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Fs laser induced apodised Bragg waveguides in fused silica

Christian Voigtländer1, Peter Zeil2, Jens Thomas1, Martin Ams3, Robert J. Williams3, Michael J. Withford2, Andreas Tünnermann1,4, and Stefan Nolte1,4

1Institute of Applied Physics, Friedrich-Schiller-University Jena, Max-Wien-Platz 1, 07743 Jena, Germany;
2Department of Applied Physics, Royal Institute of Technology, 106 91 Stockholm, Sweden
3MQ Photonics Research Centre and Centre for Ultrahigh bandwidth Devices for Optical Systems (CUDOS)
Department of Physics Astronomy, Macquarie University, NSW 2109, Australia
4Fraunhofer Institute for Applied Optics and Precision Engineering, Albert-Einstein-Strasse 7, 07745 Jena, Germany

ABSTRACT
We present apodised Bragg waveguides inscribed in fused silica using a high repetition rate fs laser system. By varying the modulation with a pulse picker, the mean refractive index over the grating length could be kept constant, while the grating strength is varied. Thus, Bragg waveguides with zero crossing Gaussian modulation profile could be demonstrated. The side-lobes were suppressed by about 10 dB compared to a uniform grating.

Keywords: Ultrafast laser processing, apodised waveguide Bragg gratings, burst technique

1. INTRODUCTION
Femtosecond laser pulsed inscription techniques allow non-photosensitive and active glasses to serve as platforms for integrated devices. The direct inscription method affords the fabrication of three dimensional structures like combiners or waveguide arrays.1 Bragg waveguides represent essential building blocks providing both narrow and broad-band integrated mirrors with applications as signal filters and cavity mirrors for waveguide lasers.2

However, so far the inscription techniques have been concentrated on the generation of gratings with a constant refractive index modulation depth over the grating length.3, 4 A reason for not writing more sophisticated grating structures are difficulties in control the highly non-linear interaction between fs laser pulses and the material. Therfore, the Bragg structures suffer from side-lobes in the spectrum beside the reflection peak disturbing the signal returning from a non-apodised grating profile. Due to the flexibility of the direct inscription technique waveguide Bragg devices have potential for dispersion management, e.g. where chirped gratings are necessary.5 Nevertheless, for chirped applications an apodisation is crucial to obtain a smooth grating response.6

2. THEORY
A Bragg grating consists of a periodic refractive index modulation acting as a narrow-band reflection element, where the Bragg reflection wavelength

$$\lambda_B = 2n_{eff}/\Lambda$$

(1)

is determined by the grating period \(\Lambda\) and the effective refractive index \(n_{eff}\) of the waveguide. A constant period leads to a very narrow reflection peak. The strength of the grating is given by

$$r = \tanh^2 \frac{\pi nL}{\lambda}$$

(2)
with the length of the grating $L$ and the refractive index modulation depth $\Delta n$. Here the bandwidth is defined as the distance between the first minima next to the main peak. Bragg gratings with a uniform refractive index modulation (see Fig. 1(a)) show additional side peaks next to the main reflection peak in the spectrum. The side-lobes are generated because the rectangular shape of the envelope of the grating acts as a cavity for the light. This Fabry-Perot cavity leads to a typical modulation in the spectrum, which can be seen in Fig. 2 (black line). The distance of the side-lobes to each other can be calculated in analogy to the free spectral range of a Fabry-Perot cavity

$$\Delta \lambda = \frac{\lambda^2}{2n_{eff}L}. \quad (3)$$

The origin of the side-lobes can also be described by a Fourier transformation of a rectangular function from the spatial domain to the frequency domain resulting in a sinc-function with many side-lobes. Thus, they do not appear, if the spatial profile of the grating modulation is invariant to the Fourier transformation like the Gaussian function.

If the envelope is a Gaussian function like Fig. 1(b) with a non-zero crossing modulation compared to the surrounding refractive index, the mean refractive index will change over the grating length. This results in a change of the Bragg wavelength as can be seen from equation (1). In such an apodised Bragg grating side-lobes will appear only at the shorter wavelength side. The blue line in Fig. 2 illustrates these spectral consequences. The side-lobes are generated from a cavity between the outer parts with a lower Bragg wavelength than the middle part. A better implementation is a zero crossing Gaussian apodisation as can be seen in Fig. 1(c), where the mean refractive index stays constant over the grating length. The different spectral response can be seen in Figure 2 (red line).

