Realization of on-chip lasers in crystalline double tungstate waveguides using focused-ion-beam nanostructuring

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We report our recent work on obtaining on-chip lasers in crystalline double tungstate waveguides using focused-ion-beam (FIB) nanostructuring. Photonic cavity structures were defined by forming deeply etched Bragg gratings in $KGd_xLu_{1-x}(WO_4)_2$:Yb^{3+} *using FIB milling. The FIB milling procedure was optimized and gratings more than 4 µm in depth with an improved total sidewall angle of about 5° were achieved. Their optical performance was assessed at 1530 nm in Fabry-Pérot microcavities realized on the waveguides. An on-chip integrated laser cavity at ~980 nm was achieved by defining a FIB reflective grating and FIB-polished waveguide end-facet. With this cavity, an on-chip integrated waveguide laser in crystalline potassium double tungstate was demonstrated for the first time.*

Introductıon

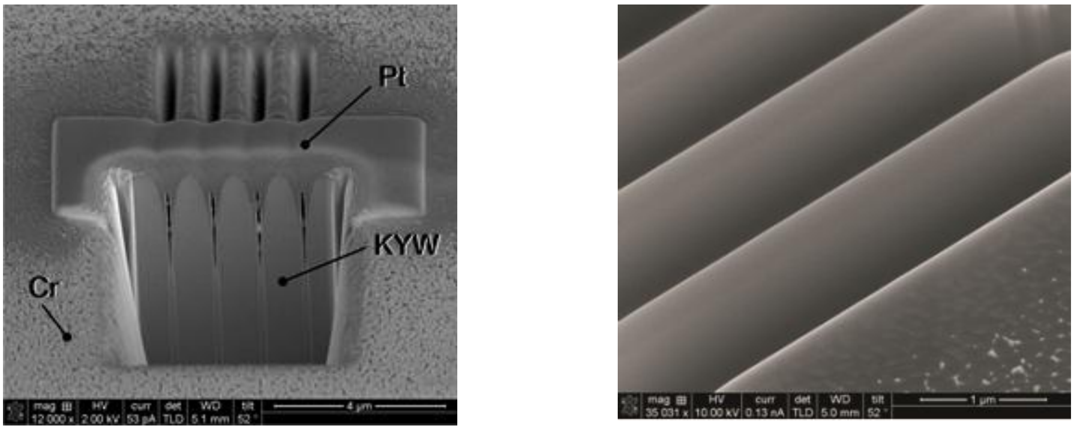
Due to the increase in the variety of materials used in the area of photonics, there is a growing demand for a material-independent nano-patterning tool. Focused ion beam (FIB) milling is emerging as such an alternative method, as it involves physical removal of a material by a beam of ions, making it adaptable to almost any material system [1]. On the other hand, the monoclinic $KGd_xLu_{1-x}(WO_4)_2$:Yb^{3+} (or KGLW) is recognized as an excellent host material for rare-earth ions, providing high absorption and emission cross sections, especially when doped with Yb^{3+}. Recently, laser emission has been obtained in this material with slope efficiencies up to 82.3% in planar [2] and 71% in channel [3] waveguides.

In this work, we report utilization and optimization of the FIB fabrication method of grating structures for integrated photonic devices in a crystalline material. We report the demonstration of a functional on-chip laser device in KGLW:Yb^{3+}.

FIB milling optimization

The KGLW channel waveguides had a 3-µm-thick core layer doped with Gd^{3+} and Lu^{3+} in order to obtain a refractive index increase of about 0.015. The channel waveguide width varied between 8 and 6 µm. The etch depth of the channel waveguides was about 1.3 µm. We used Phoenix Opto Designer and Phoenix Field Designer [4] to simulate the optical performance of the gratings and determine the optimum grating dimensions for the available KGLW channel waveguides. 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 of the sample before the milling process.

The grating structures in KGLW channel waveguides were realized by use of a FEI Nova 600 dual beam FIB machine. The acceleration voltage was set to 30 kV. The milling current was 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. Pt was in-situ and locally grown in order to avoid material re-deposition while milling the cross-section. Next, a large hole was milled using a high current of 92 nA. The trench, as shown in Fig. 1 (a), was milled with a sloped angle in order to avoid long milling times.



(a) (b)

Fig. 1. (a) SEM cross section image of a milled Bragg grating in KYW:Yb^{3+}; (b) SEM image of the grating structure forming the Fabry-Pérot cavity.

Results and discussion

Deep gratings of several micrometer depths are necessary for fully etching through the whole waveguide cross-section to obtain the required effective index contrast and enable a better overlap between the optical mode and the active layer. Straight sidewalls are desired for minimizing the out-of-plane losses. Both, high depth and straight sidewalls demand for a good control over the redeposition of material taking place during the milling process.

A procedure for FIB milling of deep grating structures in KGLW:Yb^{3+} was developed by optimizing the distribution of the pixels' location and variation of dwell time along each grating period. Re-deposition effects were significantly reduced and grating structures more than 4 μm in depth with an improved total sidewall angle of about 5º were achieved. Gratings with a period of ~0.89 μm and a total length of ~4.48 μm were defined for testing at wavelengths around 0.98 μm, see Fig. 1 (b).

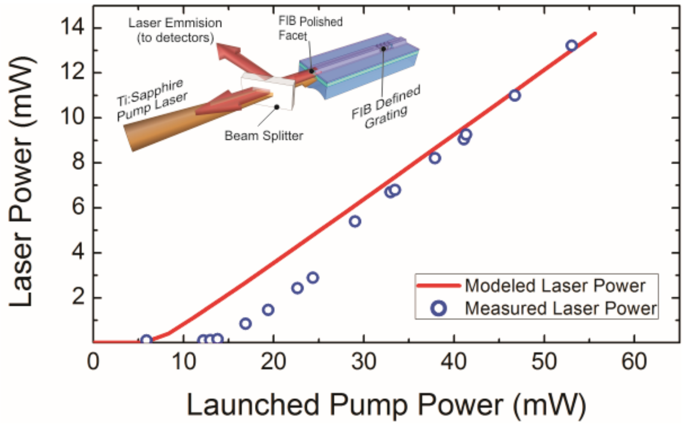


Fig. 2. Measured (dots) and modeled (line) performance of laser cavity. The inset shows a schematic of the experimental setup.

The integrated cavities designed for laser operation consisted of a single grating on one side, while on the other side a polished waveguide facet was FIB-milled. The total cavity length was ~4.5 mm. The active waveguide cavity was pumped via the polished facet by a Ti:Sapphire laser tuned to 932 nm in TE polarization. Lasing was observed for the cavity involving 12-μm-wide grating structures. The slope efficiency of the laser was 33% versus launched pump power, see Fig. 2. Modeling of the laser emission from on-chip cavities was performed with a spatially resolved, quasi-three-dimensional, steady-state rate-equation model. The theoretical model was fitted to the measured results to obtain the relevant parameters. For both lasers the reflectivity of the FIB-polished in-coupling facet was estimated to be 9%. The reflectivity of the grating structure of the laser was estimated to be 40%.

FIB milling of deep grating structures in KGLW:Yb^{3+} has been optimized to achieve the first on-chip integrated laser in crystalline potassium double tungstate. An integrated waveguide laser with 33% slope efficiency was demonstrated in KGLW:Yb^{3+} [5].

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