Optical performance investigation of focused ion beam nanostructured integrated Fabry-Perot microcavities in Al₂O₃

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Focused ion beam (FIB) milling is an emerging technology that enables fast, reliable and well-controlled nanometer-size feature definition. Since the method involves physical removal of material by a beam of ions, the technique can be adapted and optimized almost for any material system.

Recently we have reported on an optimized approach of FIB nano-structuring, which enabled patterning of DBR gratings on Al₂O₃ channel waveguides with smooth and uniform sidewalls [1]. Here we address the optical performance and limits of FIB-patterned integrated waveguide Fabry-Perot (F-P) microcavities. The 520-nm-period surface-relief DBR gratings on dielectric channel waveguides, see Fig. 1(a), were realized using a FEI Nova 600 dual-beam FIB machine. The acceleration voltage was set to 30 kV and the milling current was chosen to be 48 pA. The grating structures were milled by about 200 nm and the length of each grating was ~47.5 μm. The cavity length was varied between 100-450 μm.

Measured F-P resonances in the 1540-1577-nm wavelength range are plotted in Fig. 1 (b) (black dashed line). Using the values of finesse \( F \) and cavity length \( L_c \) obtained through a fit to the experimental data [2], for a given index \( n_C \) and the relation \( F = \left( \frac{\pi}{L_c} \right) \left( \frac{1-e^{-\alpha_l L_c}}{\alpha_l} \right) \) the total effective overall distributed-loss coefficient \( \alpha_l \) was obtained. The resulting resonator loss was found to be 6.9 dB with corresponding DBR reflectivity of 10% and finesse of 1.05. The value for the reflectivity is the minimum or lower bound for the DBR reflectance, as the total losses include also the scattering, out-of-plane losses and the losses arising due to Ga⁺ ion implantation during the FIB milling process. The most detrimental factor in reducing the overall reflectivity is likely to be the implantation of Ga⁺ ions. In order to test this hypothesis we annealed the sample at 600 °C for 17 hrs in N₂ atmosphere. Both experimental and calculated transmission spectra of the annealed F-P cavity for the previously analyzed sample are plotted in Fig. 1 (b). An analysis of the F-P resonances shows that the FSR of the cavity has increased from 3.92 nm to 7.53 nm after annealing. This is consistent with the fact that increase in reflectivity would reduce the penetration depth of the mode into the DBR grating region and reduce the effective cavity length and thereby result in increase of the FSR [3]. The finesse of the resonator has increased 3-fold from 1.05 for the as-milled cavity to 3.1 after annealing. The resonator losses were reduced from 6.9 dB down to about 2.8 dB. The reflectivity of the DBR gratings increased to 40%, which is the lower bound for the DBR reflectance.

Although annealing has reduced the losses significantly, currently alternative methods for further reduction or elimination of FIB-induced losses are being investigated. With the improved performance these resonator structures are envisaged to be used as cavities for on-chip waveguide lasers in rare-earth-ion-doped Al₂O₃.

References