Figure 1. Refractive index modulation over the length of: (a) uniform Bragg grating, (b) Gaussian apodised Bragg grating with non-zero crossing refractive index profile and (c) Gaussian apodised Bragg grating with zero crossing refractive index profile.

Figure 2. Simulated uniform (black line) and apodised Bragg grating, (blue): Gaussian apodisation with non-zero crossing refractive index modulation, (red): with zero crossing modulation.
3. EXPERIMENTS

To realize waveguides with ultrashort laser pulses the laser beam is strongly focused into the transparent sample. The non-linear absorption generates a permanent refractive index modification in the core. By moving the sample underneath the laser beam waveguides could be realized.\textsuperscript{10}

3.1 Waveguide Bragg grating fabrication technique

Here the fabrication of the waveguide Bragg gratings (WBGs) is based on the burst writing technique with a high repetition rate laser system. To generate a periodic refractive index modulation the sample is moved with a constant translation speed $v$ underneath the focused laser beam, while the beam is modulated by an external modulator with the frequency $f$. Thus, the Bragg wavelength (eq. 1) is given by

$$\lambda_B = 2n_{ef}\frac{f}{v}.$$  \hspace{1cm} (4)

The laser system used is a commercial femtosecond laser oscillator (Amplitude t-pulse 500) providing 500 nJ pulse energy at a repetition rate of 9.5 MHz and 400 fs pulse duration. The repetition rate of the laser can be tuned with an acousto-optic modulator. To increase the strength of the refractive index contrast the laser radiation is frequency doubled to a wavelength of 513 nm.\textsuperscript{11} The laser beam is focused by an aspherical lens (NA 0.55) into the fused silica sample (Corning 7980 HPFS Standard Grade) (Fig. 3). The sample is moved with a constant velocity of 10 mm/min on a high precision air bearing translation stage (AEROTECH ABL 1000).

The spectral characterization of the WBGs was done with a swept wavelength system (JDSU 15100) with a resolution of 3 pm over the C-band. Therefore, the light was coupled into and out of the device by single mode fibers, which were fixed on a 6-axis translation stage. This spectral resolution is required to investigate the side-lobes of the WBGs, because their separation decreases with increasing grating length.

3.2 Controlling the effective refractive index contrast

In principal apodisation can be achieved by several methods. The pulse energy can be changed over the grating length as well as the exposure time leading to the same effect namely, that the refractive index modulation strength is changed.
However, these methods have a huge drawback as they change the mean refractive index over the grating length as well. As a consequence, additional side-lobes on one side of the Bragg peak occur as discuss above.

Our approach to achieve apodised waveguide Bragg gratings consists of changing dynamically the refractive index modulation depth by switching the femtosecond laser ON for a short time between two refractive index modifications of the normal period. Figure 4 shows the principal of this method. The upper part illustrates a standard WBG with a fill factor of 50%. In the middle part the inscription laser is ON between two modifications of the original period. However, the additional ON-time leads to a longer total exposure time increasing the mean refractive index in the WBG. This effect can be avoided by reducing the exposure time of the main period by the same amount as the additional ON-time. Thus, the total exposure time stays constant over the grating. The lower part of Figure 4 illustrates the extreme where both the additional and original exposure times are the same, yielding a grating with half of the period of the origin grating. In the following the \( a \)-parameter is used for describing the additional exposure time. It is defined as the time of the normal exposure divided by total OFF-time of the laser during one period. Thus, the upper part of Fig. 4 has a \( a = 1 \) while the lower has \( a = 0.5 \).

### 3.3 Waveguide Bragg grating results

For the inscription of low loss waveguides (losses below 0.7 dB/cm), pulse energies of 220 nJ, repetition rates between 300 and 500 kHz have proven to be the optimal parameters. The waveguides were inscribed 60 \( \mu \)m beneath the sample surface. This is a compromise between the increasing aberration for higher depth and the possibility to use the advantage of the nonlinear absorption of femtosecond laser pulses to generate three dimensional structures inside the bulk substrate. By modulating the inscription laser with a second frequency, waveguide Bragg gratings could be inscribed in one step in fused silica. The best results could be achieved with a fill factor between 40 and 60 %. Thus, for all gratings a fill factor of 50 % has been used.

