Focused Ion Beam Nanostructured Gratings in Crystalline KYW:Yb^{3+} Channel Waveguides

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We report our recent results on utilization and optimization of the focused ion beam technique for the fabrication of grating structures for potential integrated photonic devices in crystalline $KY(WO_4)_2$:Yb^{3+}. The FIB milling procedure for the realization of grating structures in KYW channel waveguides was optimized. Grating structures more than 4 µm in depth with an improved total sidewall angle of 4.3° were achieved by varying dwell time and pixel resolution distribution. Currently optical characterization of the resonator structures for achieving on-chip waveguide lasers is ongoing.

Introduction

UV and electron-beam lithographic methods have successfully been used as main nano-structuring techniques in the field of photonics. Increase in the variety of materials used has created a growing demand for a material independent nano-patterning tool. Focused ion beam (FIB) milling is emerging as such an alternative method, as it involves physical removal of a material by a beam of ions making it adaptable to almost any material system [1-3].Furthermore, FIB has the benefit of enabling fast prototyping, resulting in considerable reduction of the design-fabrication-characterization cycle time [3].

In this work, we report our recent results on utilization and optimization of the focused ion beam technique for the fabrication of grating structures for potential integrated photonic devices in crystalline $KY(WO_4)_2$:Yb^{3+} (KYW). The monoclinic KYW is recognized as an excellent host material for rare-earth ions, providing high absorption and emission cross sections, especially when doping it with Yb^{3+}. Recently, laser emission with slope efficiencies up to 82.3% has been obtained in planar waveguides of this material [4].

The goal of the current study is to define grating structures on KYW channel waveguides and obtain on-chip resonators. For this purpose we need to identify the optimum parameters of FIB nano-structuring for deeply-etched Bragg gratings in KYW:Yb^{3+} channel waveguides. Deep gratings of several micrometers are necessary to fully etch through the whole waveguide cross-section in order to obtain a higher effective index contrast, thus requiring a fewer number of periods to obtain the same amount of light reflection. Therefore, the two initial objectives are to achieve a sufficient grating aspect ratio for KYW:Yb^{3+} by controlling the re-deposition during the milling process and to realize straight grating side-walls in order to minimize out-of-plane losses [5].

Experimental

The KYW channel waveguides had a 3 μm thick core layer doped with Gd and Lu in order to obtain a refractive index increase of about 0.015. The channel waveguide widths varied between 8 and 6 μm. The etch depth of the channel waveguides was about 1.3 μm. We have used Phoenix Opto Designer and Phoenix Field Designer [6] in order to simulate the optical performance of the gratings and determine the optimum grating dimensions for the available KYW channel waveguides. The milled grating structures had a period of 1.12 μm and a total length of 4.48 μm. In order to avoid charging of the structures, a gold palladium or Cr metal layer with a thickness of 50 nm was sputtered on top before the milling process.

The grating structures on KYW channel waveguides were realized by using a FEI Nova 600 dual beam FIB machine. The acceleration voltage was set to 30 kV. The milling current has been varied between 93 pA and 280 pA.

In order to analyze grating parameters such as grating depth or sidewall slope cross-sectioning of the milled structures was performed. The first step of the procedure consists of a local deposition of Pt layer on the region where the cross section profile is to be investigated. Pt is in-situ and locally grown in order to avoid material re-deposition while milling the cross-section. Next, a large hole is milled using a high current of 92 nA. The trench, as shown in Fig. 1, is milled with a sloped angle in order to avoid long milling times. Finally, a polishing process is applied by using a current of 93 pA in order to facilitate a high contrast image.

