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Experimental Observation of Self-Phase Modulation in ZnO Channel Waveguides

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1. Introduction

In this research we focus on ZnO as a material for optical waveguides with strong nonlinear effects, aiming to obtain broad spectrum light at wavelengths around 800 nm, for bio-medical applications [1]. Strong nonlinear optical effects have been demonstrated in nanowaveguides fabricated in silicon nitride [2], chalcogenide glass [3] and more recently, in silicon [4, 5]. However, except for silicon nitride, they are unsuitable for the visible spectrum. We selected ZnO because of its large nonlinear refractive index n_2 [6] and the high quality thin-films that can be obtained [7]. In our previous work, we presented the fabrication of the waveguides from single crystal ZnO thin-film on sapphire substrate, and estimated the expected amount of broadening due to self-phase modulation (SPM) [8]. In this paper, we present the experimental demonstration of SPM in ZnO channel waveguides, designed to enhance these nonlinear optical processes. We demonstrate spectral broadening of femtosecond pulses due to SPM in the fabricated waveguides. Using the obtained measurements, we estimate the nonlinear strength parameter γ and the nonlinear refractive index n_2.

2. Waveguide fabrication and loss measurements

The intended structure is shown in Fig. 1a). A single crystal ZnO thin film was grown on a c-axis sapphire substrate using the laser molecular beam epitaxy (laser MBE) technique [9], obtaining c-axis ZnO. The waveguides were patterned using electron-beam lithography and etched by Ar-ion milling. The resulting waveguides were around 380 nm in height and showed vertical side walls, clearly visible in the SEM image in Fig. 1b).

We used the cut-back method to estimate the propagation loss of the fabricated waveguides. We compared the loss estimated from the measurements to a model based on the standard deviation (σ) of the sidewall roughness [10]. The results are shown in Fig. 2. The shape of the measured loss curve suggests that the majority of the propagation loss is due to side-wall roughness. Single-mode propagation is expected in the waveguides of widths below 1.5 μm. The measured loss in these cases ranged from 3 to 6 dB/mm. For the multi-mode case the propagation loss was of around 1 dB/mm. Details of the measurements can be found in [8].

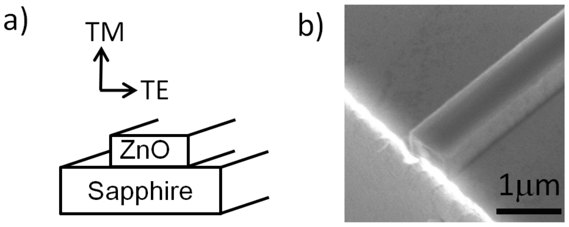

Figure 1: a) Schematic view of the intended structure. The polarization directions are shown. b) SEM image of the fabricated waveguides. Vertical sidewalls can be appreciated.

3. Nonlinear optical effects measurement

To observe the nonlinear optical effects on the fabricated waveguides, we used a Ti:Sapphire laser, emitting 160 fs pulses at a wavelength of 840 nm, with an average power of 730 mW, and a repetition rate of 76 MHz. The complete experimental setup is detailed in Fig. 3. We used free-space optics to prevent nonlinear effects to develop before the waveguide. A microscope objective was used to focus the beam to the waveguide and a lensed fiber at the output collected and guided the light to an optical spectrum analyzer. The light was TE-polarized, the electrical field is parallel to the substrate surface (Fig. 1a)).

The waveguide has a cross section of 380 nm × 2 μm and is 2 mm long. The coupling losses were about 15 dB/facet, calculated by measuring the total losses and using the previously obtained propagation loss. This value varies slightly with waveguide cross sectional area, obtaining

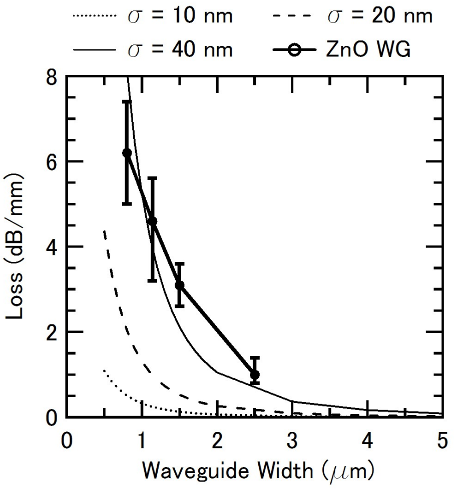

Figure 2: Propagation loss measurements results compared to a theoretical model based on the standard deviation (σ) of the side-wall roughness.

