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ZnO Channel Waveguides for Nonlinear Optic Applications

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1. Introduction

ZnO is a wide bandgap semiconductor material that has attracted a lot of interest due to its large exciton binding energy (60 meV) and its piezoelectric properties [1]. In this paper, we investigate ZnO as a material for nonlinear optical waveguides, and evaluate the possibility for realizing wide spectrum light sources at wavelengths around 800 nm for applications such as optical coherence tomography [2]. We expect spectrum widening through super-continuum (SC) generation.

High pump powers are required to generate SC effects. Channel waveguides with small cross-sectional areas are one choice for realizing such high power density. At high power densities two-photon absorption (TPA) becomes a problem [3], but the wide bandgap of ZnO prevents the TPA. It also has a large n_2 coefficient [4], which determines the strength of third-order non-linear optical effects [5], necessary for the SC generation. High quality single-crystal ZnO can be grown on sapphire (Al_2O_3) substrate [6], and the large difference in refractive index between ZnO and Al_2O_3 makes it possible to realize channel waveguide structure. We present the design, fabrication and preliminary loss measurements of ZnO channel waveguides. There have been reports of slab [7] and rib [8] type waveguides of ZnO, however, to our knowledge, this is the first report of fabrication and measurement of channel type ZnO waveguides.

2. Sample preparation

The ZnO thin film samples were grown on a sapphire substrate using the laser molecular beam epitaxy (laser MBE) technique [9]. The refractive index was measured to evaluate the quality of the thin film. The laser MBE technique allowed the addition of a thickness gradient to the film, aimed at obtaining waveguides of different heights with one sample.

The prism coupler technique was used to measure the refractive index of the ZnO thin film. We obtained refracttive index values of 1.990, 1.953 and 1.921 at wavelengths of 632.8 nm, 806 nm and 1540 nm respectively. These values are in good agreement with the refractive index values for the bulk ZnO available in the literature, which means that the quality of the grown film is adequate for optical applications.

3. Single-mode conditions

We calculated the single mode conditions for the channel waveguide with a finite elements method (FEM) based simulation program, using the obtained refractive index values.

Figure 1 shows the plot of the width versus the cutoff wavelength for several heights. The area to the left of each line is single-mode condition and to the right is multi-mode. A thickness of less than 1 μm was desired to assure a good film quality, due to the nature of the thin film epitaxy process. Therefore, single-mode condition can be obtained for a waveguide width of over 0.6 μm at a wavelength of 800 nm.

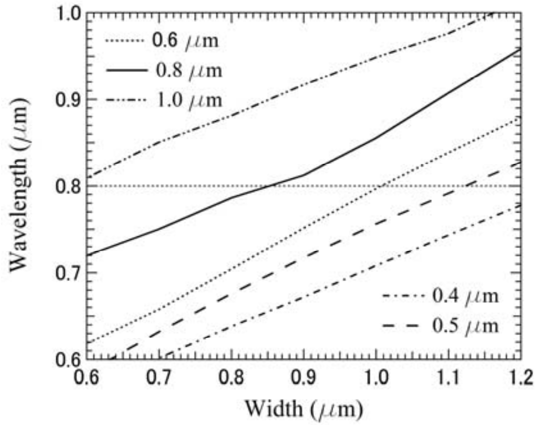

Fig.1 Single-mode condition for different waveguide parameters.

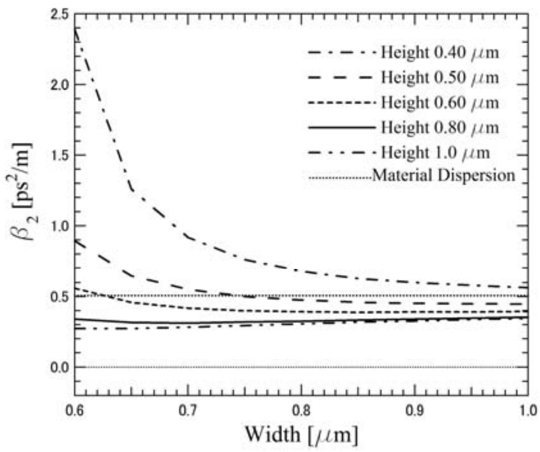

Fig.2 β_2 dependence on the height and width of the waveguide at λ = 800 nm. Material dispersion is also shown for comparison.

