositing thin films (~ 150 nm) of Ti (the *donor*) on top of transparent glass substrates (the *carrier*) by e-beam evaporation. Femtosecond pulses with a Gaussian spatial profile from a mode-locked Ti: sapphire laser (800 nm, 150 fs, FWHM ~ 4 mm) were centred on a 450 µm diameter circular aperture resulting in a reasonably spatially uniform incident pulse profile. A highly de-magnified image of the aperture was then relayed onto the *carrier-donor* interface using a commercial micromachining workstation (New Wave UP266, USA) thereby printing circular Ti discs of diameter ~10 µm (comparable to the incident laser spot size) onto a congruent undoped z-cut LN substrate on the –z face along the crystallographic y-direction. The separation between the carrier and the donor was maintained at ~ 1 µm separation using a Mylar spacer. The donor-receiver assembly was mounted on a 3-axis precision (10 nm resolution), fast (max. speed ~ 250 mm/s) computer-controlled translation stage to allow the *carrier-donor* complex to be scanned in front of the incoming laser pulses. All experiments were performed under a background pressure of $10^{-1}$ mbar. Single laser pulses were used to print each Ti dot and the laser was operated at 250 Hz. The laser threshold fluence for transfer of Ti discs was ~ 0.4 J/cm$^2$. The separation between two adjacent Ti dots was controlled by varying the scan speed of the translation stages. After printing, the deposited metal lines were diffused into the LN crystal by heating it to 1050$^o$C in an oxygen atmosphere for 10 hours.

Index tapered waveguides were produced by varying the writing speed along the segmented Ti lines at a constant acceleration. The reason for writing lines at constant acceleration was to avoid sudden changes in the final refractive index profiles to minimize losses and obtain a smooth mode filter effect from the tapered waveguides. The idea behind this technique is to have the ability to alter the behaviour of the waveguides just by manipulating the scan speed and hence the segment separation along the length of the waveguides. The amount of material deposited and then diffused per unit length decreases with increasing scan speed, which in turn decreases the average effective index of the mode. The mode confinement should therefore decrease with increasing speed and the waveguide modal behavior should change from multi-mode to single-mode. By increasing the segment separation and hence decreasing the index contrast along the waveguide a mode filter can be produced that allows only the fundamental mode to propagate. In the present set of experiments three different values of constant acceleration of 0.3, 0.4 and 0.5 mm/s$^2$ were used for fabricating the tapered waveguides. The initial velocity was kept constant at 2.5 mm/s for all the tapers. Uniform waveguides were also fabricated for comparison by depositing Ti segments with a constant separation (10 µm between the centres of adjacent segments) obtained by scanning the sample with a constant velocity of 2.5 mm/s (fig. 1). The samples were then end-polished for optical characterisation and loss measurements.

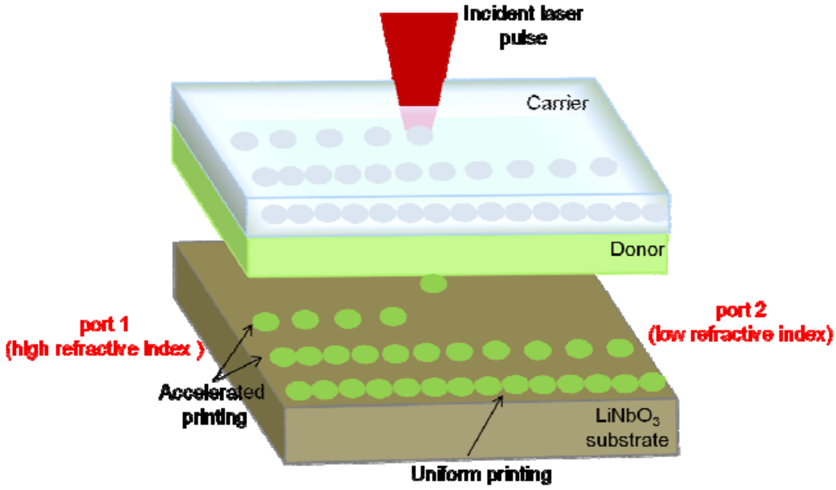


Fig. 1. Schematic of the LIFT technique for printing segmented Ti lines onto LN substrates. The exaggerated version of how the Ti dots separate out by increasing speed from one end (port 1) of the substrate to the other (port 2) for fabrication of a tapered waveguide along with constant velocity lines for comparison are also shown.

