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## Supercontinuum generation in titanium dioxide waveguides

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## INTRODUCTION

**Optical supercontinua** are a fundamental topic that has stimulated a tremendous practical interest since the early works of Alfano et al. in the 70's in bulk components. Photonic crystal fibers have then brought some remarkable potentialities in tailoring the dispersive properties of a waveguide while maintaining a high level of confinement over significant propagation distances. The next breakthrough is to further reduce the footprint of the nonlinear component and to achieve the generation of optical supercontinuum on a photonic chip. To reach this aim, several platforms have been successfully investigated such as silicon, silicon germanium, silicon nitride, chalcogenide waveguides to cite a few. Each material has obviously specific advantages but also limitations including strong two photon absorption and the associated free carrier absorption, low refractive index, low handling power, etc...

We discuss here the design and fabrication of a new component made on an alternative platform that remains relatively unexplored: **titanium dioxide (TiO<sub>2</sub>)**. This material benefits from a transparency window spanning from the visible to the mid-infrared wavelengths. It combines a high linear and nonlinear refractive index with negligible TPA beyond 800 nm. Therefore, recent experimental studies have confirmed these features and reported the spectral broadening of a femtosecond pulse [1], the parametric wavelength conversion of a continuous wave [2] as well as the efficient generation of third harmonic [3].

## TiO<sub>2</sub> WAVEGUIDE DESIGN AND FABRICATION

➤ We start from anatase TiO<sub>2</sub> layers with a thickness of 450 nm that are deposited on a 2" silicon wafer.

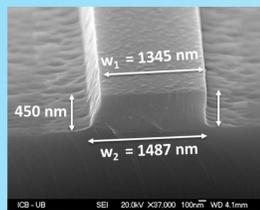
➤ 2.2 cm-long ridge waveguides with different widths are patterned thanks to an UV lithography.

➤ After the reactive ion etching, the residual mask is stripped from the waveguides.

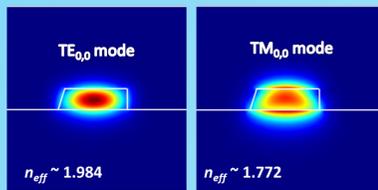
➤ Propagation losses around 5 dB/cm are obtained.

➤ Reduction of the losses can be reached in the near future.

➤ The high contrast between the TiO<sub>2</sub> (n=2.35) and the silica layer (n = 1.44) or the surrounding air is highly beneficial for a strong light confinement.



Scanning Electron Microscope image of the cleaved strip TiO<sub>2</sub> waveguide



➤ 4 optical modes can be sustained.

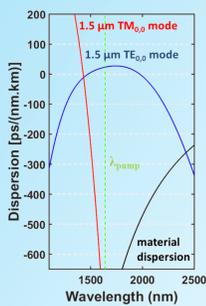
➤ The TE<sub>0,0</sub> mode has an effective area of 0.54 μm<sup>2</sup>, leading to a nonlinear coefficient of 1.2 /W/m.

Mode profiles at 1640 nm and associated effective index for the first transverse electric (TE) and transverse magnetic (TM). Numerical simulation using COMSOL Multiphysics.

➤ Operating in the anomalous regime of dispersion is crucial to obtain an energy efficient spectral broadening. However TiO<sub>2</sub> exhibits a material dispersion that is strongly normal : the waveguide dispersion will be crucial.

➤ For a transverse width below 1.5 μm, this condition is met at the pump wavelength for the TE<sub>0,0</sub> mode.

➤ The TM<sub>0,0</sub> mode remains strongly normal.



Dispersion profiles of the fundamental TE<sub>0,0</sub> and TM<sub>0,0</sub> modes of the 1.5 μm wide waveguide.

➤ In order to optimize the coupling of light, two 1-mm long tapers have been included in the device.



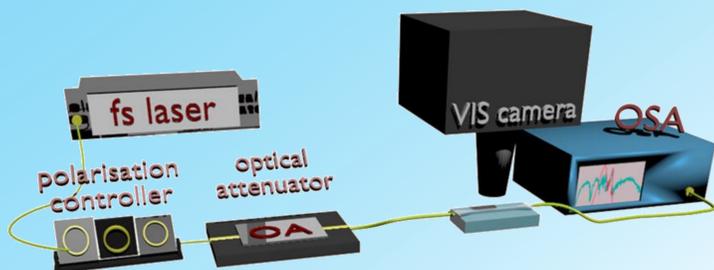
Optical microscope image of the taper used for the coupling.

## EXPERIMENTAL SETUP

➤ Femtosecond input pulses with a kW peak power are used.

