Exploring titanium dioxide as a new photonic platform

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ABSTRACT

We report the development of titanium dioxide-based waveguides for applications in the near- and mid-infrared. Thanks to embedded metal grating couplers, we demonstrate error free 10 Gbit/s optical transmissions at 1.55 and 2 µm. We also demonstrate octave-spanning supercontinuum in cm-long waveguides. We explore the way to improve such waveguides through optimized fabrication process.

Keywords: Titanium Dioxide waveguides, Integrated optical materials, Optical Communications, Supercontinuum generation, Nonlinear integrated optics

1. INTRODUCTION

Since the 1980s, it becomes clear that the speed of electronics would limit the information capacity. Therefore, integrated photonic devices were strongly desirable to avoid electronic circuits and to allow low footprint and low power consumption. Naturally, main efforts have focused on the silicon-on-insulator technology. The choice of SOI has been driven by the high nonlinearity of silicon and its compatibility with low-cost large-scale production using CMOS infrastructure. However, its strong two photon absorption (TPA) at telecommunication wavelength is still an issue. Therefore, to avoid this limitation, one could find another nonlinear platform.

Various materials have been investigated: other Silicon-based platform such as Silicon Germanium [1] or silicon nitride [2], III-V material or chalcogenides [3]. Each material provides specific advantages but also strong potential limitations. The perfect material is still to be discovered but it is true that in recent years silicon nitride has emerged as a very promising and versatile candidate.

Here, we plan to explore another platform: the titanium dioxide (TiO_2). This material, well known for its photocatalytic properties or its performance for solar cells, remains largely unexplored in the field of nonlinear photonics. Compared to silicon nitride, the titanium dioxide exhibits similar nonlinear index (~ 0.2×10^{-18} m²/W) as well as higher linear refractive index (typically 2.4 versus 2.0 for Si_3N_4). This is critical because it leads to stronger confinement and therefore to higher effective nonlinearities. It has also an easier deposition process. Here, we show that this platform can be used for optical telecommunication and confirm the strong nonlinear potential.

2. TITANIUM DIOXIDE STRUCTURES FOR OPTICAL COMMUNICATIONS

In this first part, we present titanium dioxide waveguides operating at 1.55 µm and 1.98 µm wavelengths. After having described the design of the TiO_2 devices we detail experimental set-ups and validation of the components for error-free transmission of a 10 Gb/s on-off keying signal at the two different spectral regions.

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. Thanks to the ease of TiO_2 deposition, we have been able to consider embedded metal grating couplers (Fig. 1(a)) allowing etching free process. Recently, such metal grating couplers have been used to demonstrate high coupling efficiencies [4]. Unlike previous studies, we considered a metal (Au) grating buried between two TiO_2 layers on a glass substrate. This provides an additional degree of freedom and better coupling efficiency [5].

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 µm wavelength on one side and around 2.0 µm on the other side, with an incident angle of 30° fixed by the experimental set-up 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. The fabricated devices have the following measured parameters, respectively at 1.55 µm and at 2 µm: a top layer thickness h_{top} of 189 nm and 235 nm, a grating period Λ 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_{bottom} is 69 nm and the gold thickness h_{Au} is 56 nm.

2.2 Test of the devices coupling efficiency

Before transmitting an optical signal in the titanium dioxide waveguides, we have measured their total losses. The structures under test should ideally present a good total coupling efficiency to enable high speed optical transmissions at 1.55 µm and 1.98 µm. 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, we have measured losses as low as - 8dB per facet with a -3dB transmission bandwidth covering the whole C-band with a fair agreement with numerical simulations as shown in Fig. 1(b). At 2000 nm, the coupling losses per facet reach - 10 dB. The difference between the numerical simulations and the efficiency measured experimentally can be in a large extend 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]. However, the coupling efficiencies are already sufficient for the transmission of a coded signal.

2.3 Transmission at 1.55 µm and at 1.98 µm

For both wavelengths, a 10 Gb/s signal coded through a 2^{31} pseudo random bit sequence (PRBS) generator is transmitted through the waveguides and a bit error tester or a high speed sampling oscilloscope to image eye diagrams are used as diagnostic tools of the transmission quality (show in insets of Fig. 1(b) and (c)) .

At 1.55 µm, the figure 1(b) shows wide-opened eye diagrams meaning a transmission without any degradation confirmed by an error free BER measurement (not shown here). At 2 µm, the results on BER between the back-to-back configuration and with the presence of the waveguides are very similar [6].

