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New LiNbO₃ Devices for Infrared Interferometry and Evanescent-Field Sensing: Integrated Single Mode Young's Slit Interferometer at 3.39 μm

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We present an integrated Lithium Niobate device based on single mode behaviour of a planar waveguide at 3.39 μm , made by Titanium diffusion. After an experimental and theoretical study of the waveguide in the infrared, we present the set-up that allows an interferometric measurement of the emission spectrum and thus that can be applied as an integrated spectrometer. An integrated device such as presented here could be part of an astronomical instrument in order to study spectral characteristics of stars or exoplanets.

Introduction

With the advent of spatial missions devoted to exoplanet search, astrophysical instruments are in need of integrated, stable, optic devices that could implement beam transport and analysis. In the particular case of stellar interferometry, integrated beam combiners have already been proposed for the telecom wavelengths (1.55 microns) [1]. However, for exoplanet detection, the 2.5–5 μm window has been identified as an adequate band for planet search science [2]. In particular, the L-band (3.4–4.1 μm) is most appropriate for ground-based detection of hot dust in the habitability regions of stars of the main sequence [3, 4]. As an example, the spectrum of a hot Jupiter is centered at 3.8 microns, presenting a strong emission while no atmospheric absorption lines degrade the spectrum [5]. Thus, new technological developments are compulsory in order to provide astronomers with integrated beam combiners devoted to different infrared ranges, from 2.5 to 5 microns.

We have selected LiNbO₃ in order to develop new integrated beam combiners, not only due to its transparency up to 5.2 μm , but also for its electro-optic properties, that will allow active control of phases, and the large variety of processing available to achieve waveguides (Ti-diffusion, Proton Exchange, Ion Beam Implantation, Photo-induced birefringence) with

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low optical losses (<0.2 dB/cm). Whereas these methods are well known for waveguide realization below $1.55 \mu\text{m}$, only few laboratories in the world have explored the capacities of LiNbO_3 at higher wavelengths. However, feasibility of single mode waveguides in LiNbO_3 by classical proton exchange techniques has been recently demonstrated [6], and with Ti-indiffusion, Sohler group demonstrated a first realization in the mid-IR devoted to Difference Frequency Generation [7].

In this paper, we present our results for L-band single mode realization by Titanium diffusion and some preliminary results on an integrated Young interferometer working in the L-band. It's important to note that with this fabrication technique, both polarizations (ordinary and extraordinary) are expected to guide the light, which is an important issue in astrophysics, since polarisation studies are essential to understood astrophysical phenomena. Unfortunately, most of the astrophysical instruments are not polarisation sensitive, and give only information about the intensity and not the vector direction of the electromagnetic field. Thus, metal in-diffusion is a very interesting approach to keep both polarizations and study them separately.

Waveguide Fabrication and Characterization

The samples used for waveguide realization were X-cut, 500 microns thick, LiNbO_3 substrates. Planar waveguides exhibiting single mode behaviour at $3.39 \mu\text{m}$ were fabricated at FEMTO-ST by Ti-diffusion, for 50h at 1020°C , using Ti layers of different thicknesses in order to study diffusion profiles. The best results were obtained for the samples with Ti thicknesses $\tau = 200$ nm. For the latter, single mode behaviour at $3.39 \mu\text{m}$ was observed by m-lines measurements.

Planar waveguides were characterized at LAOG using a dedicated m-lines bench, with two different wavelengths (633 nm and 3.39 microns). The experimental set-up is shown in Fig. 1:

Visible and IR laser sources are co-aligned using diaphragms, a polarizer (Glan-Thomson cube for visible or KRS-5 Wiregrid for IR) is used to properly select the polarization. An alignment cross is imaged on the sample and serves as a target for measuring the dark modes. Using a $+13\delta$ lens (L2) light is focused on to the base of a TiO_2 prism, and the reflected light is collected by a Pyrocam III camera (infrared imaging). Prism and Camera are mounted in concentric motorized rotation axis that allows dark lines detection in the infrared.

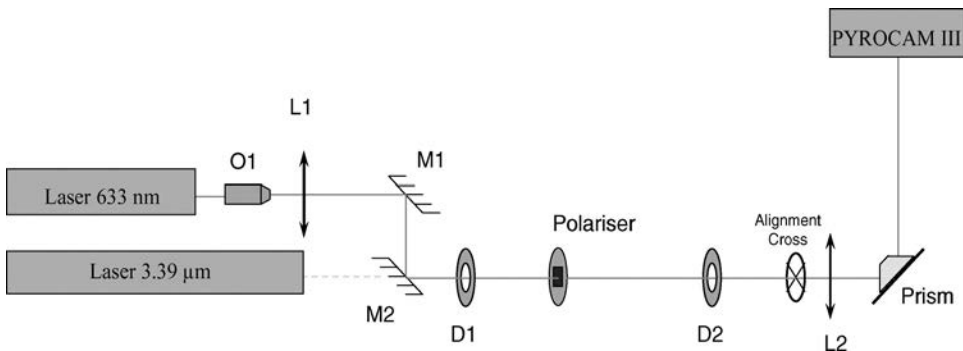


Figure 1. Experimental m-lines set-up for IR and Visible waveguide characterization.

