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Manon Lamy, Kamal Hammani, Juan Arocas, Julien Fatome, Jean-Claude Weeber, et al.. Titanium Dioxide Waveguides for Data Transmissions at 1.55  $\mu\text{m}$  and 1.98  $\mu\text{m}$ . 19th International Conference on Transparent Optical Networks (ICTON 2017), Jul 2017, Gérone, Spain. hal-01574541

**HAL Id: hal-01574541**

**<https://hal.science/hal-01574541>**

Submitted on 15 Aug 2017

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# Titanium Dioxide Waveguides for Data Transmissions at 1.55 $\mu\text{m}$ and 1.98 $\mu\text{m}$

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## ABSTRACT

We demonstrate error free transmissions of 10 Gbps signals in titanium dioxide waveguides at wavelengths of 1.55 or 2  $\mu\text{m}$ . An efficient coupling of light is achieved thanks to metal grating couplers and we have checked that the component could be used with standard CWDM SFP+ devices.

**Keywords:** Titanium Dioxide waveguides, mid-infrared telecommunications, metal grating couplers.

## 1. INTRODUCTION

Exploring new spectral bands of optical transmission is one of the solutions to overcome the inexorable increase of data traffic. The emergence of thulium doped fiber amplifiers (TDFA) has focused the attention on the wavelengths around 2  $\mu\text{m}$  [1]. This trend has stimulated studies of dedicated photonic components such as InP-based modulators [2,3] or arrayed waveguide grating [4]. High bit rate communications over distances exceeding a hundred meters have already been successfully demonstrated in low-loss hollow core bandgap photonic fibers [5,6].

Regarding integrated photonics, optical transmissions also deserve interest in the context of on-board connections as well as photonic routing. Therefore it becomes of a great interest to find a suitable platform operating both in the 2- $\mu\text{m}$  spectral region as well as in the others more conventional spectral bands (ranging from 800 nm to 1550 nm). Titanium dioxide ( $\text{TiO}_2$ ) is a good candidate for such platforms. This cost-efficient material is transparent from the visible to the mid-infrared wavelengths [7], has a negligible two photons absorption in the C-band and handles high power intensities. Moreover, it can be considered as a complementary metal-oxide semiconductor (CMOS) compatible material with an easier deposition process possible at lower temperature. Here, we present titanium dioxide waveguides operating at 1.55  $\mu\text{m}$  and 1.98  $\mu\text{m}$  wavelengths. After having described the design of the  $\text{TiO}_2$  devices, we detail experimental set-ups and validation of the components for error-free transmission of a 10 Gbps On-Off keying signal in two different spectral regions.

## 2. DESIGN AND TEST OF THE PHOTONIC STRUCTURES

### 2.1 Design and fabrication of the couplers and the waveguides

Whatever the platform used, a crucial step is always to efficiently inject the light into the device. Basically, there are two main ways to couple light from an optical fiber to a photonic waveguide: the end-fire coupling (also known as butt-coupling) or grating coupling. Here, we have chosen metal grating couplers, because in addition to not requiring an accurate alignment, the fabrication appears easier thanks to an etching free process. Recently, such metal grating couplers have been used to demonstrate high coupling efficiencies [8]. Unlike previous studies, we considered a metal (Au) grating buried between two  $\text{TiO}_2$  layers on a glass substrate. This configuration offers an additional degree of freedom and a better coupling efficiency. We consider two different waveguides: first, a 1.65  $\mu\text{m}$ -wide waveguide of a width around 1.65  $\mu\text{m}$  including a taper at each end and secondly an 8.0  $\mu\text{m}$ -wide waveguide without taper. The grating is depicted in Fig. 1a with the SEM images of the gratings (Fig. 1b) for each considered waveguide (Fig. 1c).

We optimized the geometric parameters with 2D numerical simulations using a commercial finite element based software, namely COMSOL Multiphysics, to target the best performance, around 1.55  $\mu\text{m}$  wavelength on one side and around 2.0  $\mu\text{m}$  on the other side. Note that an incident angle of 30° was fixed by the experimental setup constraints. The simulated source has a TM polarization for the considered embedded gratings. For the two considered spectral bands, the best set of parameters is obviously different.

Then the devices have been fabricated combining widely-spread techniques such as reactive DC magnetron sputtering to deposit titanium dioxide layers, electron beam lithography, thermal evaporation and reactive-ion etching. In this paper, we focus our attention on three fabricated devices: one waveguide with taper (Fig. 1c<sub>1</sub>) for each studied wavelength and a wider waveguide without taper (Fig. 1c<sub>2</sub>) for 2.0  $\mu\text{m}$  spectral region. The total length of the devices is 575  $\mu\text{m}$  (including the 85  $\mu\text{m}$  long tapers if present). The fabricated devices have the following measured parameters, respectively at 1.55  $\mu\text{m}$  and at 2  $\mu\text{m}$ : a top layer thickness  $h_{\text{top}}$  of 189 nm and 235 nm, a grating period  $\Lambda$  of 1375 nm and 1900 nm and a grating line width  $w_1$  of about 610 nm and 630 nm. For the whole devices, the bottom layer thickness  $h_{\text{bottom}}$  is 69 nm and the gold thickness  $h_{\text{Au}}$  is 56 nm.