The waveguide losses at 1550 nm were measured using the fibre mismatch technique [12]. Light from a tuneable laser (1500-1600 nm) was launched into the waveguides using a single mode fibre (SMF) and the output was first collected using a similar SMF and then with a multimode fibre (MMF). The difference in the collection efficiency gave the coupling loss of 6 dB for the SMF. In this technique it is assumed that the MMF collects all the output light from the waveguide. The propagation loss was then calculated by taking the difference between the insertion loss (total loss due to the waveguide) and the coupling loss. The insertion loss of the waveguides was measured to be 11 dB resulting in a propagation loss of ~ 3.1 dB/cm, (the waveguide length was 16 mm). The variation in the velocity along the waveguide length leads to higher values of optical loss in tapered waveguides than the previously reported constant velocity waveguides [4]. In comparison, overall optical losses of 1.6 dB and 1.05 dB have been reported for mode filters with lengths of 0.6 mm and 1.6 mm respectively prepared using soft proton exchange (SPE) method [13].

The optical characterization of the waveguides was performed using the set-up outlined in fig. 2. Light from a tuneable fiberised laser (1500-1600 nm, TM polarization) was coupled into the waveguides from port 1 using an objective lens (40 x). The output was collected using another objective lens (40 x) and the mode profiles were observed using an IR camera. All these measurements were performed at 1550 nm. The waveguide samples and objective lenses were mounted on a 3-axis (x-y-z) translational stage.

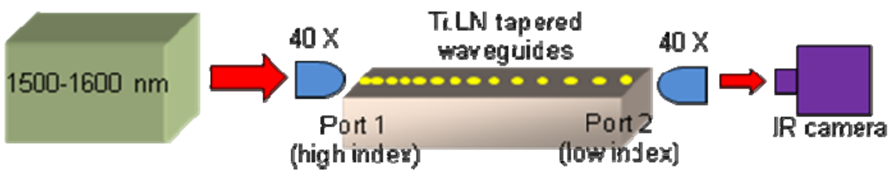


Fig. 2. Experimental set-up used for optically characterizing the waveguides

Figure 3(b) shows optical mode profiles of segmented waveguides corresponding to Ti deposition at constant velocity (2.5 mm/s). The waveguides supported two modes ($TM_{00}$ and $TM_{01}$). Figure 3 (d), (e) and (f) show the optical mode profiles of index tapered waveguides corresponding to Ti deposition with constant acceleration of 0.3, 0.4 and 0.5 mm/s$^2$ respectively with an initial velocity of 2.5 mm/s when light was launched from port 1 (fig. 2). The images clearly show that the tapers supported only the fundamental mode ($TM_{00}$) thereby exhibiting the mode filtering operation. Similar results were obtained even when the coupling conditions were altered by moving the waveguides with respect to the input beam in the transverse direction to excite higher order modes indicating that the port 2 of the tapered waveguides could support only the fundamental mode. When the acceleration value was increased beyond 0.5 mm/s$^2$ the waveguides ceased to guide altogether due to the waveguide reaching its cut-off value. Another important feature to be noticed in these images is that as the writing speed/acceleration was increased the mode size increased as well, as a direct consequence of the decrease in the index contrast with increasing segment separation that lead to a broader and less tightly confined mode. The Gaussian function fit mode field diameter (MFD) values for mode profiles captured from tapers fabricated with 0.3, 0.4 and 0.5 mm/s$^2$ acceleration respectively are presented in table 1. It clearly depicts the increase in the MFD with increasing acceleration value.

