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# Self-Phase Modulation Induced Spectral Broadening of Ultrashort Laser Pulses in Tantalum Pentoxide ($Ta_2O_5$) Rib Waveguide

Chao-Yi Tai, and James S. Wilkinson
Optoelectronics Research Centre, University of Southampton, Highfield, Southampton, SO17 1BJ, United Kingdom
cyt@orc.soton.ac.uk
Nicolas M. B. Perney, M. Caterina Netti, and Jeremy J. Baumberg
Mesophotonics Limited, Chilworth Business Incubator, 2 Venture Road, Chilworth Science Park, Southampton, SO16 7NP, United Kingdom

Abstract – *Self-phase modulation induced spectral broadening has been observed for ultrashort pulses propagating through* $Ta_2O_5$ *rib waveguide. The associated nonlinear refractive index was estimated to be* $7.23\times10^{-19}$ $m^2/W$, *which is higher by one order of magnitude than silica glass.*

## INTRODUCTION

The utilization of high peak power, ultrashort laser pulses has allowed exploitation of many new phenomena and stimulates intensive research particularly on nonlinear optical effects. Self-phase modulation (SPM) is one widely studied nonlinear effect and has been successfully applied for optical pulse compression [1][2]. It has also been known as a powerful technique for the estimation of optical nonlinear refractive index [1]. In the past, much effort has been devoted to the study of nonlinear properties in silica fibres due to their long interaction length and high power densities. However, to achieve useful optical switching, relatively high power or long fibre length is required because of the small nonlinear refractive index ($n_2$)[3]. Recently, considerable attention has shifted to the nonlinearities in planar waveguide due to the convenient processing technology and reports of newly synthesized organic materials [4]. Polymers, having the advantages of high nonlinear coefficient and ultrafast response time, are considered to be promising nonlinear media for all-optical switching devices. However, their low stability and low damage threshold limits their application. To explore alternative materials, we present in this report the experimental evidence and quantitative theoretical explanation for the observed SPM-induced spectral broadening of ultrashort laser pulses in a $Ta_2O_5$ rib waveguide.

## EXPERIMENTAL

The waveguide under investigation was fabricated by sputtering a 1-μm-thick $Ta_2O_5$ film on a Si wafer with 2 μm $SiO_2$ as a buffer layer. Subsequent photolithography and Ar ion beam milling processes create the rib structure with a cross-section of $3\times1$ $\mu m^2$. A diode-pumped frequency-doubled Nd-$YVO_4$ laser, producing single frequency output at $\lambda$=532 nm was used to pump the Ti-Sapphire crystal and generates modelocked, sub-150 femtosecond pulses at $\lambda$=800 nm with a repetition rate f=80 MHz. These pulses seed a regenerative amplifier system (RegA) working at 250 KHz repetition rate. Nearly transform-limited pulses with duration at full width half maximum $\tau_{FWHM}$=160 fs were obtained for the nonlinear property measurement.

Pulses from RegA were end-fire launched into the rib waveguide using a microscope objective lens. The light emerging from the waveguide was collected and directed into a high resolution spectrum analyzer without passing through any other optics. The incident power was controlled by using appropriately calibrated neutral density filter and the modal field profile was monitored by a CCD camera to ensure single mode operation. The experimental arrangement is shown in Fig. 1.

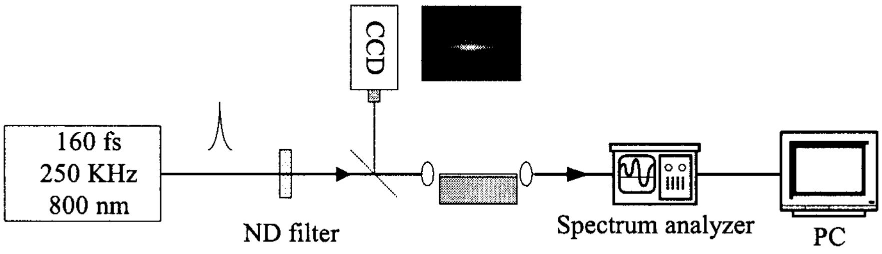

**Fig. 1**. Experimental arrangement for the optical nonlinear property measurement. The inset shows the recorded modal field profile.

