Continuous electron beam lithography writing modes for optical waveguide nanofabrication

Stitching error free writing improves optical signal propagation

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Abstract

Fabrication of long structures over several mm with highest degree of perfection has always been a challenge using electron beam lithography or FIB nanofabrication techniques. Conventional stitching in vector scanning lithography inherently results in discrete displacement errors at the write field borders. Multipass strategies, also referred to as shot shift methods, can improve on the final result; however the stitching errors are "smeared out" rather than eliminated completely, and the development of such strategies adds more complexity to the overall nanofabrication process. Using a new and unique exposure technology called Fixed-Beam-Moving-Stage (FBMS), we have been able to fabricate several mm long perfect and stitching error free arrayed (see Figure 1), coupling, and tapered waveguides.

Introduction

During the last few decades, the fabrication of functional devices on the nanometer scale has become routine in nanotechnology research. Electron beam lithography (EBL), and, more recently, focused ion beam (FIB) nanofabrication techniques, have been the key enablers for nanoresearch by providing flexible patterning at resolutions in the 10nm regime and below.

As for all nanolithography instruments, the writing field of the electron or ion optics is restricted (typically ~$(100\mu m)^2$). Limitations arise whenever the size of the device exceeds the writing field of the instrument. The conventional vector scanning lithography approach for precisely fabricating such devices relies on the accurate movement of the sample with respect to the writing field of the optical column (stitching).

To allow for the conventional stitching technique, all Raith lithography systems are equipped with a sophisticated laser interferometer stage technology enabling wafer scale sample movements with pattern placement accuracies in the nm-range. The operation principle of the conventional stitching technique is illustrated in Figure 2 (see next page).

Although the stitching accuracy is more than satisfactory for a variety of applications, the remaining ~nm sized kinks at the stitch field borders can significantly degrade the device functionality. One important example is that stitching errors cause significant optical signal loss in elongated optical wave guides.

Raith meets this challenge with a new system feature traxx, a continuous patterning mode that is unique among Gaussian, vector scanning EBL and FIB systems today.

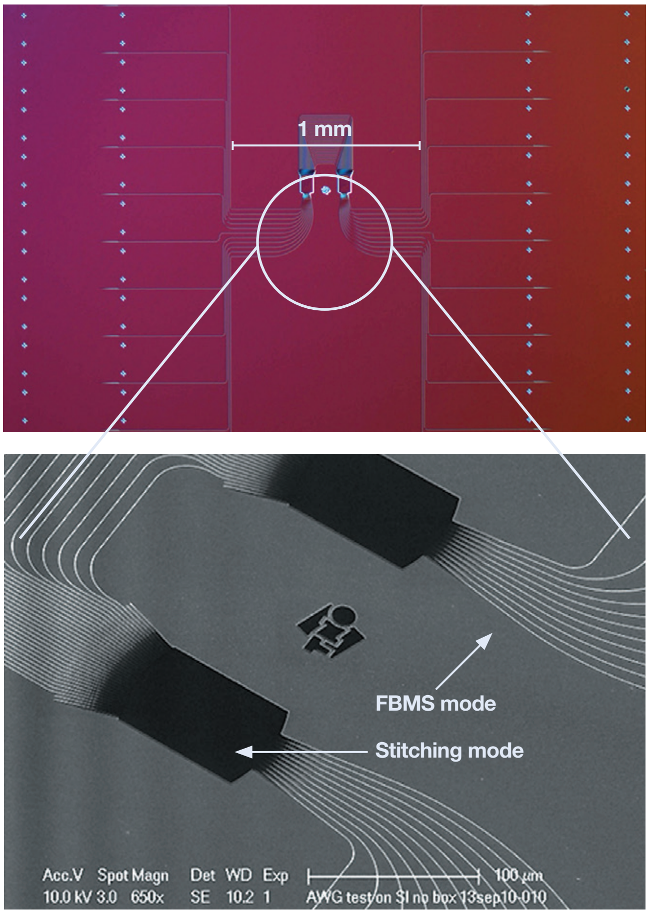

Figure 1: An arrayed waveguide grating (AWG) over several mm length. Courtesy R. Schmits et al., TNO Delft, Netherlands.