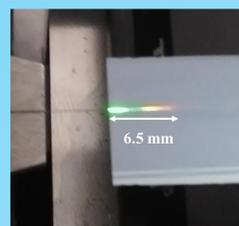
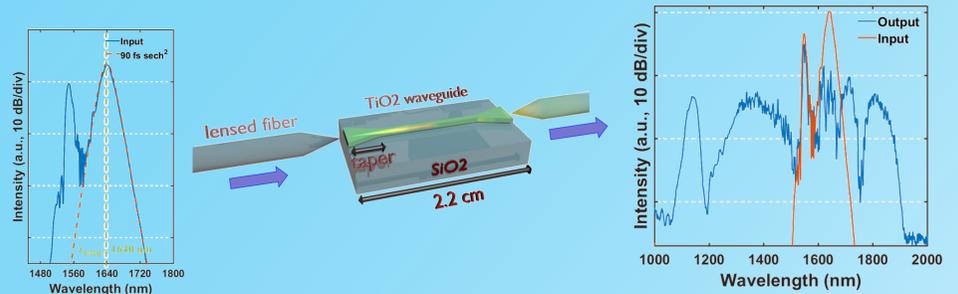
➤ Butt coupling and lensed fibers are used for launching and collecting light.

➤ Due to the silica Raman response of the fiber components (polarization controllers, attenuators and lensed fibers), the central wavelength of the ultrashort pulses is shifted up to 1640 nm. The output pulse have a soliton-like profile with a duration of 90 fs.



## EXPERIMENTAL DEMONSTRATION

➤ The first experimental demonstration of an octave spanning supercontinuum in TiO<sub>2</sub>.



Visible light emitted from the waveguide.

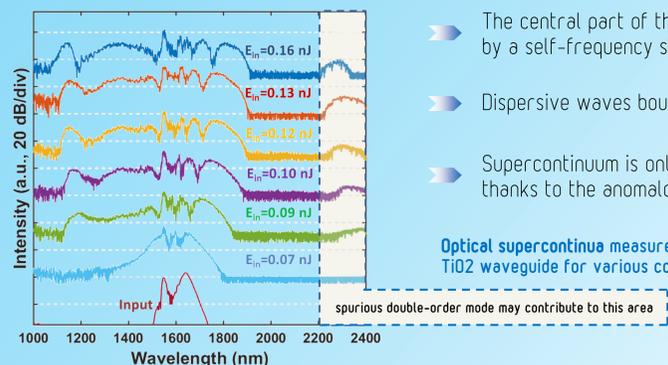


➤ Third-harmonic generation in the visible due to the existence of phase-matched higher-order modes.

➤ The central part of the supercontinuum is bounded by a self-frequency shifted soliton.

➤ Dispersive waves bound the lower part.

➤ Supercontinuum is only achieved in the TE mode thanks to the anomalous dispersion regime.



Optical supercontinua measured at the output of the TiO<sub>2</sub> waveguide for various coupled energy conditions.

## NUMERICAL SIMULATIONS

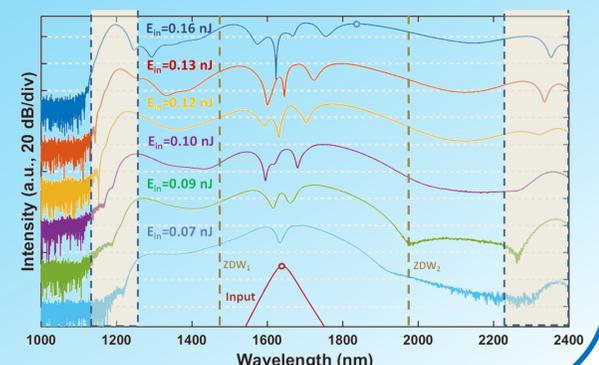
➤ The experimental results are qualitatively reproduced by numerical simulations of the generalized nonlinear Schrödinger equation taking into account the full dispersion profile and the Raman contribution.

$$\frac{\partial A}{\partial z} = -\frac{\alpha}{2}A + \sum_{l \geq 2} i^{l+1} \frac{\beta_l}{k!} \frac{\partial^l A}{\partial z^l} + i \left( 1 + \tau_{\text{shock}} \frac{\partial}{\partial t} \right) \left( A(z,t) \int_{-\infty}^{+\infty} R(t') \times |A(z,t-t')|^2 dt' \right)$$

dispersive effects  
Kerr nonlinearity  
linear losses  
Raman contribution

The nonlinear dynamics is mainly driven by Raman soliton self-frequency shift and generation of dispersive waves induced by the two zero dispersion wavelengths.

Numerical simulations of supercontinuum generation obtained in a 1.5-μm-wide TiO<sub>2</sub> waveguides for different input energies.



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