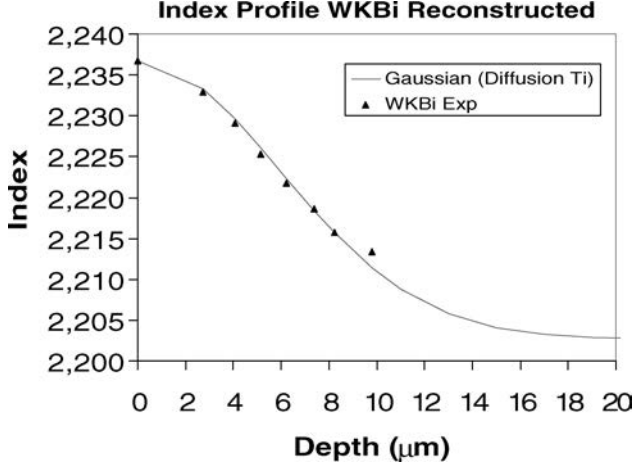


Figure 2. Extraordinary index profile of the planar Ti-diffused waveguide, reconstructed from m-lines measurements at 633 nm using the WKBi method.

First measurements in the visible allow to deduce the index profile using WKBi method [8]. Using the 633 nm laser, we obtained 7 extraordinary modes for the LiNbO_3 diffused waveguide, as shown in Fig. 2:

Fitting the experimental data with a gaussian-like index profile function, which is the distribution function used in the case of Ti-diffusion, we obtain the index profile and the depth of the waveguide:

$$n(z) = n_s + \Delta n - e^{-\left(\frac{z}{d}\right)^2} \quad (1)$$

Starting from known values $n_s = 2.2027$ (substrate index) and $\Delta n = 0.034$ (birefringence between substrate and surface mode deduced from WKBi calculation) at $\lambda = 633$ nm, we optimize the thickness parameter and obtain, $d = 8.4$ microns. With this value for thickness, we calculate the number of modes in a planar waveguide at 3.39 microns (with correspondingly lower values for n_s and Δn). We obtain an expected single mode at 3.39 microns for an output angle of $\theta = 17.8^\circ$. Experimentally, this single mode was obtained at 20.7° . This difference is mainly due to the inexact model used, since for a rapid estimation of the output angles we use a step-index model, which is not adapted to smooth profiles as obtained in metal-in diffusion.

We have thus obtained a single-mode planar waveguide at 3.39 μm , by Ti-diffusion. The goal is now to study how this single-mode waveguide can be used as an integrated beam combiner.

Integrated Young Interferometer and Experimental Set-Up

We developed a simple set-up in order to achieve a Young's Holes experiment, by carrying the infrared coherent light with the aid of two infrared fibers. These are Oxford chalcogenide fibers, with a core diameter of 250 μm and cladding diameter of 600 μm , and present multimode behaviour at 3.39 μm . The fibers extremities are inserted in cylindrical mounts, with internal cylindrical hole made by drilling, such that the cores are as close as possible (drill diameter is < 1 mm). Light from the He-Ne 3.39 μm laser source is injected in the

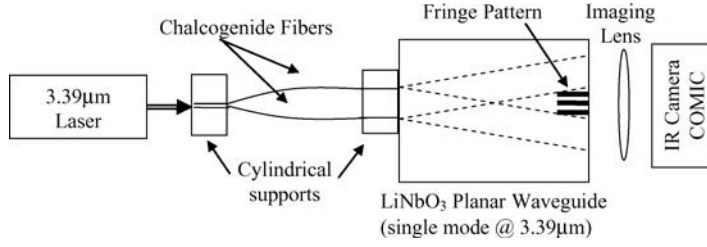


Figure 3. Experimental set-up for interferometric measurements using a planar waveguide. Two fibers act as the Young's Holes and fringes are detected in the camera by imaging the output of the planar waveguide.

fibers and then coupled into the single mode planar waveguide by fine alignment of the fibers output with the sample (see Fig. 3). Depending on the separation and numerical aperture of the fibers, and the length of the planar waveguide, we obtain a characteristic fringe pattern that is detected by an infrared camera (COMIC [9], 128×128 pixels, $50 \mu\text{m}$ width). In order to image the fringes obtained at the output end of the planar waveguide, a ZnSe lens is used to focus the light into the camera.

