Designing an integrated $Al_2O_3:Er^{3+}$ distributed feedback laser

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In this paper the design and modelling of an integrated $Al_2O_3:Er^{3+}$ distributed feedback laser (DFB) is presented. The implemented laser model combines rate equations of the population mechanisms in the erbium ion with coupled-mode theory. The model enables the estimation of the optimum Bragg grating design that is required in order to realise such a DFB laser device. Based on the modelling results, the ideal grating geometry has been identified and fabricated by making use of laser interference lithography (LIL) and reactive ion etching (RIE). Optical characterisation experiments of the gratings are currently in progress.

Introduction

The implementation of dense wavelength division multiplexing (DWDM) in telecommunication networks has spurred the development of stable single-frequency light sources. Rare-earth-ion-doped distributed feedback (DFB) dielectric lasers are of particular interest for this purpose due to their stable, single-mode, single-polarization, narrow-linewidth and low-noise emission [1, 2]. Erbium-doped aluminium oxide ($Al_2O_3:Er^{3+}$) has been identified as an excellent laser gain medium due to its good optical properties, which include low background losses and compatibility with silicon substrates. Internal optical gain over 80 nm, including the telecom C-band (1525-1565 nm), peak gain as high as 2.0 dB/cm, and compatibility with silicon substrates further highlight $Al_2O_3:Er^{3+}$ as a favourable gain medium for telecommunication optical networks [3]. In order to efficiently realise a DFB laser device, an accurate mathematical description of the laser is advantageous, since it can significantly reduce the development time and cost. In this work such a mathematical model of a distributed feedback $Al_2O_3:Er^{3+}$ is used to predict its performance, operation dynamics, and optimum design parameters. Gratings in channel waveguides have been fabricated according to the results of this model and their characterization is currently in progress.

Theory

In a DFB laser resonator the feedback of the laser radiation back into the cavity is achieved with periodic structures such as Bragg gratings which are distributed over the entire resonator. Coupled-mode theory can be used to model the interaction between the counter-propagating guided modes and the grating in an amplifying medium [4-5]. The amplitudes of the counter-propagating laser modes in the cavity are expressed by [6]

$$\frac{dA^{+}(z)}{dz} = -i\kappa A^{-}(z)e^{i2(d\beta z)} + \frac{g(z)A^{+}(z)}{2} \tag{1}$$

$$\frac{dA^-(z)}{dz} = i\kappa A^+(z)e^{i2(-d\beta z)} - \frac{g(z)A^-(z)}{2}, \qquad (2)$$

where A^+ and A^- are the z-dependent complex amplitudes of the laser modes traveling to the right and left, respectively. The Bragg wavelength of a first-order grating is given by $\lambda_B = 2n_{eff}\Lambda$, where Λ is the period of the grating and n_{eff} *is* the effective index of the laser mode. The detuning from the Bragg wavelength is given by $d\beta = \beta - \beta_0$ with $\beta = 2\pi n_{eff}/\lambda$ and $\beta_0 = \pi/\Lambda$. The grating strength is given by κ which is known as the coupling coefficient and can be calculated by performing an overlap integral between the guided mode and the grating region. By making use of erbium rate equations the population densities in the upper laser level (N_1) and lower laser level (N_0) can be determined in order to evaluate the modal gain

$$g(z) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \phi_L(x,y,z)(\sigma_l^{em} N_1(x,y,z) - \sigma_l^{abs} N_0(x,y,z) - \delta_L)dxdy, \qquad (3)$$

where δ_L is the intrinsic loss (at the laser wavelength) of the waveguide, σ_l^{abs} and σ_l^{em} denote the absorption and emission cross-sections of the laser wavelength, respectively, and $\phi_L(x,y,z)$ is a normalized laser light intensity distribution of the guided laser mode.

A traditional DFB laser is fabricated with a uniform Bragg grating with constant period and amplitude. This kind of DFB laser will oscillate at two longitudinal modes simultaneously, with the wavelengths of these two modes corresponding to the first transmission maxima on either side of the reflection gap. The laser will have symmetric output powers at both ends of the cavity, with the power equally divided between the two modes [4]. In order to produce a single-wavelength DFB laser, a π-phase-shift has to be introduced in the spatial phase of the grating. This π-phase-shifted DFB laser provides bi-directional single-wavelength (single-longitudinal-mode) emission, which coincides with the Bragg wavelength.