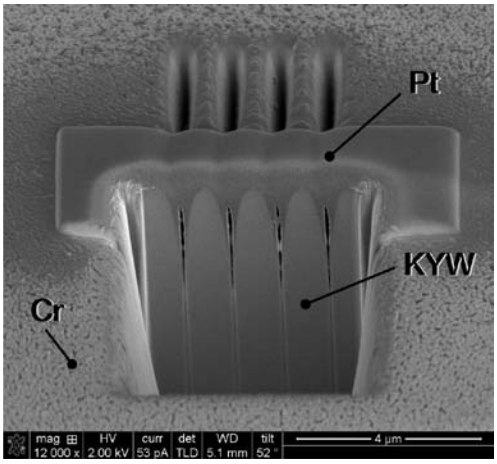
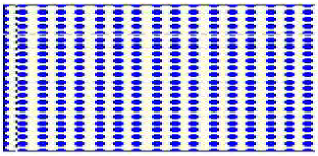
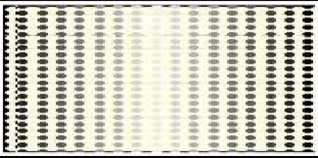
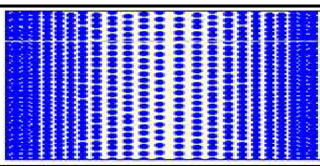


Fig. 1. Scanning electron microscope cross section image of a milled Bragg grating on KYW:Yb^{3+}.

Results and Discussion

The initial focus of the experiments was achieving high milling depths on KYW:Yb^{3+} within a short fabrication time for avoiding any possible drift problems of the focused ion beam. Two ion beam currents of 93 pA and 280 pA have been tested. The higher value allows a shorter milling duration of about 20 minutes in total. Increasing the ion dose per area increased the milling depth as expected (see Table 1, experiment A). This increase however, was not linear, as the milling depth had been strongly affected by re-deposition of material during milling. The gratings were realized using a predefined

Table 1. Optimization experiments of the milling parameters.

Experiment	Ion current and dose variation	Dose/Area ($pC/\mu m^2$)	Depth (μm)
A		7203	3.21
		15491	3.38
		36146	4.27
	Dwell time distribution	**Dwell time variation (ms)**	**Depth (μm)**
B		0.005	4.27
		0.003 - 0007	4.1
		0.003 - 0.7	4.06
	Pixel distribution	**Pixel step size**	**Depth (μm)**
C		20	4.27
		10 -20	4.24
		1 - 20	4.37

design mask file, called a stream file, that contains dell time and pixel sequence for the desired geometry.

The dwell time was set fixed to 0.005 ms for the first experiments A, while the number of loops and ion current was varied in order to obtain the desired grating depth of 4.3 µm. Table I shows the results of the first study.

The second part of this work, involving experiments B and C of Table 1, focused on diminishing the re-deposition effects during the milling process. The stream-file contains the design of the pathway by which the gratings are milled on the waveguide. A re-distribution of the pixels' location and variation of dwell time was implemented along each grating period. The goal of the experiment B was to reduce the re-deposition effects by varying the dwell time per pixel, without increasing the dose per area in order to optimize the milling process for steep sidewalls. The dwell time and pixel resolution increment at sidewalls was compensated with a loop repetition decrement. The dwell time was varied linearly with a maximum value at the grating sidewalls to a minimum value at the center. This leads to a higher dose per area near the sidewalls. In the alternative approach, experiment C, the pixel location was linearly re-distributed such that the pixel density is larger near the sidewalls than in the center (see the inset figures in Table 1).

Both techniques resulted in a reduced re-deposition effect and, therefore, steeper sidewalls compared to the initial "flat" dose distribution. For these experiments the total dose per area was about 33000 $pC/\mu m^2$. Figure 2 shows the cross section scanning electron microscope (SEM) images of two samples with grating structures. The grating structure of Fig. 2a was milled with a standard stream file without optimization. For the grating structure depicted in Fig. 2b we have applied the optimization processes described as experiment B in Table 1. The dose per area for this grating was 33000 $pC/\mu m^2$. The dwell time was varied between 0.003-0.07 ms. Figure 2 (b) reveals a