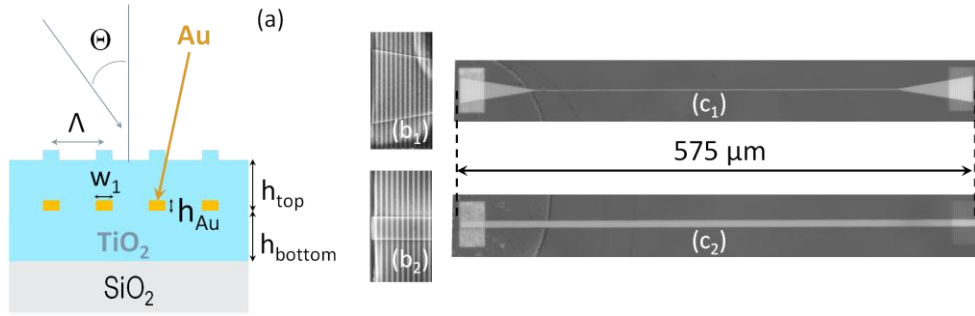


Figure 1. (a) Embedded metal grating in titanium dioxide layout (side view). (b) Electronic scanning microscope images of (b<sub>1</sub>) metal grating at the end of waveguide with taper and (b<sub>2</sub>) metal grating at the end of waveguide without taper (slab). (c) Optical images of (c<sub>1</sub>) a waveguide with taper (around 1.65  $\mu\text{m}$ -width) and (c<sub>2</sub>) a waveguide without taper (8.0  $\mu\text{m}$ -width)

## 2.2 Test of the coupling efficiency of the photonic component

Before transmitting an optical signal in the titanium dioxide waveguides, we have measured their total losses. The structures under-test should have a good total coupling efficiency to enable high speed optical transmissions at 1.55  $\mu\text{m}$  and 1.98  $\mu\text{m}$ . Their losses are measured with a set-up composed of two optical focusers based on lensed fibers. IR and visible cameras allow us to adjust the focusers onto the grating couplers to optimize the injection and collection of the light. A powermeter and optical spectrum analyzer allow us to optimize the focusers adjustment and record the output light.

At 1550 nm, the light source used is a supercontinuum with a spectrum ranging from 1300 nm to 1900 nm, generated from a high peak power picoseconds laser, centred at 1550 nm and injected into a highly nonlinear fiber. We have measured losses as low as -7 dB per facet with a -3-dB transmission bandwidth covering the whole C-band (Fig. 2a) for the waveguide with taper, which is in fair agreement with numerical simulations.

To test waveguides at 2.0  $\mu\text{m}$  wavelengths, an amplified spontaneous emission (ASE) source spanning from 1900 nm to 2050 nm is used. The total coupling losses for the single-mode waveguide (around 1.65  $\mu\text{m}$  width) and the multimode slab (8.0  $\mu\text{m}$  wide waveguide without taper) are represented in Fig. 2b. Note that oscillations of high amplitude and short period are particularly marked for the multimode waveguide. We can connect these spectral oscillations to a Fabry-Perot effect. The difference between the numerical simulations and the experimental results can be in a large extent assigned to discrepancies between the targeted values and the values reached at the end of the various fabrication processes. Future improvements may involve metal mirror under the gratings [9] or parabolic gratings [10]. Let us however note that, as we will see in the next section, the obtained coupling efficiencies are already sufficient for the purpose of our study, i.e. to transmit an optical coded signal.

