Sub-nm pitch control of stitch error free, millimeter-long periodic structures

Superior nanophotonic and plasmonic device performance using periodixx based on unique MBMS technology

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Abstract

Nanofabrication of large area periodic structures with high pattern fidelity are important for numerous applications in photonics and plasmonics. Whereas stitching errors are evident and unavoidable in periodic patterning tasks with conventional electron beam lithography, they can now be resolved applying a new and unique exposure technology called Modulated-Beam-Moving-Stage (MBMS). In MBMS, the electron beam is periodically deflected and synchronized with the laser interferometer stage, which is moving the sample with constant speed over long distances (see Figure 2). Pitch measurements demonstrate that MBMS can fabricate periodic structures like distributed feedback DFB gratings and photonic crystal waveguides (see Figure 3) with sub-nm pitch control and virtually no stitching errors. The total writing process time overhead is negligible thus enhancing overall throughput significantly. As compared to conventional electron beam lithography with ubiquitous writefield distortions and non-negligible line edge roughnesses when applying large writefields, these effects can now be reduced to a minimum using MBMS.

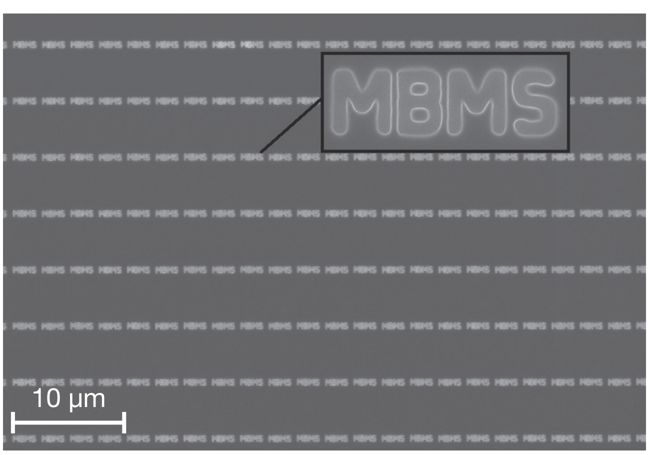

Figure 1: Modulated-Beam-Moving-Stage (MBMS) allows fabrication of any periodic structure without stitching.

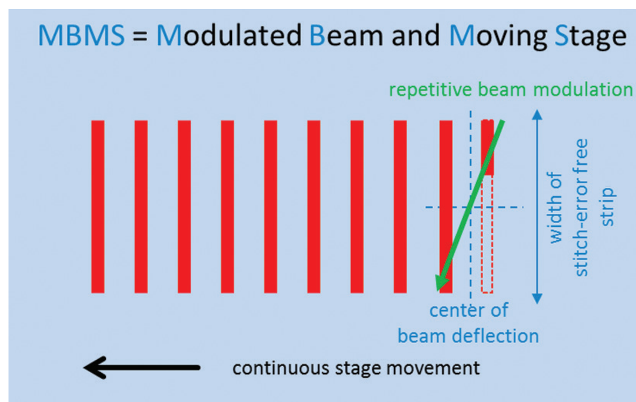

Figure 2: Principle of Modulated-Beam-Moving-Stage: Continuous stage movement with repetitive beam modulation, resulting in stitch-error-free strips with a length of several mm or even cm.

Introduction

Periodic structures are essential for photonics and can be found in distributed feedback lasers (DFB), fiber Bragg gratings, optically variable devices (OVD), holograms, UV / X-ray optics, photonic crystals, or charge modulation in quantum cascade lasers. Electron beam lithography (EBL) and FIB nanofabrication provide patterning resolution in the 10 nm regime and below, and offer more flexibility for writing periodic structures over large areas, as compared to direct write laser lithography or optical interference lithography.