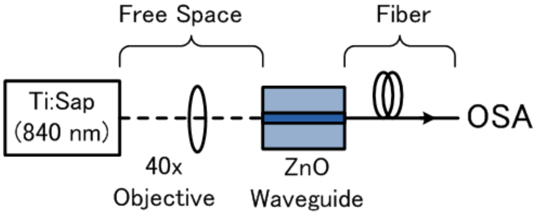

Figure 3. Schematic of the nonlinear effects measurements. The free space and fiber propagation sections are indicated.

higher losses for smaller waveguides.

Figure 4 shows several measured spectra, corresponding to different peak power levels. The values shown correspond to the power inside the waveguide. No broadening is present at a peak power of 70 W. However at a power level of 220 W, the broadening becomes evident, and several peaks that are characteristic of SPM can be appreciated. A higher peak power causes a broader spectrum, with at least 3 clearly visible peaks when input power reaches 800 W. We measured a maximum FWHM broadening of around 30 nm, which corresponds to a nonlinear phase shift of around 2π. The broadened spectrum is more than 6 times the input pulse width.

4. Discussion on the results

From the broadening we estimated the nonlinear parameter γ, of the waveguide, using its proportionality to the spectral broadening [11]. We obtained a value of $\gamma = 4.8 \pm 1\ \mathrm{W}^{-1}\mathrm{m}^{-1}$, around 500 times that of a highly non-linear optic fiber [12]. The parameter γ is defined as $\gamma = (n_2 \cdot \omega)/(c \cdot A_{eff})$, where n_2 is the intensity dependant refractive index and A_{eff} is the effective area. From this, we can see two factors that contribute to this high value. First, n_2 is more than 20 times higher in ZnO than in silica, thus there is an improvement in the nonlinearity intrinsic to the material. Second, the effective area is greatly reduced thanks to the high confinement of the channel waveguide structure. The A_{eff} for the ZnO waveguides calculated from the simulations is 0.775 $\mu\mathrm{m}^2$, which represents a reduction of 15-20 times, compared to a highly non-linear fiber. The combination of both factors causes the high increment in γ, which is consistent with the obtained measurements.

Finally, from γ, we obtained the intensity dependant refractive index n_2. This gives $n_2 = 5.0 \pm 1 \times 10^{-15}\ \mathrm{cm}^2/\mathrm{W}$, a value that is in agreement with previously reported values for ZnO [6].

5. Conclusions

We verified experimentally SPM-induced spectral broadening of femtosecond pulses in ZnO channel waveguides. We demonstrated a broadening of more than 6 times the input pulse spectrum, corresponding to a phase shift of about 2π, at a peak power of 800 W. This resulted in a value of γ more than 500 times higher than a highly non-linear fiber. We showed ZnO channel waveguides to be a promising material for optical waveguides intended for nonlinear applications.

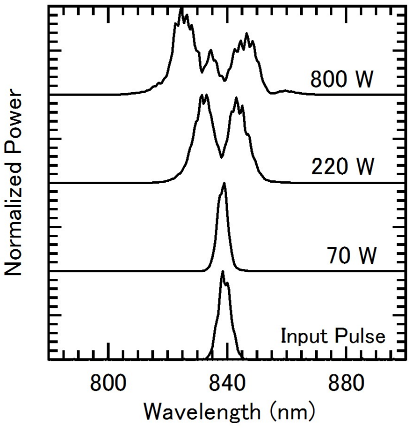

Figure 4. Spectra of SPM-broadened femto-second pulses from the 2 mm long 0.38 × 2.0 μm waveguide. The peak power in the waveguide is shown. Spectral broadening is clearly visible for higher peak powers.

Acknowledgements

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