9th International Conference on
Photonic Technologies LANE 2016

Industrial Paper

Ultra-short pulses from a 2 µm fiber laser source and applications in materials processing

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Abstract

A novel source of ultrashort pulses in the 2 µm wavelength range is presented: The frequency shifted pulses of a mode-locked erbium fiber laser are stretched in a chirped volume Bragg grating. A subsequent pulse picker reduces the repetition rate of the oscillator from 30 MHz to 50 - 500 kHz. At low repetition rates the pulses are amplified to micro-joule energy levels and efficiently recompressed with the chirped VBG. The 2 µm laser source is used for a controlled material modification inside glass. We demonstrate that the focused laser light induces a localized modification of glass at the position of the focus. This allows for direct laser writing inside glass material, whereas we demonstrate structures with dimensions as small as 5 µm. This approach bears potential for manufacturing waveguides, tunnel networks and cavities inside glass and other materials.

Keywords: ultra-fast fiber laser; amplifier; Tm doped fibers; 2 µm wavelength; volume Bragg grating; laser induced modification of glass; selective laser-induced etching (SLE); waveguides; microfluidics

1. Fiber laser source

High energy ultrafast fiber lasers in the 2 µm wavelength range are increasingly attracting attention for their potential applications in mid-IR-spectroscopy, eye-safe remote sensing, surgery and material processing. Thulium (Tm) doped silica fibers with a broad amplification bandwidth between 1850 and 2100 bear a straightforward access to laser sources in this spectral region, Engelbrecht et al. (2008), Stutzki et al. (2015).

In this paper we present a novel chirped pulse master oscillator power amplifier (MOPA) system (Yang et al. (2012)) based on a mode-locked seed oscillator followed by a chain of three Tm doped fiber amplifiers, see Fig. 1 (a). The seed pulses are generated in an Erbium doped fiber oscillator at 1.55 µm, compressed to femtosecond pulse durations and spectrally broadened in a highly nonlinear fiber to a supercontinuum spanning from 1 µm to 2.2 µm, cf. Kumkar et al. (2012). The spectrum between 1750 nm and 2150 nm is shown in Fig. 1 (b). After a first polarization maintaining fiber amplifier the pulses are free space coupled and directed to a large area chirped volume Bragg grating (CVBG), with a reflection bandwidth of 25 nm and linear chirp of 18 ps/nm. The reflected, stretched pulses are coupled back into the fiber and in an optical circulator directed to a 3 m long Tm doped fiber amplifier pumped by two diode lasers operating at 793 nm emission wavelength providing a maximum power of 8 watts. In order to gain the high pulse energies necessary for material processing a fiber coupled acousto-optic modulator reduces the 30 MHz repetition rate of the oscillator to user selectable frequency between 50 kHz and 500 kHz prior to the last amplification step. After this amplifier stage the pulses are collimated and reciprocally sent to the CVBG, Liao et al. (2007). The reflection in the CVBG exactly compensates for the dispersion imposed on the pulses before amplification. In order to prevent cross talk between amplifiers the beams are offset laterally in the CVBG. Incident and reflected beam are separated using a polarizing beam splitter cube and a quarter wave plate. A maximum output power of 540 mW was measured for the recompressed pulses at a

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repetition rate of 500 kHz. Autocorrelation measurements show pulse durations as short as 2 ps. By removing the remaining dispersion from the pulses this duration might be brought to values below one picosecond.