After measuring the fringes, i.e. the spatial frequencies, we realize a Fourier Transform to recover the spectral signature of the source and thus determine its spectral characteristics.

Theoretical Model

The intensity distribution at the waveguide output can be expressed as:

$$I(Y) = 4I_0 \underbrace{\sin^2\left(\frac{\pi b Y n}{\lambda D}\right)}_{\text{diffraction}} \left[1 + \underbrace{e^{\frac{(2Y\Delta\lambda)^2}{\lambda^4}}}_{\text{temporal coherence}} \underbrace{\cos\left(\frac{2\pi a Y n}{\lambda D}\right)}_{\text{interferences}} \right] \quad (2)$$

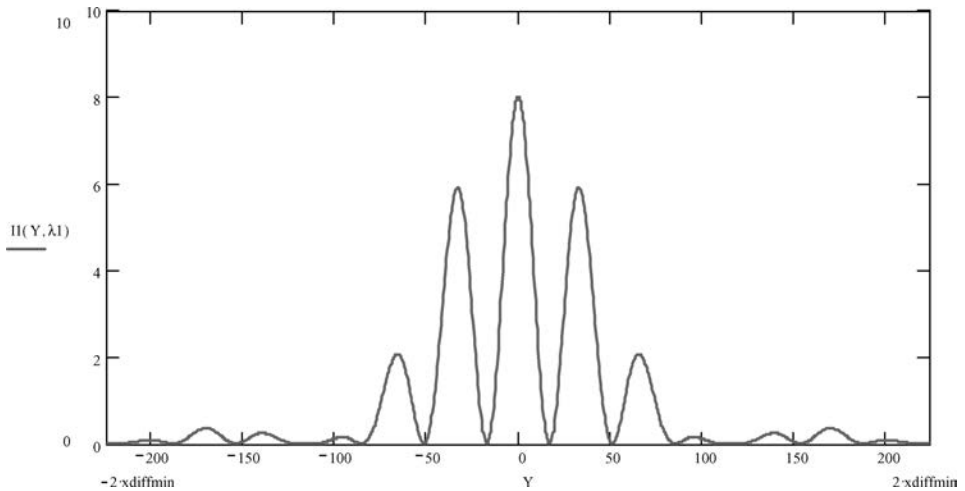


Figure 4. Theoretical distribution of fringes at the output of the waveguide.

Where b is the fiber core diameter, D is the planar waveguide length, a is the separation between the sources, n is the effective refractive index of the fundamental guided mode and Y is the lateral position along the output side. The term $\Delta\lambda$ represents the spectral width of the source, which can be considered as quasi-monochromatic and thus, neglected in the calculations.

In our system, using Oxford Chalcogenide Fibers (core diameter $b = 250 \mu\text{m}$, Cladding radius $300 \mu\text{m}$), we obtained a physical separation on the dedicated cylindrical mounts of $a = 820 \mu\text{m}$. Using the He-Ne Laser Source at $3.39 \mu\text{m}$, considering a quasi-monochromatic source ($\Delta\lambda \rightarrow 0$) and a single mode planar waveguide with $D = 18 \text{ mm}$ and $n = 2.14$ for the extraordinary fundamental guided mode at this wavelength, we obtain a theoretical distribution of fringes at the output given by Fig. 4.

That is, a diffraction limited pattern, with the fringe period $i = \lambda D/a \cdot n_{eff} = 34.77$ microns for a $D = 18 \text{ mm}$ long waveguide and a first maximum of diffraction of width $w = 228$ microns. We expect thus to observe seven fringes inside the first diffraction maximum.

Infrared Results

The results obtained for $3.39 \mu\text{m}$ excitation are shown in Figure 5. The extrapolated first diffraction maximum has a width of $250 \mu\text{m}$ (camera pixel position from $375\text{--}625 \mu\text{m}$). The experimental period is then $i = 37.16 \mu\text{m}$, in good agreement with the theoretical expected values.