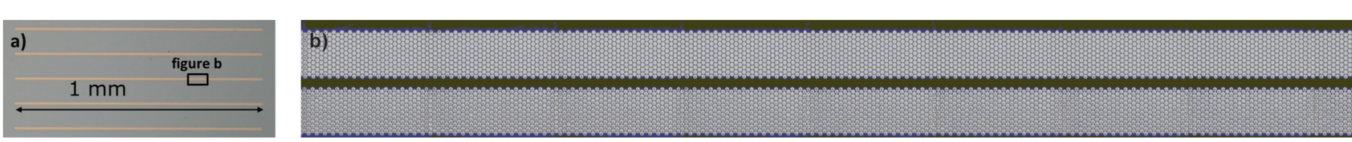

Figure 3: Stitch-free photonic crystal waveguides of 1 mm length fabricated by MBMS.
Figure a) shows an overview with 5 waveguides (optical microscope, 10×).
Figure b) was made out of 10 SEM images with a size of 10 × 10 µm.

As for all existing nanofabrication tools, the area which can be addressed by EBL and FIB systems in one shot is restricted to the size of the writing field (WF) of the electron or ion optics (typically ~(100 µm)²). Limitations arise whenever nanostructures are exceeding the WF of the instrument. The stitching approach for precisely writing such large area patterns relies upon accurate lateral movement of the sample with respect to the column (see Figure 4).

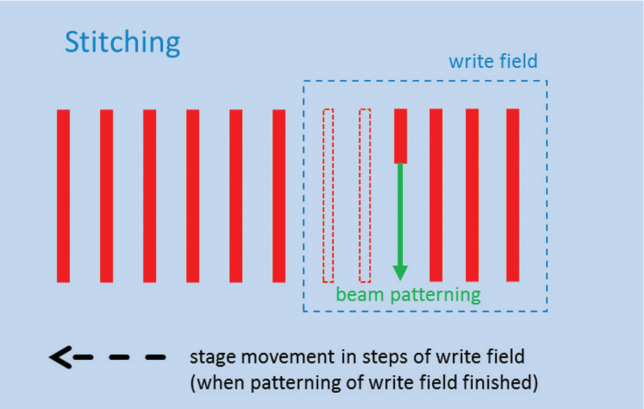

Figure 4: Illustration of conventional stitching mode: Beam deflection and subsequent stage movement.

As a prerequisite for the conventional stitching technique Raith lithography systems are equipped with sophisticated laser interferometer stage technology enabling wafer scale sample movement with nm resolution. Typical stitching accuracies of the order 10 nm and better can be obtained with state-of-the-art EBL systems, which is more than satisfactory for a variety of applications.

Nevertheless, even within this range, small positional errors such as shifts at stitch field borders within periodic structures can significantly degrade the device functionality and performance, causing side modes in DFB lasers [1] and dips in the transmission spectra of photonic crystals [2]. Although exposure strategies with overlapping writing fields - also known as shot-shift or multipass techniques - can smear out stitching errors and thereby reduce them, it's impossible to eliminate them completely by these methods.

In order to meet the need for stitch-error-free exposures of periodic structures, Raith offers a dedicated continuous patterning mode which is unique among Gaussian, vector scanning EBL and FIB systems. This feature is called periodixx and is based on Raith´s Modulated-Beam-Moving-Stage (MBMS) technology, which is complementing the existing traxx exposure mode, using Raith´s well established Fixed-Beam-Moving-Stage (FBMS) technology. FBMS allows continuous writing of elongated paths like optical waveguides without stitching [3], where the width of the path is defined by a dynamic beam expansion. In MBMS exposure mode, the beam movement is now defined such that the combination of repetitive patterning and synchronized continuous movement of the laser interferometer stage results in stitch-free, strip-shaped periodic structures (see Figure 2).

Application examples

1. Bragg gratings

Bragg gratings are used as optical filters on waveguide structures, e.g. in DFB lasers. MBMS has been used to expose 50 µm wide and 1 mm long gratings with periods of 185 nm, 185.4 nm, 185.8, and 186.2 nm, respectively (see Figure 5). Afterwards, the pitch distribution has been measured by a set of distance measurements between 100 lines.