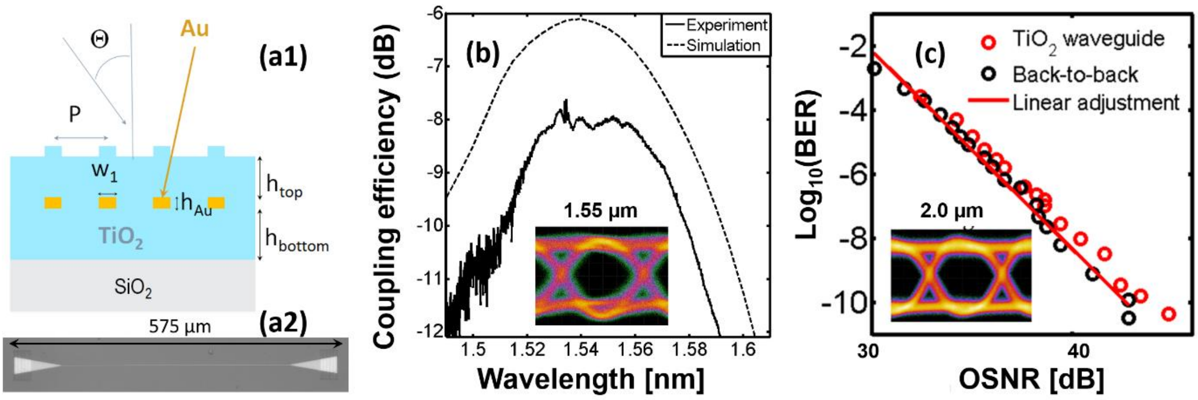

Figure 1. (a1) sketch of the embedded metal grating in titanium dioxide layer (side view). (a2) Top view of 1.5 µm-wide waveguide with visible camera. (b) Coupling efficiency per facet of embedded grating coupler as a function of the injected wavelength. The experimental results are compared with numerical simulations. The inset shows eye diagram of 10Gb/s signal transmitted into the waveguide. (c) BER measurement as a function of the OSNR. The inset shows the typical eye diagram after the waveguide at 2 µm.

3. TITANIUM DIOXIDE WAVEGUIDES FOR SUPERCONTINUUM GENERATION

To become an interesting photonic platform for nonlinear functionalities, a material has to exhibit a strong Kerr coefficient. A way to stress the nonlinear potential of TiO_2 waveguides is to evaluate its potential in the context of supercontinuum generation [7].

Contrary to previous waveguides, here we consider thicker TiO_2 layers of 450 nm that are deposited on a 2” silicon wafer, covered with 2 µm of silica, still by reactive direct current magnetron sputtering of a 99.9% pure titanium target under argon and oxygen-controlled atmosphere. Then, 2.2 cm-long ridge waveguide having about 1.5 µm is patterned thanks to an UV lithography. After the reactive ion etching, the residual mask is stripped from the waveguides. Details of the structure used in the following experiments are presented in Fig. 2(a) as well as the dispersion profile of the fundamental TE mode (Fig. 2(b)).

The input pulses are provided by a femtosecond laser source centered at 1560 nm with a peak power up to a few tens of kW. Due to the length of standard anomalous fiber between the fs-laser output and the TiO_2 waveguide, the central wavelength of the pulse is shifted toward 1640 nm. In order to optimize the light injection through butt-coupling, two 1-mm long tapers have been included in the TiO_2 device. The broadest spectrum we obtained is plotted in Fig. 2(c1) along with the input pump spectrum. An octave-spanning supercontinuum is generated from 1050 nm up to 1910 nm, which represents an improvement by much more than one order of magnitude compared to [8]. The third harmonic is also generated into the waveguide so that visible light is also clearly observed by the naked eye as can be seen from the picture taken from the top of the waveguide (Fig. 2(c2)).

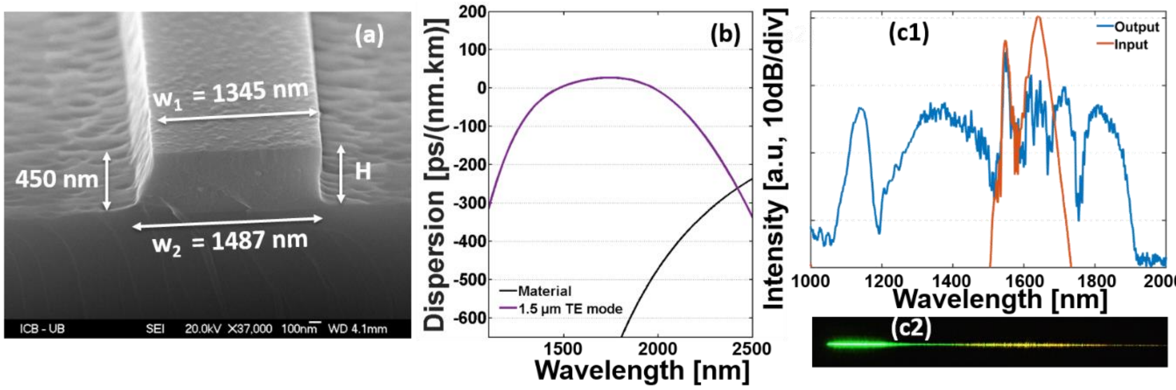

Figure 2. (a) Scanning Electron Microscope image of the cleaved strip waveguide (b) Dispersion properties for the fundamental $TE_{0,0}$ mode. (c1) Optical supercontinuum obtained at the output of the waveguide (solid blue line) compared to the input pulse spectrum (red solid line). (c2) Image of the emitted visible light from the waveguide (total length ~ 6.5 mm).

4. CONCLUSIONS

We have demonstrated error-free transmission of high bit rate signals through titanium dioxide waveguides. A new design of embedded metal grating has been tested for coupling / decoupling the signal in the C-band as well as around 2 µm. Such embedded configuration was made possible thanks to the ease of fabrication of this material. In order to confirm the nonlinear potential of the TiO2, we have demonstrated the generation of an octave spanning supercontinuum.

These studies clearly demonstrate that titanium dioxide can be an alternative platform for integrated photonic. However, to date, the main drawback remains the propagation losses. We are currently working on different ways to improve the fabrication mainly regarding the etching that has been identify as the main origin of losses since it causes strong roughness of sidewall [9].

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) and by the French “Investissements d’Avenir” program, project ISITE-BFC (contract ANR-15-IDEX-0003).

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