Total reflection mirrors fabricated on silica waveguides with focused ion beam

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Efficient total reflection mirrors are fabricated on silica-based waveguides by direct milling with a focused ion beam. To reduce the excess losses of the mirrors, a two-step milling technique is employed that reduces the roughness of the mirror surface while maintaining a high milling rate. A focused ion beam is used to fabricate low-loss mirrors with small excess losses of about 1.0 dB.

Introduction: Various approaches have been proposed for realising light-turning mirrors on silica planar lightwave circuits (PLCs) [1–3] to achieve planar photodiode integration for PLCs and other devices that need vertical optical coupling with PLCs, such as surface-emitting laser diodes, and optical interconnection between waveguide circuits. One is the formation of an angled structure (e.g. gold-angled pits [1] or a resin slope [2]), which is placed in a vertical rectangular hole formed by reactive ion etching. The problem with this approach is that it results in a larger footprint (>100 × 100 μm/mirror), which makes it unsuitable for the high-density integration of mirrors. Another approach involves installing a slope on the substrate or undercladding layer as a front-end process before forming the core layer [3]. This approach requires the metal to be embedded in the silica to provide a mirror surface. This metal layer reduces the temperature budget of the process.

A promising way to overcome these problems is to use total internal reflection mirrors, consisting of air slits fabricated with focused ion beam milling (FIB mirrors). Some FIB mirrors on semiconductor materials have already been used to realise folded cavity surface-emitting lasers [4]. However, as yet there has been no report with respect to silica. Fabricating the angled slits in silica with FIB is more difficult than in semiconductors, because silica is a dielectric material and easily becomes charged. Moreover, a silica waveguide is larger than a semiconductor waveguide owing to its lower refractive index contrast. These characteristics of silica waveguides mean that FIB milling takes a long time and makes the mirror surface rough. Therefore, the most important technical aspect when fabricating FIB mirrors on silica-based PLCs is finding a process for milling silica at high speed while simultaneously obtaining a smooth mirror surface.

In this Letter, we propose a two-step milling technique for fabricating an FIB mirror on a silica waveguide. For the first step, an angled slit is milled with a high ion-current in combination with a gas, which enhances the silica-milling rate. In the second step, the mirror surface is cleaned quickly without gas enhancement and a smooth surface is realised. By using this method, we can obtain low-loss FIB mirrors on silica-based PLCs.

Structure and fabrication of FIB mirrors: Fig. 1 schematically shows the cross-section of the mirror structure. The channel waveguides were formed on a Triplex^{TM} waveguide platform [5], and have a pure silica core covered with a thin silicon nitride film (100 nm) and a core size of 1.1 × 1.1 μm^2. The undercladding and overcladding were both 6 μm-thick (a total thickness of 12 μm). The structure of the Triplex^{TM} waveguide is reported in detail elsewhere [5]. In this structure, to avoid back reflection from devices integrated on the PLC, the incident angle to the mirror surface was designed to be 50°, which is larger than the critical angle between the silica glass and air. Under this condition, light turned at the mirror propagates at an angle inclined at 10° from the vertical axis. The proposed mirror was fabricated as follows. First, a 100 nm-thick gold film was deposited on the overcladding to avoid charging during alignment. Then a 15 μm-wide and 10 μm-deep slit was formed by FIB milling with a high current (7 nA, 30 keV) using a gallium ion beam (rough milling step). The milling angle of this step was set at 34° from the horizontal plane. We supplied trifluoroacetamide ($C_2H_2F_3NO$) gas from the gas injection-needle which was placed 1 mm from the sample during this step to increase the etching rate of the silica cladding layer. The chamber pressure was 0.17 Pa. This gas enabled us to achieve high-speed milling of the silica glass layer (the milling time (5 min) was about five times shorter than that without the gas (27 min)). At that stage, the mirror surface roughness was considerable owing to the re-deposition of milled material. Then the mirror surface in the slit was milled by FIB milling with lower current (3 nA, 30 keV) without the gas (polishing step) at an angle of 39° (−1° from the designed angle) for 1 min. The gold layer was then removed.

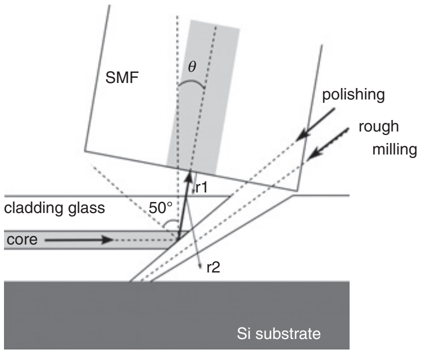

Fig. 1 *Cross-section schematic of proposed mirror structure*

The photograph in Fig. 2*a* shows a top optical microscope image of the mirror after the gold layer had been removed. An air slit is formed perpendicular to the waveguides running along the A to A′ direction. In this photograph, the surface of the mirror shows up in black, since the light from the mirror does not return to the microscope. Fig. 2*b* shows a scanning electron microscope image of the cross-section along A–A′ in Fig. 2*a* after the polishing step. Note that the scales are different in the vertical and horizontal directions. This is because this image was taken at 38° from the horizontal plane. An angle ruler showing 40° can also be seen in this image. A platinum layer deposited to make the cross-section and resist and gold layers can be seen at the top surface. This picture confirms that an angled air slit with a depth of over 12 μm is successfully formed. Although some platinum is also deposited inside the slit, we can clearly recognise the mirror surface at the edge of the core layer. The tilted angle is almost 40° and agrees well with the designed value.