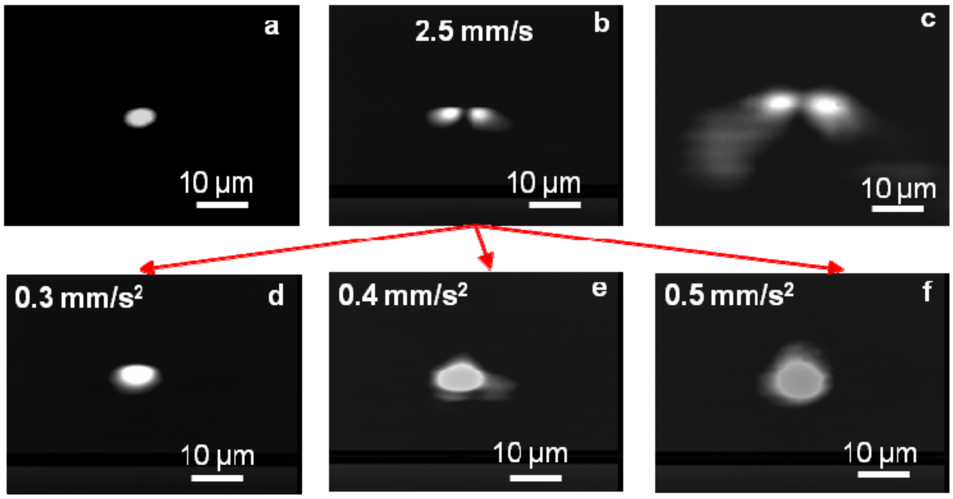


Fig. 3. (b) Near field intensity profiles captured from a waveguide written with a constant velocity of 2.5 mm/s. (d-f): near field intensity profiles of tapered waveguides written at accelerations of 0.3, 0.4 and 0.5 mm/s$^2$ respectively when the light was launched from port 1. (a) and (c): near field intensity profiles corresponding to the waveguide written with an acceleration of 0.3 mm/s$^2$ when the light was launched from port 2.

When the laser light was launched from port 2 (fig. 2) a much better confined fundamental mode was obtained on the higher index port 1 of the tapers (fig. 3 (a)) as expected. The Gaussian fit MFD value for this mode is also presented in table 1. However upon altering the launching angle a higher order mode was monitored at the same port as shown in fig. 3 (c) for a waveguide written with an acceleration of 0.3 mm/s$^2$. This behavior is not expected for an adiabatic taper however the corrugation in the refractive index distribution along the waveguides caused by the shape of the printed Ti dots is believed to be responsible for this non-adiabatic behavior of the device. Modeling results, which will be discussed in the next section, confirmed this observation.

**Table 1. Gaussian Fit MFD Values for Mode Profiles Captured from Waveguides Written with Acceleration of 0.3, 0.4 and 0.5 mm/s$^2$ respectively When the Light was Launched from Port 1 along with the MFD Value for the Fundamental Mode on the Higher Index Port 1 for Tapered Waveguide Written with 0.3 mm/s$^2$ Acceleration When Light was Launched from Port 2.**

| Waveguides written with constant acceleration of | Gaussian fit MFD (μm) |
|---|---|
| 0.3mm/s$^2$ (light launched form the port 1) | ~ 11.5 |
| 0.4 mm/s$^2$ (light launched form the port 1) | ~ 14.5 |
| 0.5 mm/s$^2$ (light launched form the port 1) | ~ 16.5 |
| 0.3 mm/s$^2$ (light launched form the port 2) | ~ 8.5 |

## 3. Theoretical modeling

To understand the non-adiabatic nature of the segmented tapers fabricated using LIFT the light propagation both along segmented Ti:LN and continuous index tapers was modeled. First a 3D model of Ti diffusion of LIFT-deposited dots at high temperature was developed with dot separation varying from zero to 3 μm in steps of 0.5 μm. This Ti distribution was then converted to the corresponding 3D refractive index profile using the method discussed in [14]. The zero and 3 µm separation values corresponded to the initial and final Ti dot separation for the tapered waveguides written using 0.3 mm/s$^2$ acceleration. The maximum refractive index contrast values over this range of segment separation vary from 0.0406 to 0.0322. In the actual experiments the samples were ~ 16 mm long but theoretical modeling was not possible for these lengths due to excessively large computer memory requirements. The simulation of light propagation in the waveguides was therefore restricted to shorter lengths (~ 700 µm) and qualitative results were obtained using Comsol multiphysics software. The structure was built by drawing 7 sections each section containing 10 Ti discs with 0, 0.5, 1, 1.5, 2, 2.5 and 3 µm separations respectively. The corresponding refractive index profile was calculated and is illustrated in fig. 4 (a) as variation of the intensity of the segments along the waveguide. The structure which is visible in some of the segments in fig. 4 (a) is due to limitations in the image generating capabilities of the software. Cross sections of the profiles showed a smooth refractive index distribution. The light propagation pattern as shown in fig. 4 (b) was obtained using a Gaussian ($TM_{00}$) distribution as an input to the port corresponding to the 3 µm separation side of the waveguides. The results revealed that during propagation, part of the $TM_{00}$ mode gradually converted to $TM_{01}$ mode at the zero separation port of the taper. The intensity profiles obtained from the 3 µm and zero end of the tapered waveguide at the positions marked by red lines are shown in fig. 5 (i) and 5 (ii) respectively.