Figure 6 shows that the average pitch in Figure 5 is within a ± 0.1 nm (3-sigma) environment of the target pitch across the complete, 1 mm long gratings. This demonstrates that MBMS can fabricate periodic structures with sub-nm pitch control with virtually no stitching errors. Reasons for the high quality are the continuous stage movement and excellent pattern placement accuracy with lower distortions due to smaller beam deflections, as compared to those in large writefields ap-

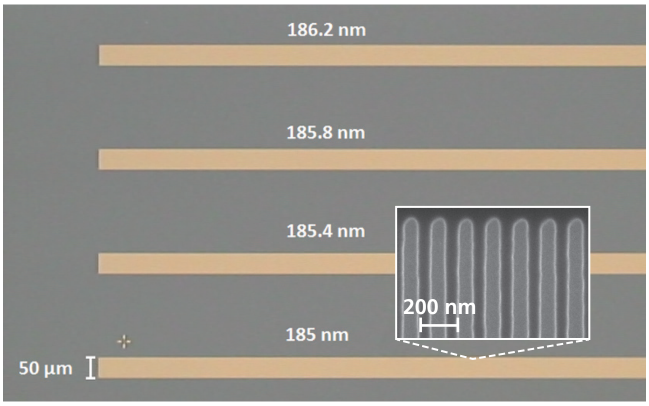

Figure 5: Optical microscope image (10×) of Bragg gratings with periods from 185 nm to 186.2 nm.

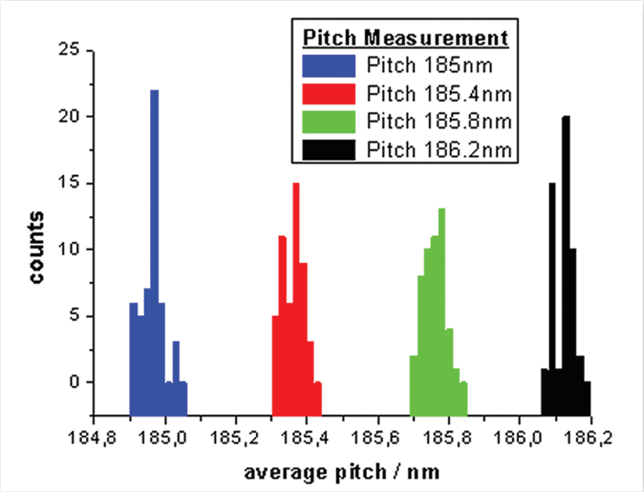

Figure 6: Pitch variation within Bragg gratings. The pitch was measured as an average of distance measurements between 100 lines.

plying conventional stitching mode. Apart from that, the line edge roughnesses (LER) of the gratings fabricated with MBMS are by far superior to those obtained with conventional EBL. Applying latter technique, one has to typically use large, several 100 µm- or even mm-sized writing fields in order to achieve a stitching error free device. Doing so however, one has to compromise on the achievable signal-to-noise ratio and consequently the achievable LER, which is limited by the DAC noise of the EBL tool in such large writing fields. Not so for MBMS, as the stitch error free strips can have lengths of cm without the need to chose large writefields, but rather typically apply beam deflection ranges less than 100 µm.

Furthermore, MBMS enhances the throughput by eliminating or reducing the times associated with stage acceleration, stage deceleration, pattern data preparation and transfer, and beam and stage settling times in conventional vector scanning lithography. In addition to Bragg gratings with a single fixed pitch, chirped gratings can be generated by using a repetetive beam pattern with a variation of periods. Phase shifted gratings can be made by exposing two MBMS gratings with an offset of L/4.

2. Area gratings

The exposure of multiple strips in parallel results in area gratings (see Figure 7). The grating lines can be orientated both perpendicular and parallel to stage movement, and the whole grating can be rotated on the sample. Such area gratings are completely stitch-free in stage movement direction only, but the stitching quality in perpendicular orientation is superior as compared using conventional stitching mode. One reason is that there are no stitching boundaries in direction of stage movement. Moreover, stitching-errors between strips are smaller compared to conventional stitching, mainly due to lower distortions because of smaller beam deflections in this mode. In addition, the enhanced throughput results in reduced stitch-errors caused by drift effects. Figure 8 demonstrates the superior quality of area gratings written in MBMS exposure mode: Optical microscope images are generally very sensitive to periodic stitching errors even in the nm-regime and exhibit stitching boundaries clearly. In figure 8 such boundaries are not visible, which is a clear proof for highest pattern placement accuracy and pattern fidelity.