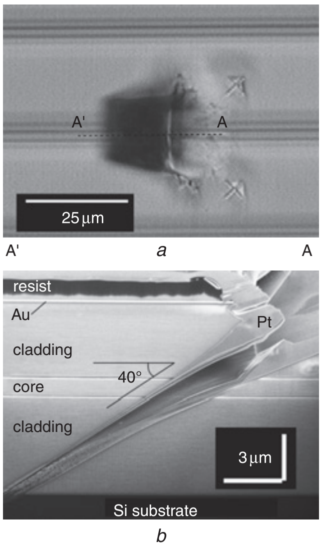

Fig. 2 *Optical microscope image and cross-section*

a Optical microscope image
b Cross-section SEM image

Experimental results: Fig. 3 shows the measured insertion losses against the angle of the detecting fibre (θ) at a wavelength of 1550.0 nm. We used singlemode fibres (SMFs) as the input/output. For comparison, also the losses of a mirror fabricated without the polishing step are shown (the slit angle was optimised). The insertion loss was determined as follows. First, to estimate the coupling loss between the fibres and a waveguide, the insertion loss of a reference waveguide was measured with the input/output fibres aligned horizontally. Then, to measure the excess loss of the mirror, light turned by the mirror was picked up with an output fibre kept at an angle as shown in Fig. 1. After that, the insertion loss of the waveguide including the excess loss of the mirror was measured for different θ values. For each θ value, the output fibre was actively aligned in the xyz directions. The insertion loss of the reference waveguide was about 12.6 dB. The loss was caused by the mode field mismatch between the waveguide and the SMF. This means that the coupling loss between the SMF fibre and the waveguide is 6.3 dB/facet. This value is not very small, but is not relevant for evaluating the mirror quality. The minimum insertion loss for mirrors without the polishing step was greater than 24 dB. The large excess loss ($>$12 dB) originates from the mirror surface roughness caused by the re-deposition of milled material. In contrast, the minimum insertion loss for mirrors obtained with the polishing step is only 13.6 dB, which means that the mirrors have an excess loss of only 1.0 dB. Moreover, Fig. 3 shows that the coupling angle exhibiting the minimum loss agrees well with our designed value of 10°, and proves that we can successfully control the milling angle with FIB. The mirror excess loss of 1.0 dB includes reflection losses at the interfaces between the cladding-surface/air (r1 in Fig. 1) and between the air/fibre facets (r2). These are calculated to be about 0.3 dB. Thus, the actual loss of the mirror surface itself is less than 1.0 dB.

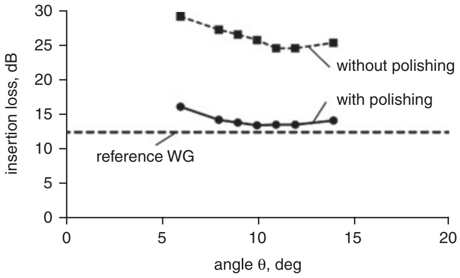

Fig. 3 *Detecting fibre-angle (θ) dependence of measured insertion losses*

Conclusions: An efficient total reflection mirror on a silica-based PLC fabricated by direct milling with a focused ion beam is demonstrated. To reduce the excess losses of the mirror caused by high-speed milling, we employed a two-step milling technique, which consists of using a trifluoroacetamide gas for high-speed milling followed by cleaning with a low current. By adopting this method, we were able to fabricate low-loss mirrors using a focused ion beam with excess losses of only 1.0 dB at the designed angle, which was 10° from the normal direction.

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References

1 Kouta, H., *et al.*: 'WDM power-level monitor with micro pyramid mirrors formed in arrayed optical waveguide'. Electronic Components and Technology Conf., 2003, pp. 801–804
2 Terui, H., *et al.*: 'Novel micromirror for vertical optical path conversion formed in silica-based PLC using wettability control of resin', *J. Lightwave Technol.*, 1998, **16**, pp. 1631–1639
3 Bazylenko, M.V., *et al.*: 'Fabrication of light-turning mirrors in buried-channel silica waveguides for monolithic and hybrid integration', *J. Lightwave Technol.*, 1997, **15**, pp. 148–153
4 Lee, H.P., *et al.*: '1.57 μm InGaAsP/lnP surface emitting lasers by angled focus ion beam', *Electron. Lett.*, 1992, **28**, (6), pp. 580–581
5 Heideman, R.G., *et al.*: 'Low loss, high contrast optical waveguides based on CMOS compatible LPCVD processing'. Proc. 13th ECIO, Copenhagen, Denmark, 2007, p. 6