High-Quality, Distributed Phase-Shift, Distributed Feedback Cavities in Al₂O₃ Waveguides

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Abstract: Distributed phase-shift holographically-written surface relief Bragg gratings have been integrated with Al₂O₃ waveguides via reactive ion etching of SiO₂ overlay films. The realized optical cavities are highly reflective and demonstrate Q-values as high as 125000.

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1. Introduction

Due to its favorable optical properties and compatibility with existing silicon waveguide technology, erbium-doped aluminum oxide (Al₂O₃:Er³⁺) has been recognized as a very promising gain material to realize a variety of integrated optical structures [1,2]. The ability to incorporate low-loss, highly reflective Bragg gratings with these optical structures would provide a higher degree of monolithic integration and enable the realization of specialized devices such as optical sensors, wavelength filters, wavelength multiplexers and distributed Bragg reflector (DBR) lasers. The addition of a $\pi/2$ phase-shift to an optical cavity which is formed by the Bragg grating opens up a narrow transmission window inside the stop band of the Bragg grating, which extends the versatility of such gratings to enable the realization of single-longitudinal-mode distributed feedback (DFB) lasers.

In this work we report on the fabrication and characterization of high-quality distributed phase-shift DFB optical cavities in Al₂O₃ ridge waveguides. The cavities are formed by surface-relief Bragg gratings which were defined by means of laser interference lithography (LIL) and written in plasma enhanced chemical vapor deposited (PECVD) SiO₂ overlay films via reactive ion etching (RIE). A distributed $\pi/2$ phase-shift is integrated to each cavity via a localized adiabatic widening of the waveguide [3,4].

2. Grating fabrication

Ridge waveguides were fabricated in 1- μ m-thick Al₂O₃ layers which were deposited onto standard thermally oxidized silicon wafers [5]. The ridge waveguides were 1 cm long, 3 μ m wide and were etched 0.1 μ m deep via a reactive ion etching process [6]. A 650-nm-thick PECVD SiO₂ cladding layer was deposited on top of the ridge waveguides. The waveguide geometry was designed to support only single transverse-mode operation in the 980 nm to 1550 nm wavelength range, which makes it particularly suitable for the realization of erbium-doped lasers.

The 1-cm-long Bragg grating structure was defined in a 120-nm-thick negative resist layer on top of the SiO₂ by means of laser interference lithography (LIL). The grating pattern was then etched into the SiO₂ layer by using a CHF₃:O₂ reactive ion plasma, after which the residual resist was removed by an O₂ plasma. The resultant Bragg gratings had an etch depth of ~100 nm with a period of 488 nm and a duty cycle of ~ 50%. Figure 1a. shows a cross-sectional representation of the waveguide layer structure, while Fig. 2a. shows a scanning electron microscope (SEM) image of a top-view of the Bragg gratings.

A localized adiabatic sinusoidal tapering of the waveguide width in the center region of each cavity was used to realize the $\pi/2$ phase-shift (Fig. 1b.). The taper extends over 20% of the total cavity length. To manufacture the phase-shift in this manner does not require any additional fabrication steps since the phase-shift is defined during the same photolithography step in which the waveguides are defined. Inside the phase-shift region, the waveguide width was increased adiabatically from 3.0 μ m to a maximum of 3.4 μ m.

3. Grating characterization

The transmission characteristics of the phase-shift DFB cavities were measured by launching either TE or TM polarized light from a tunable laser into the waveguides via a butt-coupled polarization maintaining (PM) fiber and then collecting the transmitted light from the opposite side of the cavity with an ultra-high numerical aperture fiber which was connected to a power meter. A typical TE transmission spectrum of one of the cavities is shown in Fig. 2b. The gratings exhibit a narrow stop band with a width of ~0.75 nm at a wavelength of 1540.5 nm.

Fig. 1. (a) Representation of the cross-sectional layer structure. (b) Top-view depiction of the implementation of the distributed phase-shift.

Fig. 2. (a) Scanning electron microscope image of a top-view of the Bragg gratings. (b) The normalized TE transmission spectrum of a 1-cm-long distributed phase-shift DFB cavity.

A single transmission peak with a width (FWHM) of ~ 12 pm is observed inside the stop band of the grating due to the $\pi/2$ phase-shift. It indicates that the cavity has a Q-value of 125000 at this particular wavelength. These high-quality DFB cavities were implemented in $\text{Al}_2\text{O}_3:\text{Er}^{3+}$ to successfully demonstrate the first DFB laser in this material. The laser has a low pump power threshold of 15 mW, a slope efficiency of more than 30% versus absorbed pump power and a single-mode linewidth below 15 kHz. These laser performance data along with the wide gain bandwidth of $\text{Al}_2\text{O}_3:\text{Er}^{3+}$ across the entire telecommunication C-band (1530-1565 nm) make $\text{Al}_2\text{O}_3:\text{Er}^{3+}$ DFB lasers very attractive for dense wavelength division multiplexing (DWDM) purposes.

4. Conclusions

High-quality distributed phase-shift DFB optical cavities were successfully fabricated in Al_2O_3 waveguides by etching Bragg gratings into SiO_2 overlay films. The transmission characteristics of the cavities revealed high Q-values of up to 125000. This performance illustrates their low loss and applicability for the realization of resonator structures in monolithic optical sensors and rare-earth-ion-doped Al_2O_3 waveguide lasers.

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5. References

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