In order to solve the complex modal amplitudes and gain along the propagation direction, the abovementioned system of differential equations is solved with standard numerical integration techniques such as Euler or Runge–Kutta methods. The DFB laser model implementation was done in Matlab. Parameters that were investigated and optimized include the laser wavelength, erbium doping concentration, as well as the waveguide and grating geometry.

As an example of the optimization possibilities, Fig. 1 shows the optimum grating strength and position of the π-phase-shift in order to maximize the laser output power at the unpumped end of a 20-mm-long erbium-doped DFB cavity. The optimum grating strength is estimated to be 250 m^{-1}, which implies a Bragg-grating with a refractive index modulation of ~2.5×10^{-4}. It also follows that the best position to place the π-phase-shift is around 12 mm (where z = 0 mm is the pumped end of the cavity).

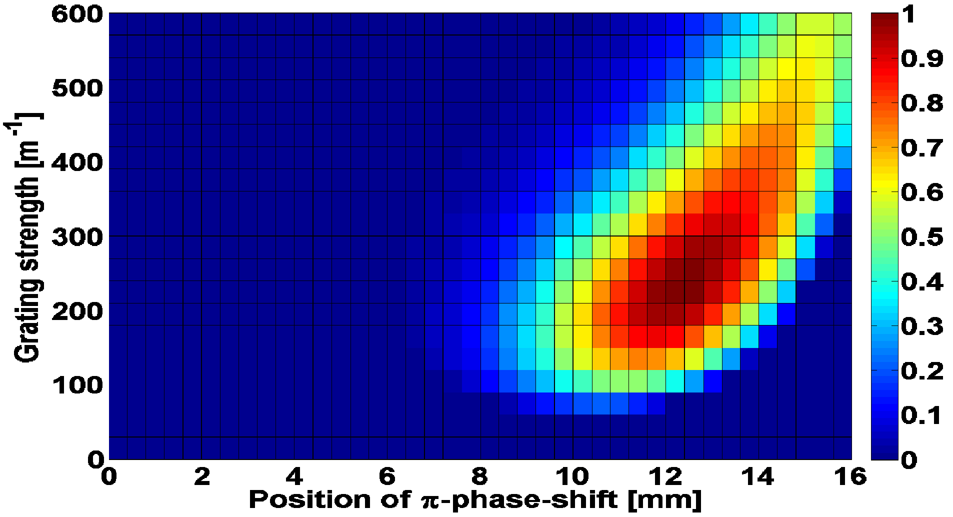


Figure 1: Normalised laser output power as a function of grating strength and phase-shift position

Fabrication

$Al_2O_3:Er^{3+}$ layers with a thickness of 1 μm were deposited onto thermally oxidised Si wafers [7]. Ridge waveguides with an etch depth of 100 nm and a width of 3 μm were etched into the layers via reactive ion etching (RIE) [8]. Plasma enhanced chemical vapour deposition (PECVD) was then used to deposit a 700-nm-thick SiO_2 cladding layer on top of the waveguides. By making use of laser interference lithography (LIL) the grating pattern was defined in a negative resist layer on top of the SiO_2. The grating pattern was then transferred into the SiO_2 layer by means of a $CHF_3:O_2$ reactive ion plasma. To achieve the required low refractive index modulation, the gratings were fabricated in the cladding rather than in the waveguide itself. The resultant gratings have an etch depth of ~100 nm with a period of 490 nm and a duty cycle of ~ 50%. Figures 2 and 3 show scanning electron microscope (SEM) and atomic force microscope (AFM) images of the Bragg gratings that were realised in the SiO_2 cladding layer.

