High-Quality Monolithic Distributed Bragg Reflector Cavities and Lasers in Alumina Channel Waveguides

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The design, fabrication, and characterization of surface relief Bragg gratings integrated with aluminum oxide ridge waveguides are reported. The grating lengths varied between 1.25 mm and 4.75 mm and were used to create various distributed Bragg reflector (DBR) cavities. The measured grating induced loss was 0.08 ± 0.01 dB/cm, while the maximum grating reflectivity exceeded 99%. DBR cavities with a finesse up to 147 and quality factors of more than 1.0 × 10^6 were demonstrated. The grating technology enabled the demonstration of the first DBR laser in this waveguide platform with a pump-power-limited output power of 47 mW and a slope efficiency of 67%.

Introduction

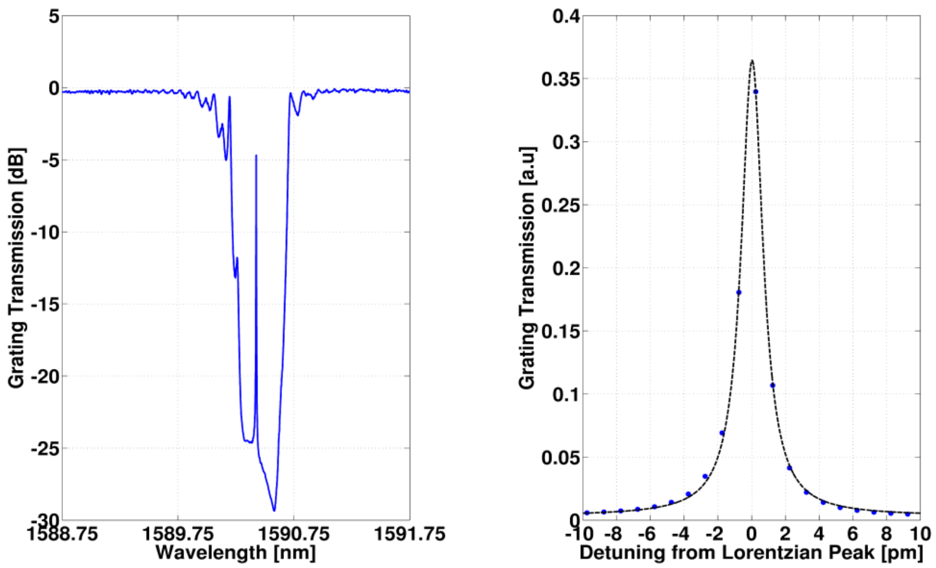
The ability to integrate Bragg grating structures with optical waveguides provides the opportunity to realize a variety of compact monolithic optical devices such as distributed feedback (DFB) lasers [1] and distributed Bragg reflector (DBR) lasers [2], which are widely used in telecommunication systems and integrated optical sensors.
Due to its favourable optical properties, making it an excellent host for rare-earth ions, and its compatibility with existing silicon waveguide technology, amorphous aluminum oxide (Al_2O_3) has been recognized as a very promising waveguide platform to realize a variety of integrated optical structures. Its relatively high refractive index of 1.65 and the resulting high refractive-index contrast between waveguide and cladding allow for the fabrication of compact integrated optical structures and small waveguide cross sections. It is possible to deposit Al_2O_3 on a number of substrates, including thermally oxidized silicon wafers, which permits integration with the existing silicon-on-insulator waveguide platform [3].
In this work we describe the fabrication and characterization of holographically written integrated Bragg gratings and passive DBR cavities in Al_2O_3 ridge waveguides. As an application of this grating technology, we have demonstrated the first DBR laser in the Al_2O_3 waveguide platform.

Fabrication

Al_2O_3 ridge channel waveguides were fabricated in a 1-μm-thick Al_2O_3 layer which was deposited onto a standard thermally oxidized silicon 4-inch wafer [4]. The waveguides supported single-transverse-mode operation and were 1 cm long, 2.5 mm wide, and etched to a depth of ~0.1 μm via a chlorine reactive ion etching process [5]. A 670-nm-thick plasma enhanced chemical vapor deposition (PECVD) SiO_2 cladding layer was deposited on top of the passive ridge waveguides. The surface-relief Bragg gratings were fabricated on the top surface of the PECVD SiO_2 cladding by means of laser interference lithography (LIL). A grating pattern was defined in a 120-nm-thick negative resist layer on top of the PECVD cladding and was etched into the SiO_2 layer using a CHF_3:O_2 reactive ion plasma. The resultant Bragg gratings had an etch depth of ~100 nm with a period of 507 nm for the passive DBR cavities which operated at the Bragg wavelength of ~1590 nm. In the case of the DBR laser the Al_2O_3 waveguide layer was doped with ytterbium with a concentration of approximately 5.8×10^{20} cm^{-3}, while the cladding thickness was 340 nm and the grating period was 316 nm. By choosing such a shallow-ridge waveguide geometry, it is possible to fabricate the grating in the cladding layer without the need to planarize the surface before the grating is written.

Passive Distributed Bragg Reflector Cavities

Various DBR cavities were fabricated in order to investigate their grating reflectivity, finesse and Q-factor. The length of the Bragg gratings on either side of the DBR cavities was varied from 1.25 mm to 4.75 mm, such that the total physical cavity length was 10 mm in all cases. By doing a systematic study of the finesse of each DBR cavity [6], the grating loss and reflectivity was determined. The maximum measured reflectivity exceeds 99% and was measured for the DBR cavity with the 4.75-mm-long Bragg gratings, while the total waveguide propagation loss was measured to be 0.14 ± 0.07 dB/cm with a grating induced loss of 0.08 ± 0.01 dB/cm. The TE-polarized transmission spectrum for this cavity is shown in Fig. 1(a). The maximum measured finesse for this cavity exceeds 147. The measured Q-factors varied between $6.4 \pm 0.02 \times 10^4$ for the DBR cavity with the 1.25-mm-long Bragg gratings to $1.02 \pm 0.01 \times 10^6$ for the cavity with the 4.75-mm-long Bragg gratings. The highest Q-factor of $1.02 \pm 0.01 \times 10^6$ corresponds to a Lorentzian linewidth of 1.56 pm (Fig. 1(b)).