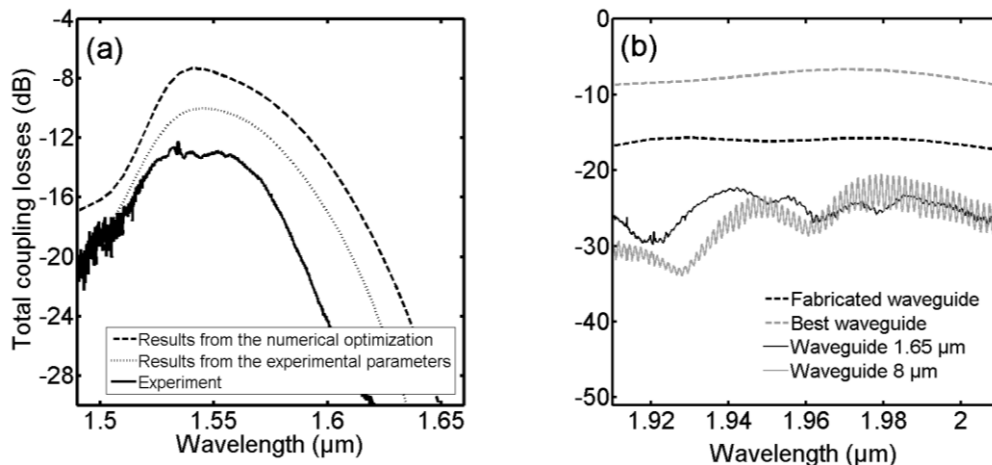


Figure 2. (a) Total coupling losses as a function of the injected wavelength for a waveguide optimised in the 1.55  $\mu\text{m}$  spectral region. The black dashed curve is the simulation for the best set of parameters. The grey dashed curve corresponds to the simulation with the measured parameters of our fabricated waveguide. (b)

Total coupling losses for a waveguide and a slab in the 2.0  $\mu\text{m}$  spectral region. The curves in dashed line correspond to the total coupling losses obtained in simulations. The grey dashed line is the simulation for the best set of parameters we found. The black dashed line is the simulation with the measured parameters of our fabricated slab.

### 3. VALIDATION OF A HIGH SPEED OPTICAL TRANSMISSIONS

#### 3.1 Transmission at 1.55 $\mu\text{m}$ with commercial components

To demonstrate the availability of high speed optical transmission at conventional telecommunication wavelengths, we used enhanced small form-factor pluggable (SFP+) to transmit and receive light. These transceivers are commonly used as part of wavelength-division multiplexing (WDM) optical networks. The 10 Gbps signal is coded through a  $2^{31}$  pseudo random bit sequence (PRBS) generator. A bit error tester and a high speed sampling oscilloscope to image eye diagrams are used as diagnostic tools of the transmission quality. Since the photonic devices are polarization-sensitive, polarization controllers are inserted before the focusers. Firstly, four SFP+ emitting at different wavelengths are tested in a single channel configuration. For SFP+ emitting at 1530 nm, 1550 nm and 1570 nm, error-free transmission are achieved with bit error rates (BER) lower than  $10^{-12}$ . For the SFP+ emitting at 1510 nm, the BER decreases to  $1.6 \cdot 10^{-11}$  due to extra losses in the transmission line. Then, in order to go beyond, WDM experiments with 1550 nm and 1570 nm wavelengths have been performed in co- and in counter-propagation configurations. The experimental set-up for co-propagating configuration is illustrated in Fig. 3a. At 1550 nm, the transmission is still error-free for both configurations whereas at 1570 nm, the BER is about  $4 \cdot 10^{-8}$  and  $7.5 \cdot 10^{-7}$ , respectively. The difference with the single channel configuration can be explained by the presence of two optical couplers at the input and output adding 2 dB losses approximately.

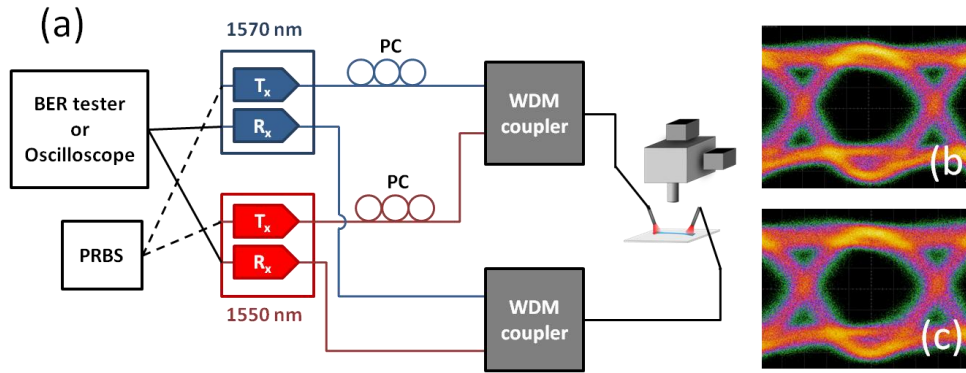


Figure 3. (a) Experimental set-up for a 10 Gbps transmission in co-propagating configuration at 1550 nm and 1570 nm  $\mu\text{m}$ . Each SFP+ is composed of a transmitter Tx and a receiver Rx. WDM : wavelength division multiplexer. PC : polarisation controller. Eye diagrams (b) at 1550 nm and (c) at 1570 nm in counter-propagation configuration.