## Results And Discussion

Fig. 2(b)-(d) shows the spectral evolution of the transform-limited Gaussian pulse (As shown in Fig. 2(a)) propagating through a 1-cm-long rib waveguide at various peak-coupled powers. From the broadened spectra and characteristics of the developed substructures, very rich nonlinear effects can be extracted. As the peak power in the waveguide was increased, the spectra broadened significantly, accompanied by the development of oscillatory structures with intense outermost peaks. The multipeak structure, arising from the interference of the chirped frequency components induced by SPM, is the signature of a SPM spectrum [1] and is clearly in evidence in Fig. 2. As the peak coupled power is increased to 176 W, the spectrum (Fig. 2(d)) has a shape that no longer resembles the typical SPM spectrum indicating that higher order competing nonlinear effects such as optical wave breaking (OWB), self-steepening, stimulated Raman scattering (SRS) and combined effects with group velocity dispersion (GVD) have taken place. The abovementioned phenomena were featured by the appearance of sidelobes and the asymmetric broadening in the spectra [5][6].

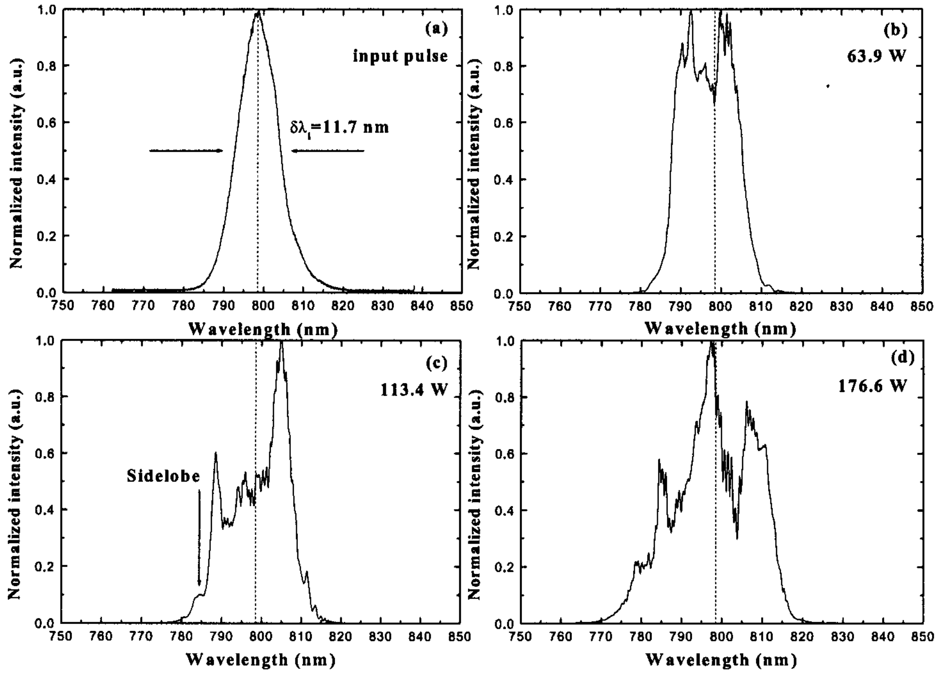

**Fig. 2**. Spectrum (labeled with peak-coupled power) measured at the output of the waveguide.

To calculate the nonlinear refractive index $n_2$, a simplified theory which ignores the influence of GVD was employed as the lowest-order approach [1]. Since the waveguide length (1 cm) used here is very short, we should be well within the region where GVD has a negligible impact on the pulse broadening [7]. SPM-induced frequency shift is a consequence of a temporally varying phase and can be expressed by the intensity-dependent refractive index $n_2$ as