3. Photonic crystals and further applications

As mentioned in the introduction, reduced stitching-errors are essential for the performance of devices with photonic crystals. MBMS allows for photonic crystal waveguides fabrication (see Figure 3) with a length of several mm or even cm without any stitching. Photonic crystals over large areas are made like area gratings by stitching of strips, which are fabricated using specific repetitive patterns with MBMS (see Figure 9). There is a wide range of further applications for MBMS writing, e.g. honeycomb structures (see Figure 10), plasmonic structures in sensors [4], arrays of nanoantennas

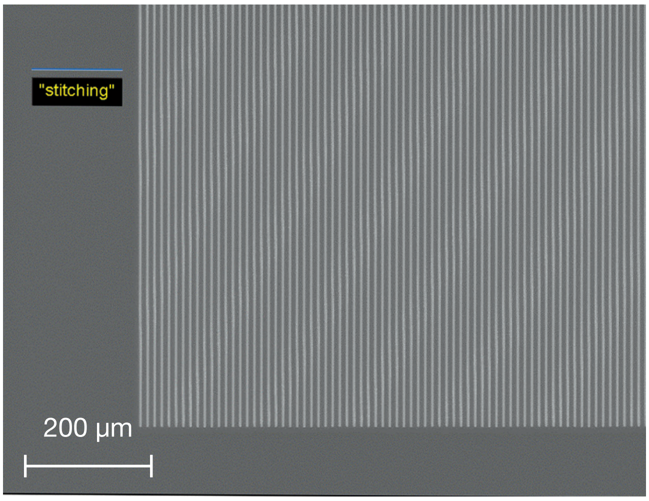

Figure 7: Area grating with a pitch of 1 µm, fabricated by “stitching” of 50 µm wide strips patterned by MBMS.

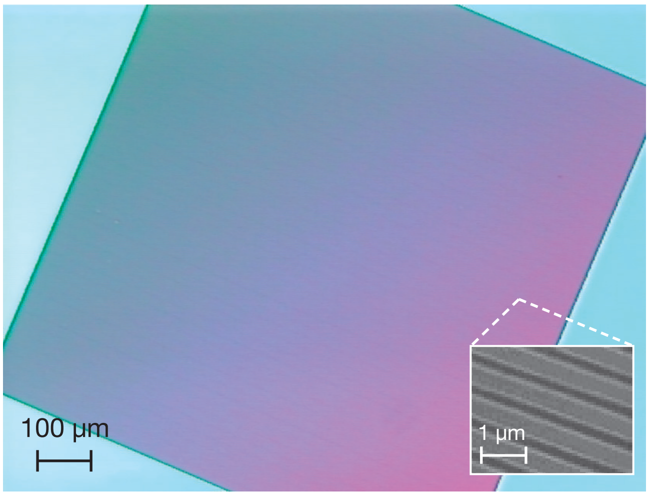

Figure 8: Optical microscope image (×10) of a 1×1mm2 large area grating with a pitch of 0.7 µm and rotated by 20°, showing no visible stitching boundary.

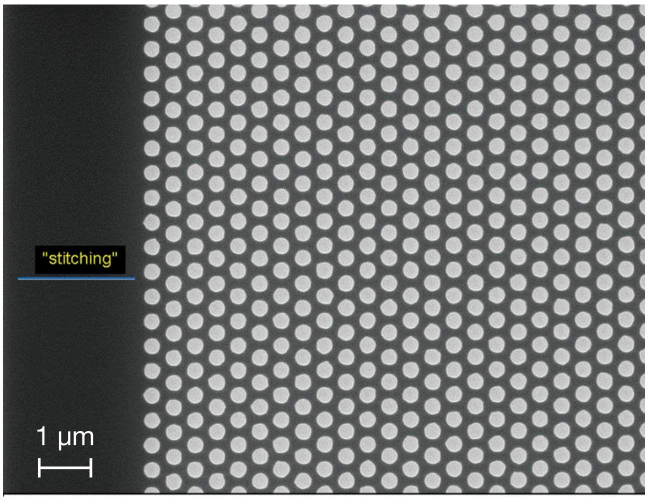

Figure 9: Photonic crystal.