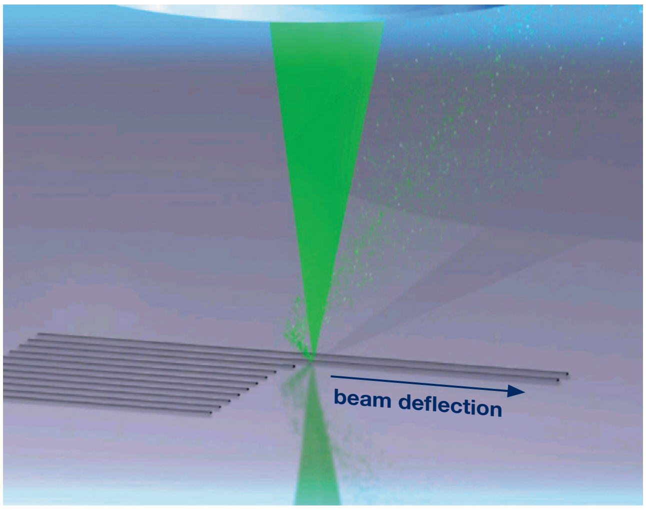

Figure 2: Illustration of conventional stitching mode. The beam is deflected while the stage is stationary, resulting in stitching errors of some nm.

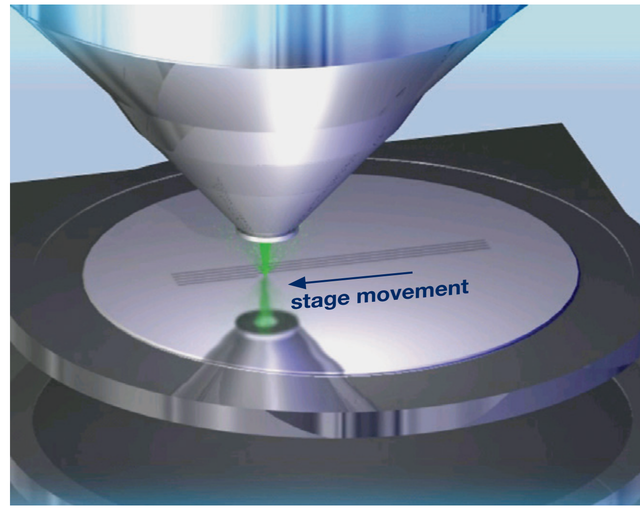

Figure 3: New Fixed-Beam-Moving-Stage mode enables patterning of endless paths with virtually no stitching errors: The beam is fixed while the stage is moving.

The sample is moved continuously under the optical column while the beam hits the sample surface in a spot mode (see Figure 3). This "zero-stitching error" approach - called "Fixed Beam Moving Stage" (FBMS) technology - guarantees the fabrication of up to several cm long, thin, and smooth paths of arbitrary curvature, including tapered paths. Using the FBMS mode in combination with the conventional stitching lithography enables the nanoresearcher with a whole new dimension in nano-device fabrication.

Fixed Beam Moving Stage (FBMS) – sub modes

Different modes of operation are available using FBMS patterning strategy:

- **"high resolution mode"**

  In "high resolution mode" the beam is kept at a fixed position while the sample is moving laterally with constant speed (see Figure 4). Single pixel lines below 20nm line width can be written in high resolution mode.

- **"area mode"**

  In "area mode", an increase in line width up to several 10µm is achieved by periodic and continuous deflection of the beam in a specific circular pattern. At the same time the sample is moving laterally along the designed path. The applied dose is constant over the design line width, and its circular symmetry guarantees the same linewidth regardless of the direction of the sample motion.

As a result, an extremely smooth line of arbitrary shape, width and length can be fabricated on the sample without any irregularities or stitching errors. An example is given in Figure 5.

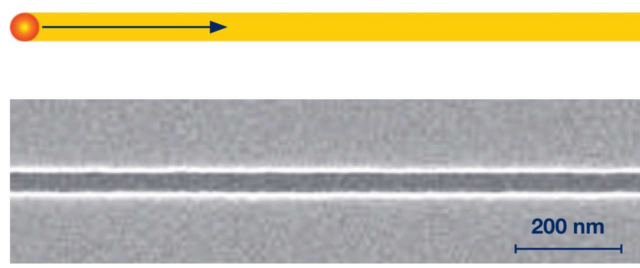

Figure 4: A perfectly straight FBMS line of about 13mm length etched in Si. The orange dot represents a fixed beam in high resolution mode. Courtesy of H. Neubauer et al., University of Göttingen, Germany.