In order to test, how the effective refractive index constrast can be decreased, we inscribed WBGs with constant periods and different \( a \)-parameters. The additional exposure time was increased and \( a \) decreased resulting in a drop of the reflectivity for the same sample length. Figure 5(a) illustrates the dependence of the refractive index modulation depth \( \Delta n \) calculated from the reflectivity (Eq. 2) of different gratings with decreasing \( a \). A spectrum of a waveguide Bragg grating with \( a = 1 \) is shown in 5(b). The grating was inscribed in a 10-mm long sample with a pulse energy of 200 nJ and a translation speed of 10 mm/min. The grating was written in 1st order, thus the period is 536 nm. Investigations of 2nd order inscribed gratings showed very poor reflectivities leading to the assumption of a sinusoidal refractive index profile. The WBG has a total out of band transmission loss of 1.2 dB consisting of coupling and guiding losses. The additional losses of about 2 dB at 1548.5 nm are radiation losses. As the grating is uniform the reflection spectrum shows the expected strong side-lobes beside the main peak.

We made use of the dependence of the modulation depth on the \( a \)-parameter to inscribe apodised waveguide gratings. The apodisation function we have chosen was a Gaussian function. Due to non-infinite position speps it is not possible to fabricate gratings with a continuously changing modulation depth. Therefore, stepwise apodised gratings have been realized. The number of steps is given by the minimal accuracy (2 nm) of the translation stage and the period of the
Figure 5. (a): Dependence of the refractive index modulation depth $\Delta n$ on the $a$-parameter, (b): transmission (blue) and reflection (black) spectrum of a 10-mm long 1st order WBG with $a = 1$. The inscription energy was $E = 200$ nJ and the translation speed $v = 10$ mm/min.

Figure 6. (a): Measured spectra of a constant WBG with $a = 0.85$ and a length $L = 4.4$ mm and an apodised WBG in a 10 mm sample with Gaussian apodisation, (b): Gaussian profile used for the inscription of the apodised grating in (a).

For a grating with 536 nm period there are no more than 67 steps to apodise the profile. Figure 6(b) shows a step Gaussian profile of the $a$-parameter over the grating length with a FWHM of 4.4 mm. This profile was used to inscribe the apodised grating in Fig. 6(a) (blue line). It can be seen that the first side-lobes on both sides of the main peak are suppressed by more than 10 dB compared to the non-apodised WBG (black line). However, since the dependence of the refractive index profile on the $a$-parameter is not linear, the apodisation function deviates slightly from a Gaussian function.

In addition, the spectrum of both gratings show strong irregular modulations beside the main peak, thus only the first side-lobes of the uniform grating are visible in the spectrum. The apodised WBG shows no discernible side-lobes, which would be expected with a separation of 83 pm as the sample length is 10 mm. As a comparison the blue spectrum in Figure 7 shows the simulation with the help of the transfer matrix method of an apodised Bragg grating with the same parameters as the measured one.7 Here the side-lobe suppression is about 60 dB compared to the main peak, while the measured suppression background is about 40 dB higher. The irregular modulations show no evidence of noise and are suspected as inaccuracies of the waveguide and in the grating period. Furthermore, the bandwidth of the Bragg peak is slightly increased from 160 pm for the simulation to 180 pm for the experimental grating. This can be confirmed by adding a small random period fluctuation on top of the simulated period. The consequences of a fluctuation of $\pm 600$ pm can be seen in the red dotted spectrum in Fig. 7, where side-lobes become highly irregular and and their strength is increased, as well as the background reflection. Additionally the bandwidth of the main peak is slightly increased and fits well to the measurements.
4. CONCLUSION

In conclusion we have for the first time, to the best of our knowledge, fabricated apodised femtosecond inscribed waveguide Bragg gratings in fused silica. We have established a method to apodise the Bragg waveguides by keeping the mean refractive index constant. The technique is realized by exposure the region between two grating modification for a short time. This decreases the refractive index modulation. If the additional exposure time is changed, the modulation depth will vary. To avoid a mean refractive index change, the original exposure time has to be reduced by the same amount. A side-lobe suppression of about 10 dB compared to a uniform grating could be realized. However, all of the WBGs show strong irregular spectral modulations, which can be explained by localized refractive index variations of the waveguide and inaccuracies the grating period. This could be proofed by simulations with small random period fluctuations increasing the background of the simulated spectra. Thus, the performance of the apodised WBG is only limited by the accuracy of the writing setup. Nevertheless, this technique provides an easy way to generate apodised waveguide gratings.

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