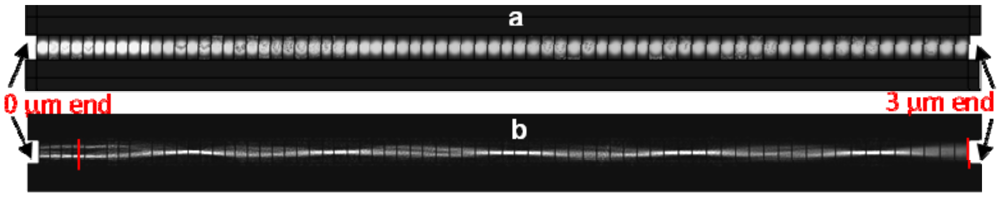


Fig. 4. (a) Shows the refractive index profile for the segmented Ti:LN waveguide with the brighter regions corresponding to higher index. (b) Shows the light propagation pattern when $TM_{00}$ mode was launched from the 3 µm end of the waveguide.

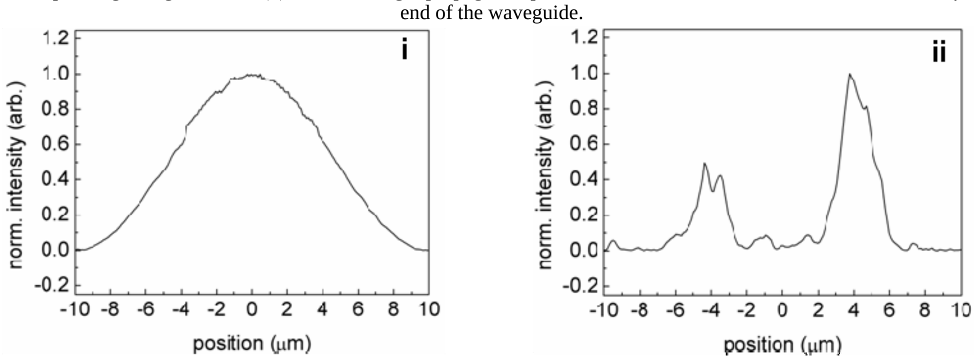


Fig. 5. Mode profiles obtained from the (i) 3 µm end and (ii) 0 µm end of the segmented Ti:LN waveguide. The positions where the modes were captured are marked as red in fig. 4 (b).

The case of light propagation through a continuous Ti:LN tapered waveguide was simulated using the beam propagation method (BPM) in the commercially available RSoft Beamprop software, with the refractive index contrast values varying linearly from 0.0406 to 0.0322 throughout the length ( ~ 1 cm in this case) of the taper. The results depicted that the mode size increases from the higher index port of the taper to the lower index port, as expected for an adiabatic taper. The simulated mode profiles both for the higher and lower index ports are presented in figs. 6 (a) and 6 (b) respectively. This confirms the dot-induced non-adiabatic refractive index structure observed for the segmented Ti:LN waveguides.

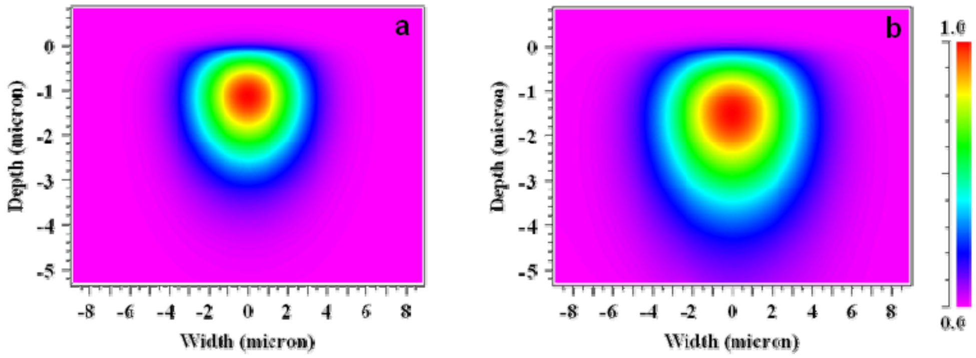


Fig. 6. Simulated near field intensity profiles obtained from (a) the high index and (b) the low index port of a continuous Ti:LN waveguide. The mode size increases as the refractive index contrast decreases along the length of the waveguide.

## 4. Conclusions

The control over the waveguide refractive index contrast obtained by adjusting the separation between adjacent segments of Ti which were LIFT-deposited and diffused into LN substrates has been used to fabricate a refractive index tapered waveguide device to be used as a mode filter. The propagation losses of the tapers were measured to be ~ 3.1 dB/cm at 1550 nm using the fibre mismatch technique. The mode profile pictures captured confirmed the mode filtering action performed by the index tapered waveguides. The corrugations introduced in the refractive index profile due to the segmented geometry of the deposits induce a non-adiabatic behavior in the tapers and this was confirmed by the theoretical modeling results.

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