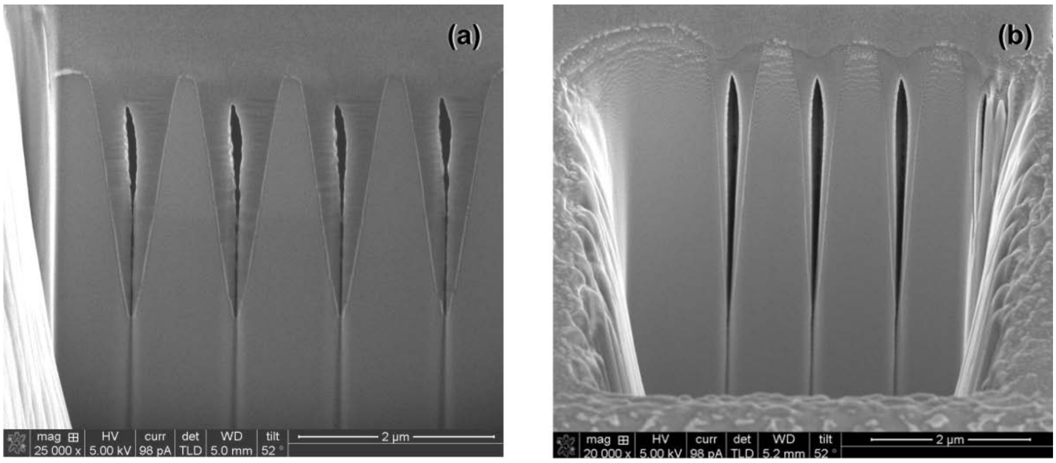


Fig. 2. Cross section profiles of milled Bragg grating in KYW:Yb^{3+} (a) without optimization and (b) by varying the dwell time per pixel.

strong improvement of the total angle between the sidewalls and milling depth increase when applying the dose distribution scheme.

Conclusions

Successful optimization procedure for FIB milling of deep grating structures in KYW:Yb^{3+} was developed. The re-deposition effects were significantly reduced and grating structures more than 5 µm in depth with an improved total sidewall angle of about 4° were achieved by varying dwell time and pixel resolution distribution for the same dose per area. Optical characterization of the resonator structures for achieving on-chip waveguide lasers is currently ongoing.

Acknowledgments

This work was supported by the Netherlands Organization for Scientific Research (NWO) trough the VICI Grant no. 07207 “Photonic Integrated Structures”.

References

[1] J. P. Reithmaier, and A. Forchel, "Focused ion-beam implantation induced thermal quantum-well intermixing for monolithic optoelectronic device integration," IEEE Journal of Selected Topics in Quant. Electr. 4, 595-605 (1998).

[2] D. Gerace, M. Galli, D. Bajoni, G. Guizzetti, L. C. Andreani, F. Riboli, M. Melchiorri, N. Daldosso, L. Pavesi, G. Pucker, S. Cabrini, L. Businaro, and E. Di Fabrizio, "Wide-band transmittance of one-dimensional photonic crystals carved in Si_3N_4/SiO_2 channel waveguides," Appl. Phys. Lett 87, 211116, (2005).

[3] W. C. L. Hopman, F. Ay, W. B. Hu, V. J. Gadgil, L. Kuipers, M. Pollnau, and R. M. de Ridder, "Focused ion beam scan routine, dwell time and dose optimizations for submicrometre period planar photonic crystal components and stamps in silicon," Nanotech. 18, 195305, (2007).

[4] D. Geskus, S. Aravazhi, E. Bernhardi, C. Grivas, S. Harkema, K. Hametner, D. Günther, K. Wörhoff, and M. Pollnau, ”Low-threshold, highly efficient Gd^{3+}, Lu^{3+} co-doped $KY(WO_4)_2$:Yb^{3+} planar waveguide lasers”, Laser Phys. Lett. 11, pp. 800-805, Aug. (2009).

[5] T. F. Krauss and R. M. De La Rue, “Optical characterization of waveguide based photonic microstructures,” Appl. Phys. Lett., vol. 12, pp. 1613-1615, Mar. (1996).

[6] PhoeniX Software, version 3.0.6 beta, www.phoenixbv.com