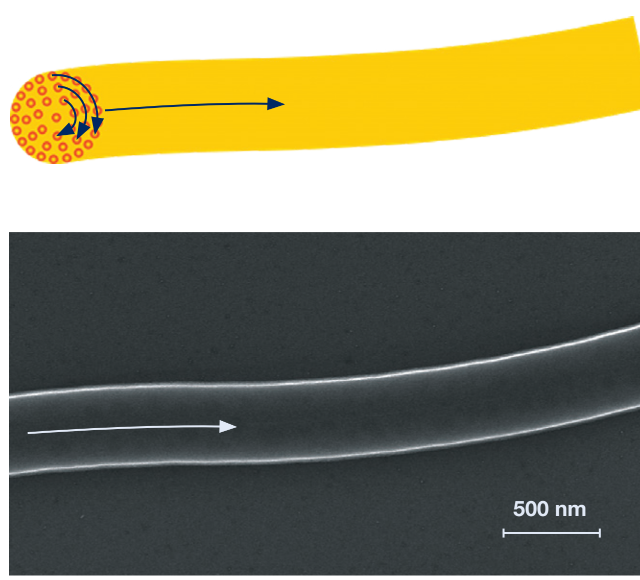

Figure 5: A 500nm wide path exposed in FBMS mode with uniform dose distribution in 200nm thick HSQ. The orange dots in the FBMS area sketch represent repetitively applied lateral beam deflection. G. Piaszenski, Raith GmbH.

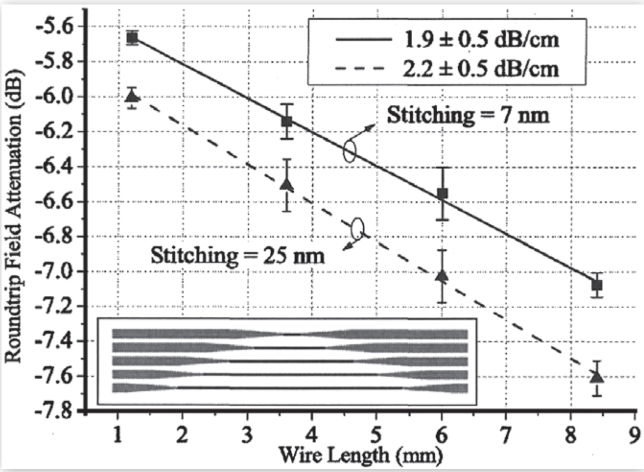

Figure 6: Propagation loss data for two sets of photonic wire waveguides that have different average stitching errors. The inset shows a sketch of the pattern used for the experiment. Adapted from [1]. Stitching errors increase the propagation loss dramatically.

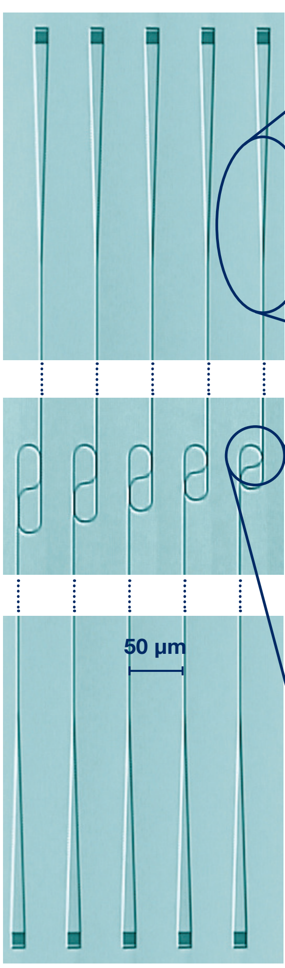

Figure 7: Optical micrograph of 2 mm long waveguides with tapers. G. Piaszenski, Raith GmbH.

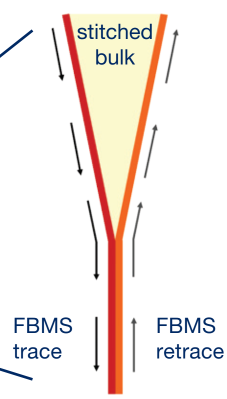

Figure 8: Boundary of tapers are written in FBMS mode. Bulk is written in conventional stitching mode.

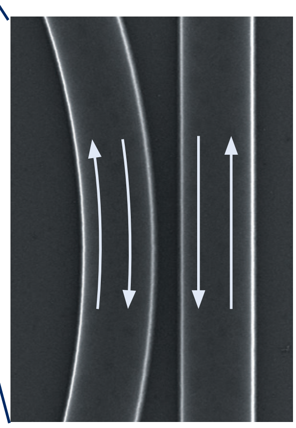

Figure 9: The waveguides were patterned in trace-retrace-technique to optimize the transition from tapered area to constant line width.

Application examples

1. Extremely long waveguides

Due to their sensitivity to any kind of kink or roughness, elongated optical waveguides are one of the most challenging devices to fabricate. In the example presented in Figure 1, an arrayed waveguide grating was created in FBMS mode over a length of several mm.