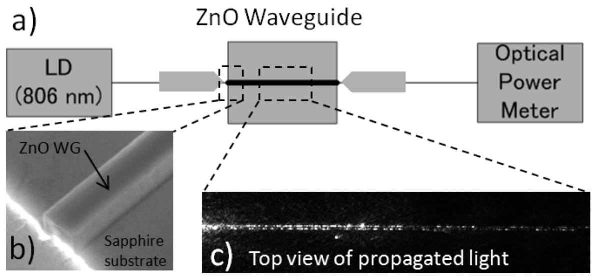

Fig.3 a) Schematic set-up for propagation loss measurements. b) SEM image of the waveguide facet. c) Top view image of the optical waveguide, showing guided light.

4. GVD and non-linearities

To verify which nonlinear optical effects are to be expected, the group velocity dispersion of the waveguide was calculated. We used a mode solver based on FEM to obtain the effective index n_{eff} of the channel waveguide. The values obtained of the n_{eff} for different frequencies are fitted using a polynomial, whose derivatives gave the values of β_2.

The values of β_2 for the wavelength of 800 nm are shown in figure 2. We can appreciate that the channel waveguide has normal dispersion for the entire range of sizes considered.

5. Waveguide fabrication and measurement

The waveguides were fabricated using electron-beam lithography for the patterning and etched by Ar-ion milling. The resulting waveguides were around 400 nm in height and showed smooth vertical side walls, as shown by the SEM picture in figure 3(b), due to a nice anisotropic etching. We fabricated waveguides with various widths of 0.762, 1.031, 1.238, 1.631 and 2.083 μm.

Preliminary propagation loss measurements were carried out. The schematic view of the experiment is shown in figure 3(a). A diode laser of wavelength of 806 nm was used as power source. We used tapered optical fibers to launch the laser light to the waveguides and to connect to the optical power meter (Fig. 3(c)). Results are shown in figure 4. If we assume the coupling loss values were about 15 dB/facet, we can roughly estimate the propagation losses to be 1.5 to 2.8 dB/mm for single mode waveguides. Cut-back measurements are to be done to obtain more accurate loss values.

6. Conclusion

We demonstrated channel waveguides with ZnO thin film on sapphire substrate for the first time, and measured the propagation loss. Taking the measured loss value of around 2 dB/mm on a 1 cm long waveguide and considering 10 ps pulses, according to the spectrum broadening factor equation for self-phase modulation explained in [5], we would need a peak power of 200 W to generate a spectrum widening of around 20 nm with SC effect. With a propagation loss of 1 dB/mm we would need a peak power of 400 W to obtain a 50 nm spectrum widening, which would be enough for the intended application. ZnO channel waveguides showed to be a promising option for optical devices on the near-infrared spectrum. More research is required towards lowering the propagation losses and obtaining a more dramatic spectrum widening.

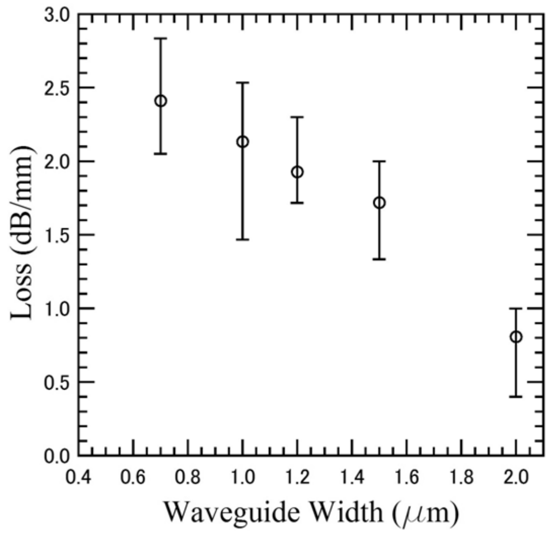

Fig.4 Preliminary propagation loss measurement results.

Acknowledgements

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