$$\delta\omega = -\frac{\partial\phi_{NL}}{\partial t} = -\frac{2\pi}{\lambda}\cdot n_2 \cdot L_{eff}\cdot\frac{dI(t)}{dt} \qquad (1)$$

where I(t) is the temporal intensity profile of the incident pulse and $L_{eff}$ is the effective length defined by

$$L_{eff} = \frac{1-\exp(-\alpha L)}{\alpha} \qquad (2)$$

Here L is the real sample length and $\alpha$ is the attenuation constant. For an unchirped Gaussian pulse, the full width half maximum (FWHM) spectral bandwith $\delta\lambda$ of the SPM pulse can be deduced from Eqn. (1) as [8]

$$\delta\lambda = \delta\lambda_i + 4\sqrt{\frac{2\ln 2}{e}}\cdot\frac{\lambda n_2 L_{eff}}{cA_{eff}}\cdot\frac{P}{t_p} \qquad (3)$$

where $\delta\lambda_i$ and $t_p$ represent the bandwidth and pulsewidth of the input laser pulse, respectively. P is the peak power and $A_{eff}$ is known as the effective core area.

In Fig. 3. the SPM induced spectral bandwidth (FWHM value) is plotted against the peak coupled power with a least-squares fitting to the data points. The linear relationship was verified as predicted by equation (3). Extrapolating the line to P=0 yields an interception value of 12.07 nm, which represents the bandwidth of the input pulse from RegA, is in good agreement with the recorded spectrum ($\delta\lambda_I$=11.7 nm), as shown in Fig. 2(a). The nonlinear refractive index $n_2$ was estimated from equation (3), with the fitted slope (0.083 nm/W), and the following values for the parameters: $\alpha$=0.345 $cm^{-1}$ measured by imaging of scattered light [9], L=1 cm, $A_{eff}=3.5\times10^{-8}$ $cm^2$ estimated from the recorded modal field profile, $\lambda$=800 nm and $t_p$=160 fs. The resultant $n_2$ has a value of $7.23\times10^{-19}$ $m^2/W$, which is higher by one order of magnitude than silica. To our knowledge, this is the first estimation of the nonlinear coefficient from SPM-induced spectral broadening for a $Ta_2O_5$ rib waveguide.

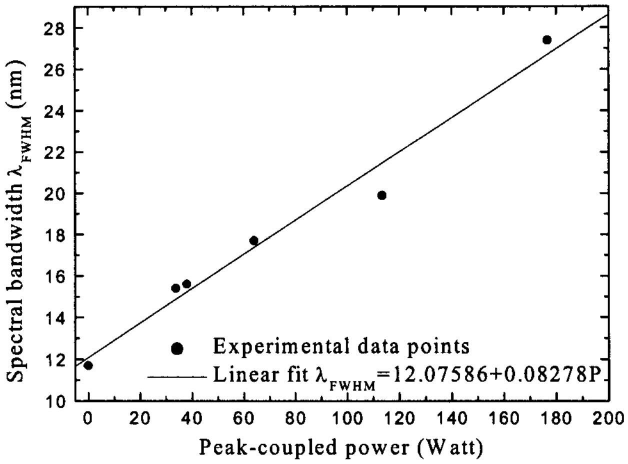

**Fig. 3**. SPM spectral bandwidth versus peak-coupled power.

## CONCLUSION

In conclusion, we have demonstrated the measurement of the nonlinear refractive index of a $Ta_2O_5$ rib waveguide by directly monitoring the SPM-induced broadened spectra. The obtained value of $n_2$ was $7.23\times10^{-19}$ $m^2/W$, which is larger than the value of silica glass by one order of magnitude. This larger $n_2$ value is useful for designing various all-optical nonlinear devices and indicates the capability for operating at a relatively low switching power.

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