(a) (b)

Fig. 1 (a) Measured TE transmission spectrum for the DBR cavity with 4.75-mm-long Bragg reflectors. (b) Enlargement of the single Fabry–Perot transmission peak in (a), where the blue dots are the measured data points, while the dashed line is a Lorentzian fit to the data. This peak represents the highest measured Q-factor of $1.02 \pm 0.01 \times 10^6$, which corresponds to a linewidth of 1.56 pm.

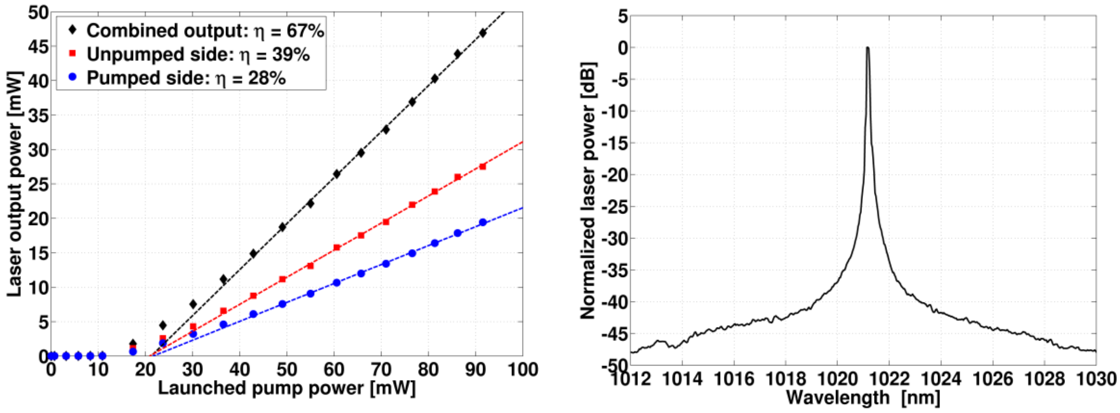
Ytterbium-doped Distributed Bragg Reflector Laser

The realized DBR cavity consisted of two integrated Bragg reflectors with a length of 3.75 mm on either side of a 2.5 mm long, grating-free waveguide region, to form a total DBR cavity length of 1 cm. Each of the Bragg reflectors was designed to have a grating strength of 6 cm^{-1}, which yields a grating reflectivity of 96%. Although the interaction between the guided laser mode and the grating region is very weak per unit length (~0.1% transversal overlap), the Bragg reflectors are sufficiently long to accumulate this high reflectivity.

The measured power characteristics of the laser is shown in Fig. 2(a). The DBR laser oscillation commenced at 10 mW launched pump power. This low threshold is a direct consequence of the high pump intensity which is achieved due to the tight light confinement in the Al_2O_3 waveguides. The laser delivered a maximum bidirectional output power of 47 mW at 92 mW of launched pump power, resulting in a slope efficiency of 67% with respect to launched pump power. No saturation of the output power was observed, and further scaling of the laser output power was limited only by the maximum available pump power. Since the DBR cavity was fabricated to be symmetric, one would expect nearly equal powers emanating from each side of the cavity. However, the laser power measured on the unpumped side of the cavity was 1.4 times higher than that measured on the pumped side. This is likely caused by a slightly higher outcoupling of the Bragg reflector on the unpumped side of the cavity and is consistent with a reflectivity difference of ~2% between the two respective ends of the cavity.

The measured laser emission spectrum at the maximum output power is shown in Fig. 2(b). The laser operated at a wavelength of 1021.2 nm with a measured linewidth which was limited by the 0.1 nm resolution of the optical spectrum analyzer.

Characterization of passive Bragg gratings in undoped Al_2O_3 with a similar geometry showed that the measured grating strength for the TM mode is approximately 60% lower than that of the TE mode, which results in a reflectivity of less than 50% for the TM polarization. With such a high outcoupling it is not possible to reach threshold, which led us to conclude that the laser was operating TE-polarized at all times.



(a) (b)

Fig. 2. (a) Measured power characteristics of the Al_2O_3:Yb^{3+} DBR waveguide laser. (b) Measured laser emission spectrum at the maximum output power.

Summary

We have reported the fabrication and characterization of holographically written integrated Bragg gratings and DBR cavities in Al_2O_3 ridge waveguides. Due to the low total waveguide propagation losses of 0.14 ± 0.07 dB/cm and grating induced losses of 0.08 ± 0.01 dB/cm, it was possible to realize Bragg gratings with reflectivities exceeding 99%. This enabled the demonstration of passive DBR cavities with a finesse of more than 147 and a Q-factor as high as $1.02 \pm 0.01 \times 10^6$. This is, to our knowledge, the highest demonstrated Q-factor of any passive monolithic DBR cavity on a silicon chip. The ability to integrate Bragg grating structures with optical waveguides also provided the opportunity to demonstrate an efficient, low threshold, monolithic Al_2O_3:Yb^{3+} DBR waveguide laser operating at 1021.2 nm. The laser exhibited a pump-power-limited output power of 47 mW and a slope efficiency of 67%.

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