The difference in length of the individual paths causes a well defined phase shift between the signals. For this reason the precise control of the line width along each of the waveguides as well as their exact positioning with respect to each other is crucial for the performance of the final device. The shape and position of the lines have to be as perfect as possible in order to optimize signal transmission in the final application. Compared to other fabrication strategies such as stitching or multipass, FBMS mode is the superior and simplest method for the fabrication of this kind of device. Figure 6 illustrates the effect of stitching errors on extremely long waveguides. The FBMS mode becomes yet more powerful when combined with conventional stitching lithography in the same process step, as is the case for the arrayed waveguide grating shown in Figure 1. The FBMS and conventional stitching structures can be designed together within the Raith NanoSuite software's GDSII editor, in the same layer, or in separate layers, allowing the nanoresearcher to easily design complex patterns and optimize the design according to his/her specific needs.

2. Tapered wave guides

The connection of waveguides to further functional parts very often requires a tapering of the individual paths (see Figure 7). This can be realized by fabricating the boundary (contour) of the taper in FBMS mode, and separately fabricating the bulk of the taper in stitching mode. This principle is illustrated in Figure 8.

If the taper flows into a long waveguide of constant width, an interruption of the patterning process must be avoided in order to achieve perfect smoothness of the waveguide. This can be achieved by "trace-retrace-technique," which was used to achieve the structure shown in Figure 9. The waveguide is split into two FBMS paths along the path direction. First one boundary of the taper and one side of the waveguide is patterned (trace) before the direction of the stage movement is reversed. The second half of the waveguide together with the second boundary of the taper is patterned in opposite direction (retrace). Even over a distance of several mm, the placement of the two parts of the waveguide is perfect resulting in one single structure at the end of the process. This is achieved by the accuracy of the extremely precise and stable laser interferometer stage used in the Raith lithography systems, which is mandatory

Figure 10: Optical viewgraph of tapered waveguides with a final grid structure. The tapers flow into elongated paths of constant width of 2mm length. J. Sanabia, Raith America.

for this approach. An example of 2 mm long curved waveguides fabricated in trace-retrace-technique is given in Figure 7: The two parts of the waveguide join perfectly forming one single waveguide of superior quality.

Another even more impressive example of this technique is presented above. Figure 10 shows a 1 mm long taper with a continuous change of width from 0.344 µm to 10.400 µm from left to right without any visible stitching error.

3. Continuous FBMS patterning and combination with conventional vector scanning lithography

The coupling of evanescent light for highly precise optical filters can be realized by placing a ring structure in the vicinity of a waveguide. The coupling strongly depends on the gap size between ring and waveguide as well as on their exact dimensions. Any stitching error or placement inaccuracy would reduce the measurable signal drastically.

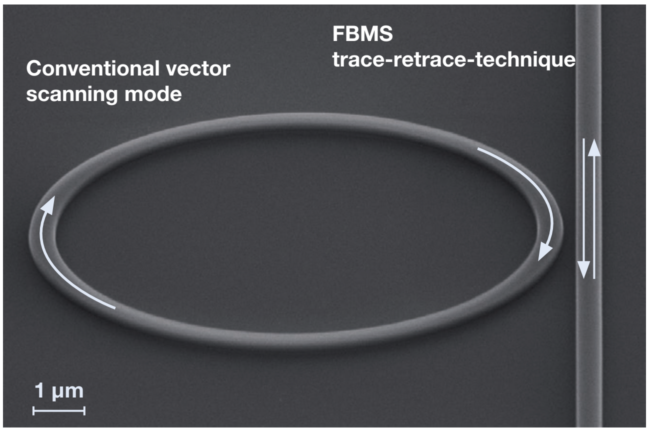

Figure 11: Microring resonator structure. G. Piaszenski, Raith GmbH.

As an example, a typical arrangement of such kind of resonator is presented in Figure 11. The ring was exposed in conventional vector scanning mode (stationary stage) whereas the waveguide was patterned in FBMS trace-retrace-mode (moving stage).

Conclusion

In this application note we have demonstrated the capability of Raith's unique continuous patterning mode called "Fixed Beam Moving Stage" (FBMS) towards optical waveguide fabrication. In contrast to conventional writing strategies using stitching or multipass technique, the beam is kept at a fix spot while the sample is moving with respect to the beam.

In combination with conventional stitching mode the FBMS patterning strategy gives the user access to a wide variety of applications: Elongated smooth paths of any shape and width can be fabricated in perfect quality together with conventionally stitched elements. As stitch field borders are not present at all, no kinks arise in the exposed structures which would cause losses in the signal transmission of the final device.

The "zero-stitching error" FBMS mode for nanolithography applications is therefore the perfect choice for nanofabrication of optical waveguides and resonators.

Acknowledgements

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References

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