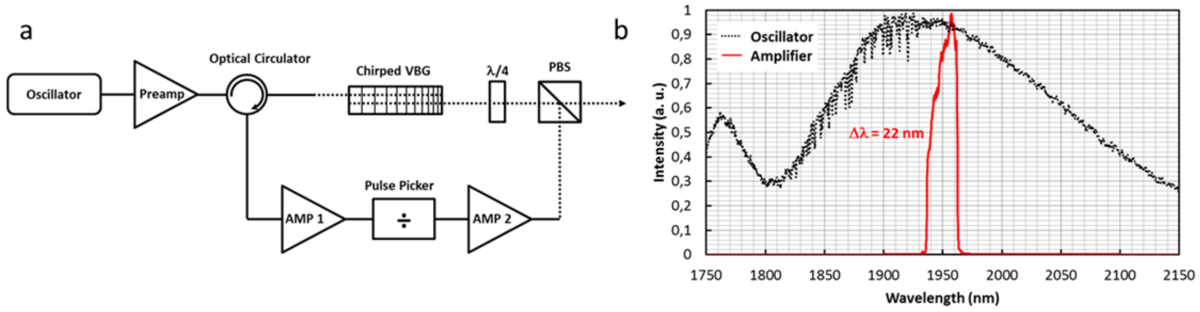

Fig. 1. (a) Schematic setup for the 2 µm fiber chirped pulse amplification system. The CVBG is used for stretching and compressing the pulses, Liao (2007). Prior to the final amplification the repetition rate is reduced to frequencies of 50 – 500 kHz. (b) Output spectra of seed oscillator (dotted line) and amplified pulses (red solid line).

2. Laser induced modification of glass

The 2 µm laser source is used for a controlled material modification inside a glass work piece. In our experimental setup, a molded IR aspheric lens, f = 4.0 mm, NA = 0.56, focuses the laser light. Using the knife-edge method we determine a beam radius of $w_0 = 2.7 \pm 0.1$ µm in the focus, where the beam radius is defined as the radius at which the intensity has fallen to $1/e^2$ (13.5%) of its maximum value at the center of the beam (Figure 2).

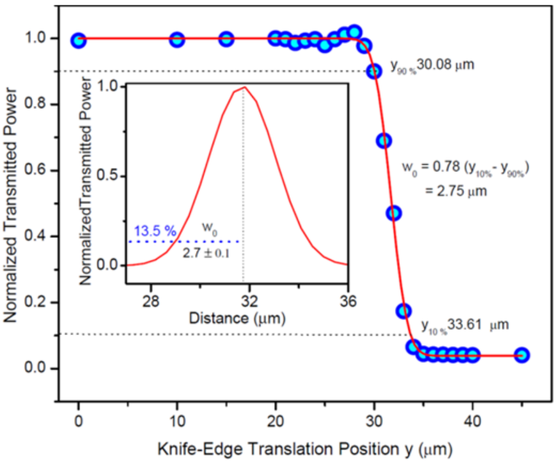

Fig. 2. Blue circles are the normalized transmitted power as a function of the position of the knife-edge. The red line is a fit of equation (1) (see appendix A) to the experimental data. Inset is the normalized differential form of the fit showing the beam radius (w_0) at 13.5 % of maximum power.

Laser writing experiments inside a glass work piece were performed for pulse energies of 1 µJ/pulse (measured in front of the lens), a repetition rate of 300 kHz and a pulse length of 2 ps. With this, we reach intensities of about 2×10^{12} W/cm^2 in the focus. The glass work piece (IDL GmbH, microscope slide) is mounted to a computer controlled 3-axis manipulator, which allows to position the glass precisely with respect to the position of the focus. The x and y-axis represent the direction parallel and perpendicular to the propagation of the laser beam, respectively. The z-axis allows to displace the glass work piece in the vertical direction with regard to the laser focus (see Figure 3).

Using this experimental setup, we observe that focusing the light into the glass leads to a modification of the glass at the position of the laser focus. This allows for direct laser writing of micrometer scale structures into the glass material. Figure 3 shows microscope images of a set of lines which were written into the glass at various different distances x from the front surface of the glass onto which the light impinges (surface at x = 0 µm). The 1 mm long lines were written by moving the glass in the y-direction with a speed of 0.1 mm/s. The width of the lines is about 5 µm which corresponds to the size of the laser focus. The spacing between lines in the x-direction was set to 50 µm. The individual lines are imaged with an optical microscope by scanning the focus of the microscope from the front surface of the glass (x = 0 mm) towards the back surface. Every time that a line was in the focus of the microscope an image was recorded (Figure 3). Lines appear with a spacing of about 50 µm which is consistent with the preset spacing. In order to demonstrate that individual lines do not significantly overlap in the x-direction, the glass work piece was placed at a slight angle with regard to the optical axis of the microscope. Accordingly, the lines in Figure 3 show a continuous small displacement from left to right.