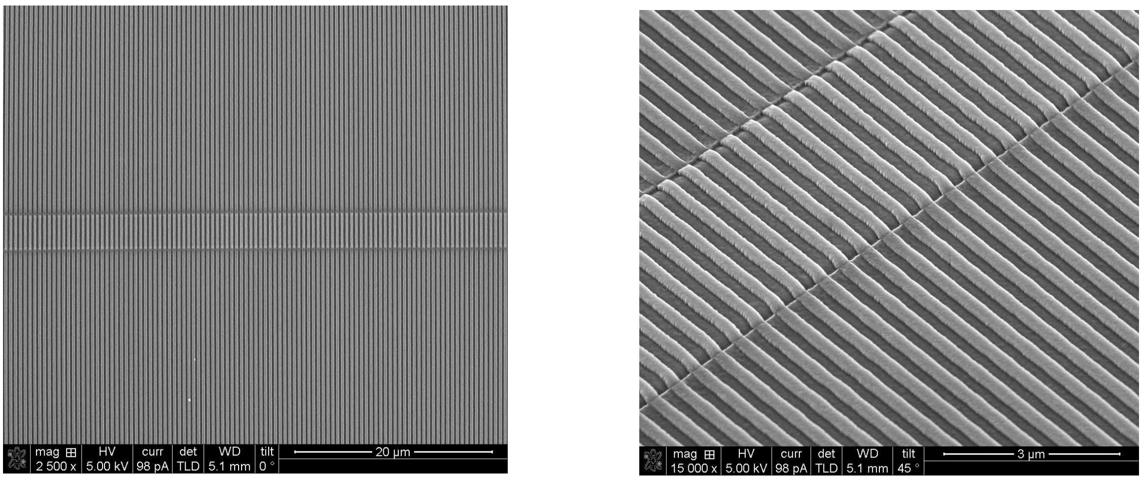
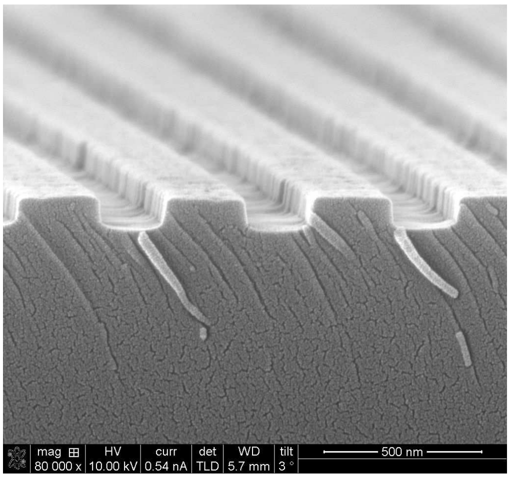
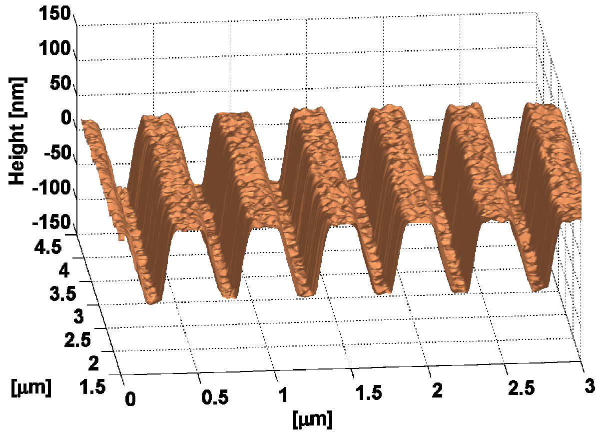


Figure 2: SEM images of the Bragg gratings in the SiO_2 cladding on top of an $Al_2O_3:Er^{3+}$ waveguide



(a)



(b)

Figure 3: (a) SEM cross-sectional image of a Bragg grating in the SiO_2 cladding;
(b) AFM profile of a Bragg grating

Conclusion

By making use of laser rate equations and coupled-mode theory, a mathematical description of a DFB $Al_2O_3:Er^{3+}$ waveguide laser was implemented and used to estimate the optimum laser fabrication parameters. The development and implementation of the model completes a crucial step towards the successful fabrication of a stable, single-mode, narrow-linewidth $Al_2O_3:Er^{3+}$ ridge waveguide laser. An ideal grating geometry has been identified and fabricated by means of laser interference lithography and reactive ion etching. Optical characterisation experiments to determine the losses and reflection features of these gratings are currently in progress.

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