#### 3.2 Transmission at 1.98 $\mu\text{m}$

For the 2.0  $\mu\text{m}$  band, SFP+ do not exist commercially. Then, we have established a more complex experimental set-up in order to demonstrate the suitability of our devices for 10-Gbps data transmissions around 2  $\mu\text{m}$ . The experimental set-up is detailed in Fig. 4a. The transmitter is based on a laser diode emitting at 1.98  $\mu\text{m}$  and intensity modulated by a lithium niobate modulator. The resulting coded signal is based on Non-Return-to-Zero On-Off-Keying modulation.

Fig. 4b summarizes the experimental results obtained at 1.98  $\mu\text{m}$  for the two considered waveguides (1.5  $\mu\text{m}$  wide and 8.0  $\mu\text{m}$  wide). Error-free optical transmissions have been achieved with the  $\text{TiO}_2$  waveguides. The eye diagram on the graph illustrates one of these transmissions. Finally, a more quantitative study of the transmission quality was made by means of BER measurements as a function of the OSNR incoming on the receiver for both devices. The results obtained in the back-to-back configuration and in presence of the waveguides are very similar. For the considered waveguide length (575  $\mu\text{m}$ ), the waveguide width and thus its multimode character seems to have no impact on the transmission quality.

### 4. CONCLUSIONS

We have shown for the first time to our knowledge an efficient coupling with embedded metal gratings in titanium dioxide waveguides which allowed us to transmit 10 Gbps optical signal in titanium waveguides at two different spectral regions. At 1.55  $\mu\text{m}$ , we have demonstrated that it was possible to use commercial integrated transceivers (SFP+) to transmit such coded signals without any error even in WDM configuration [11]. At 2  $\mu\text{m}$ , we have demonstrated an error free high speed transmission for both 1.65 and 8.0  $\mu\text{m}$  wide waveguides [12]. No significant power penalty has been observed. This study paves the way to integrated photonics at 2  $\mu\text{m}$  and introduces titanium dioxide as a serious candidate for nonlinear applications in near-infrared [13] and for photonics from the visible to the near-infrared.

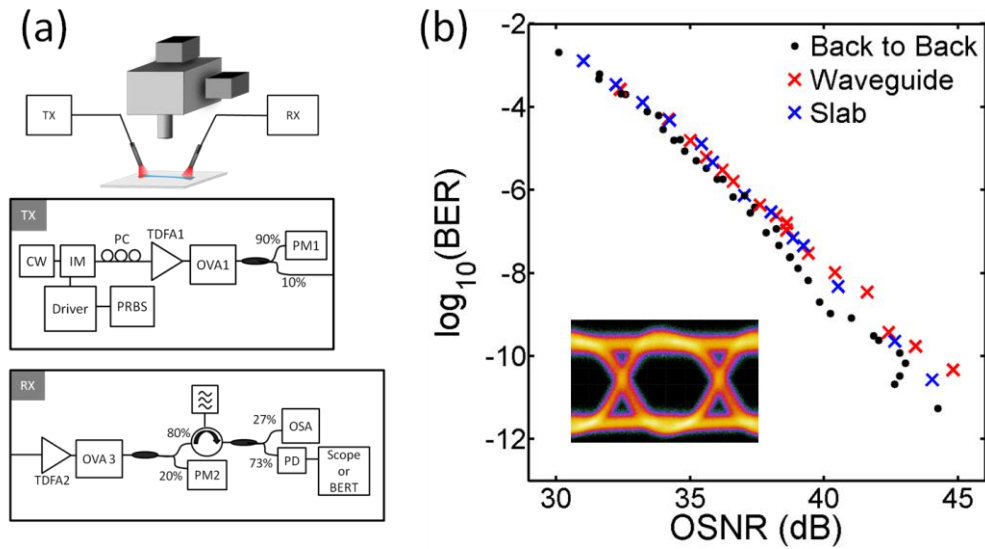


Figure 4. (a) Experimental set-up for a 10 Gbps optical transmission at 1.98  $\mu\text{m}$ . CW : continuous wave ; IM: intensity modulator ; PC : polarization controller ; TDFA : thulium doped fiber amplifier ; OVA : optical variable attenuator ; PM : powermeter ; PRBS : pseudo-random binary sequence ; OSA : optical spectrum analyzer ; BERT : bit error rate tester ; PD : photodiode. (b) BER measurements as a function of the OSNR for a waveguide and a slab at 1.98  $\mu\text{m}$ . The associated eye diagram has been recorded for error-free measurement and after the transmission in the 1.5  $\mu\text{m}$  wide waveguide.

## ACKNOWLEDGEMENTS

This work was supported by the European Union within the framework of the operational Program FEDER-FSE Bourgogne 2014/2020, by the Région Bourgogne (Pari Photcom), by the Agence Nationale de la Recherche (Labex Action ANR-11-LABX-01-01) and by Carnot Arts Institute (PICASSO 2.0 project).

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