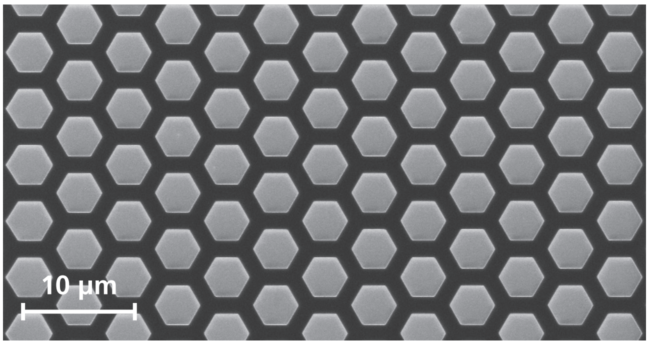

Figure 10: Honeycomb structure.

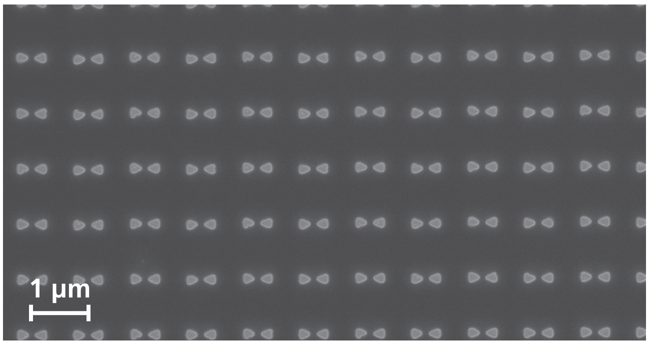

Figure 11: Array of bowtie structures for nanoantennas.

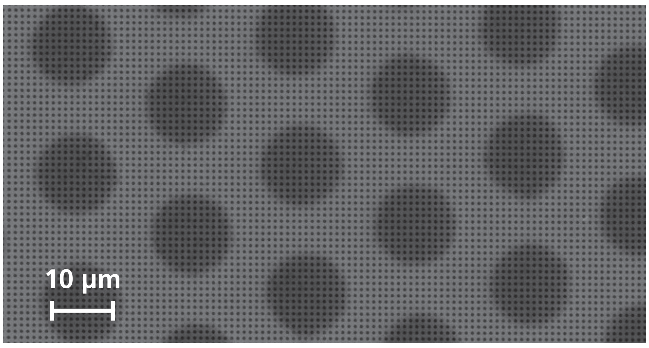

Figure 12: Nanosieve with periodic holes [5].

(see Figure 11), metamaterials, or arrays of holes for nano sieves (see Figure 12). Some of these result in superior performance of the fabricated devices due to reduced stitch-errors when made by MBMS, while some benefit from enhanced throughput for large area patterning with reproducibly repeated base structures.

Conclusion

In this application note we have demonstrated the capability of Raith's innovative continuous patterning mode for periodic structures called periodixx based on Modulated-Beam-Moving-Stage technology, which is unique and not available for any other vector scan addressing Gaussian EBL tool. MBMS combines continuous stage movement and repetetive beam patterning for stitch-free writing within strips. Smaller beam deflections compared to conventional stitching exposure mode cause lower distortions and thus reduced stitch-errors between strips. Exposure times are reduced by eliminating or reducing overhead times for stage and beam settling, pattern data preparation and transfer. Due to small beam deflection ranges, line edge roughnesses even for extended stitch-free structures are significantly reduced as compared to results achieved with conventional EBL. Consequently, MBMS results in periodic structures with superior quality at enhanced throughput.

Application examples include devices with Bragg gratings and photonic crystals, which are made without stitch-errors and resulting in improved performance. Moreover, enhanced throughput allows for patterning of larger areas of any periodic structures within reasonable exposure times and thus gives access to new applications, e.g. with metamaterials or plasmonic structures. In short: The unique MBMS patterning strategy offers users of Raith EBL and FIB systems a new approach to a myriad of applications with periodic structures.

References

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