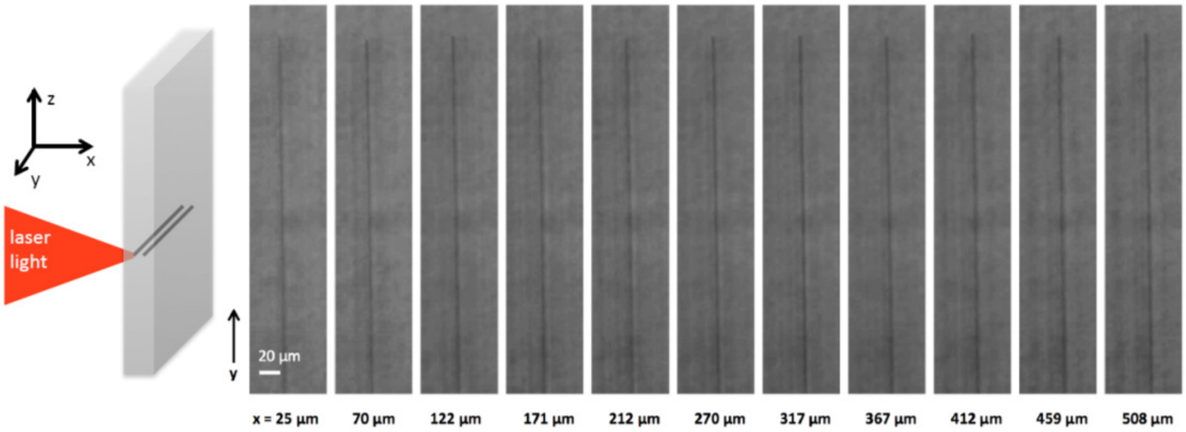

Fig. 3. Geometry of the experiment and series of microscope images of laser-inscribed lines. The lines were inscribed at different depths x with respect to the front surface of the glass at x = 0 µm.

We attribute the laser-induced modification of the glass material to the results of a multiphoton process which takes place in the confined volume of the laser focus. In the laser focus, multiphoton absorption within the nonabsorbing glass material leads to material alteration (see reference by Gattass and Mazur (2008)). Such a localized laser-induced material modification is of great interest with regard to the fabrication of waveguides as demonstrated by Nolte et al. (2003) and of three-dimensional (3D) microstructures inside transparent solid materials. Three-dimensional cavities and tunnels inside the material are obtained by selectively removing the modified material with wet chemical etching (see references by Kiyama et al. (2009), Gottmann et al. (2013)). Key is that the etching rate of modified material is higher than the etching rate of unmodified material. This procedure allows to manufacture complex 3D networks for microfluidic devices and related applications (see references by Liao et al. (2012) and Meineke et al. (2015)).

Laser-induced material modifications with the laser parameters used in this study have not previously been demonstrated. Besides the fabrication of micro scale structures into transparent solid materials such as glass, the 2 µm wavelength opens up the possibility to expand the above mentioned material processing techniques to a broader range of materials; in particular to materials which are opaque in the visible spectral range but optically transparent at wavelengths of 2 µm.

Acknowledgements

This project was financially supported by the Zentrales Innovationsprogramm Mittelstand (ZIM) of the Bundesministerium für Wirtschaft und Energie (BMWi).

Appendix A. Knife edge measurement

We determined a beam radius of $w_0 = 2.7 \pm 0.1$ µm in the focus using the knife-edge method. In this method, the laser beam at the focal spot is progressively blocked by a knife-edge (razor blade), fixed on a computer controlled stage and moved stepwise (in the direction perpendicular to the laser beam (y-axis)). The transmitted power is recorded at each step. In order to obtain the beam radius, we fitted a plot of the transmitted power as a function of the position of the knife-edge (Figure 2) to the following equation:

$$P = P_0 + \frac{P_{\max}}{2}\left[1 - erf\left(\frac{\sqrt{2}(y - y_0)}{w_0}\right)\right] \tag{1}$$

where P_0 is the background power, P_{max} is the maximum power, y_0 is a position of shift with the half of the real power, w_0 is the beam radius (at the focus). We obtained the following fit parameters: $y_0 = 31.7$ and $w_0 = 2.7$ µm.

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