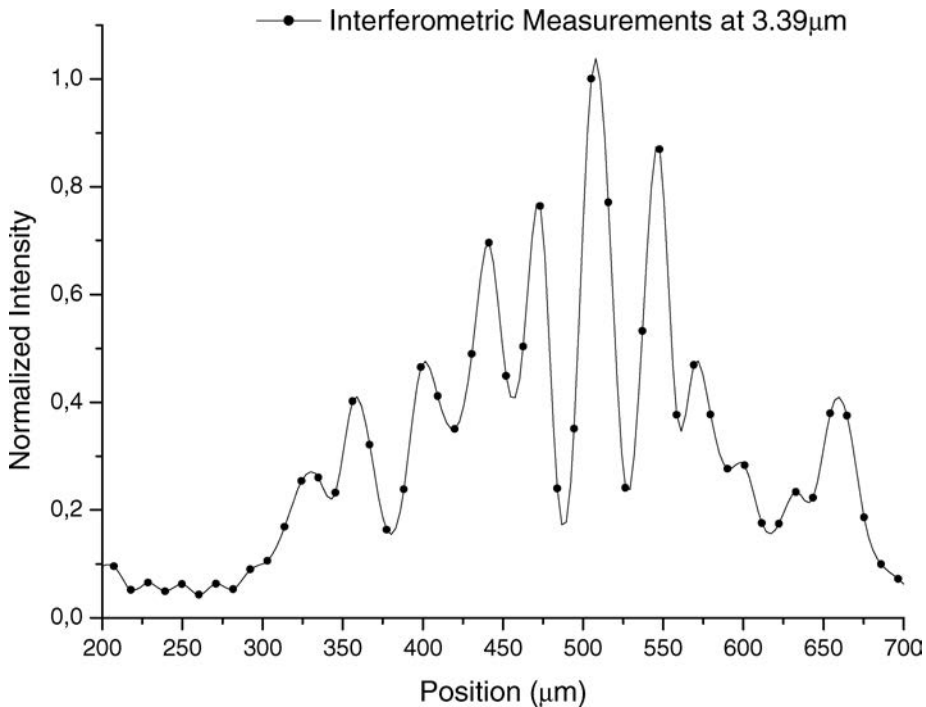


Figure 5. Experimental observation of IR fringes as detected at COMIC camera and corrected by the gain of the imaging optics.

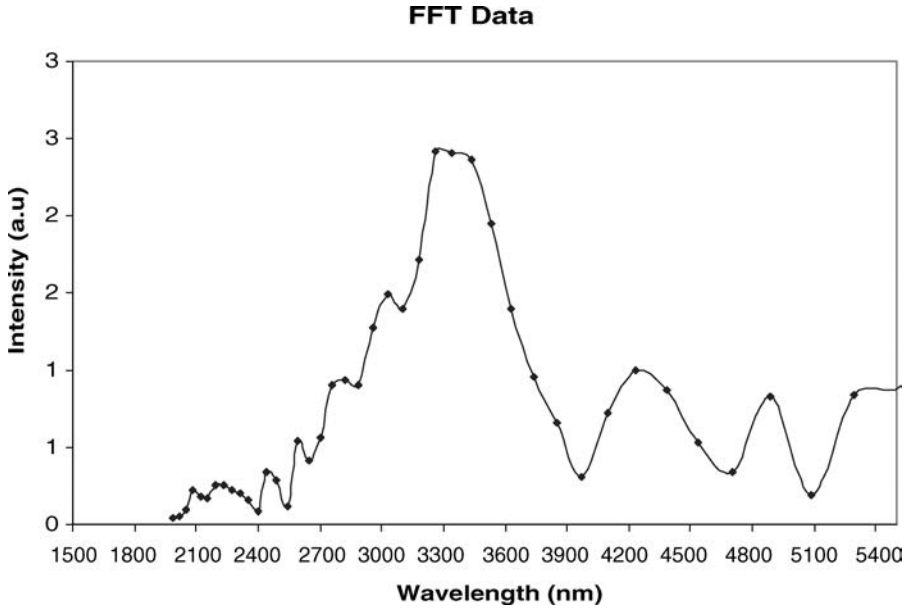


Figure 6. Fast Fourier Transform over the fringes allows to obtain the spectrum of the source.

Implementing a Fast Fourier Transform (FFT) over the measured fringes, we obtain a peak at 3344 nm (see Fig. 6), compared to 3390 nm of the theoretical emission line of the source.

Note that an error of one data pixel in the localisation of the FFT maximum gives an uncertainty of $\Delta\lambda = 38$ nm for the value of the source emission wavelength. Although the obtained spectra is weakly resolved, due to the scarce number of fringes and the poor number of pixels available, we can confirm that our interference pattern allows to measure the emission peak wavelength of the source.

Conclusion and Perspectives

We have realized a single mode planar waveguide in the L-band (around $3.4 \mu\text{m}$) and have shown the possibility to achieve spectroscopical measurements in the infrared by means of an integrated planar device. As this set-up can also be used as an evanescent-field sensor, by dropping a liquid containing an absorbing molecule on top of the planar waveguide, future work will consist on absorption studies using CHCl_3 , which presents a strong absorption line at $3 \mu\text{m}$. This will induce a “hole” in the spectrum of the source, and should be detected by this interferometric method, as long as the emission spectrum is large enough to cover the absorption line of the molecule (which is the case when using a black-body source). We could thus study the sensibility of the detection, by progressively diluting pure Chloroform.

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