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Temperature Dependence of Spectral Characteristics of Distributed-Feedback Resonators

C. C. Kores^a, N. Ismail^a, D. Geskus^a, M. Dijkstra^b, E. H. Bernhardt^{a,c}, M. Pollnau^{*a,d}

^aDepartment of Materials and Nano Physics, KTH–Royal Institute of Technology, 16440 Kista, Sweden; ^bOptical Sciences, MESA+ Institute, University of Twente, 7500 AE Enschede, The Netherlands; ^cVisiting scientist; ^dAdvanced Technology Institute, University of Surrey, Guildford GU2 7XH, United Kingdom

ABSTRACT

The spectral response of a distributed-feedback resonator with a thermal chirp is investigated. An Al₂O₃ channel waveguide with a surface Bragg grating inscribed into its SiO₂ top cladding is studied. A linear temperature gradient along the resonator leads to a corresponding variation of the grating period. We characterize its spectral response with respect to wavelength and linewidth changes of the resonance peak. Simulated results show good agreement with the experimental data, indicating that the resonance wavelength is determined by the total accumulated phase shift. The calculated grating reflectivities at the resonance wavelength largely explain the observed changes of the resonance linewidth. This agreement demonstrates that the linewidth increase is caused by the increase of resonator outcoupling losses.

Keywords: Distributed-feedback laser; Bragg grating; Thermal grating chirp; Resonance wavelength; Resonance linewidth

1. INTRODUCTION

Periodic corrugated structures have been extensively investigated over the past four decades, for their significant and wide range of applications, being employed as spectral filters [1,2], temperature and strain sensors [3], couplers [4], beam splitters, as well as part of the resonant structure in distributed-feedback (DFB) [5] and distributed-Bragg-reflector (DBR) lasers, which can be employed for microwave beat-signal generation [6] and optical sensing [7,8]. DFB and DBR lasers relies on the fact that the Bragg grating provides very high wavelength selectivity [9], hence allowing for the development of ultranarrow-linewidth lasers [10–15]. The grating period has a strong influence on the longitudinal-mode selectivity [16–18]. Gratings with non-uniform period (chirped gratings) have received much interest [19–21], and substantial attention has been paid to the design of chirped gratings that manipulate the intracavity power distribution and avoid spatial hole burning in DFB lasers [22–24].

Rare-earth-doped amplifiers [25–30] and lasers [31–33] in amorphous materials can be integrated on a silicon chip [34] and combined with other materials, such as silicon-on-insulator [35] or polymer [36] waveguides. Although the gain per unit length can be significantly higher in crystalline materials, up to 1000 dB/cm [37], whereas amorphous materials suffer from inhomogeneous linewidth broadening and quenching processes [38,39], overcoming the losses is sufficient to achieve efficient lasing [40]. However, despite careful design of DFB resonators for ultranarrow-linewidth laser operation, optically pumped DFB lasers [41] exhibit asymmetric heating due to non-uniformly absorbed pump power, which is partially converted into heat and may, therefore, cause an undesired chirp in the Bragg structure [42]. The resulting changes in refractive index as well as material expansion influence the resonance frequency and linewidth of the central emission line. Thermally induced chirped gratings are reported in the literature under the scope of power stability and spectral response [43–49], however, to the best of our knowledge, a complete and satisfactory explanation of the relationship between the chirped grating profile and the linewidth produced by the resonator is still lacking.

We investigate the spectral characteristics of DFB resonators with a thermally induced chirp in their Bragg grating [42]. A temperature gradient with an approximately linear profile is experimentally produced along the waveguide resonator, and the wavelength of the resonance peak and its linewidth are characterized. The experimental results show good agreement with simulations based on Born and Wolf's [50] characteristic-matrix approach.

*m.pollnau@surrey.ac.uk

2. EXPERIMENTAL

The sample investigated in this work is an amorphous $\text{Al}_2\text{O}_3:\text{Yb}^{3+}$ rib waveguide with an Yb^{3+} concentration of $4.37 \times 10^{20} \text{ cm}^{-3}$, deposited by RF reactive co-sputtering from metallic Al and Yb targets onto a thermally oxidized silicon wafer [51]. Al_2O_3 can be micro-structured in various ways, e.g. by focused-ion-beam etching [52], Ar^+ milling [53], or reactive ion etching [54]. Here we used chlorine-based reactive ion etching [55]. The rib waveguide has a length of $\ell = 1 \text{ cm}$ and $2.5 \times 1.0 \mu\text{m}^2$ lateral cross section, designed to support only fundamental-transverse-mode propagation. The refractive index of the layer depends on the dopant concentration [56]. A SiO_2 top cladding of 350 nm thickness was added. A corrugated homogeneous Bragg grating, where $\kappa = 8.33 \text{ cm}^{-1}$ is the grating coupling coefficient per unit length [13], is inscribed into the SiO_2 top cladding by laser interference lithography and subsequent reactive ion etching [12,13], providing the necessary feedback for single-longitudinal-mode laser operation at the Bragg wavelength λ_B [57]. The propagation losses are 0.20 dB/cm and the Yb^{3+} absorption losses are 0.33 dB/cm [58], resulting in a sum of propagation and absorption losses of 0.53 dB/cm.

The $\lambda_B/4$ phase shift required for producing a resonance within the reflection band of the Bragg grating is achieved by an adiabatic tapering of the waveguide structure [59,12], in which the waveguide width first increases and then decreases gradually according to a $\sin^2$ function from 2.5 to $2.85 \mu\text{m}$ over a total length of 2 mm. As a consequence, the effective refractive index to which the propagating mode is subject also increases with the same function. The tapered section of the waveguide is designed to result in an accumulated phase shift of $\lambda_B/4$. The phase-shift region is centered at the position $z_{ps} = 7 \text{ mm}$ in order to yield higher output powers in one direction [60,12]. Having introduced the tapering of the waveguide, the resultant modulation of the refractive index is no longer periodic, and therefore the Bragg grating becomes non-periodic.

We generate a temperature gradient by controlling the temperature in the sample holder along the waveguide direction. The temperature on the top surface of the sample holder is measured using a thermocouple sensor, in several positions along the surface where the waveguide is to be placed. The temperature along the waveguide is fitted by a linear function, from which the temperature at the center of the phase shift is estimated.

The approximately Lorentzian-shaped resonance near 1028.25 nm is measured in the unpumped sample, and the peak wavelength and full-width-at-half-maximum (FWHM) linewidth of the resonance are characterized, providing information about the behavior of light inside the optical resonator [61]. As a probe beam, the signal from a scanning narrow-linewidth laser centered at 1028.25 nm is fiber-coupled to the waveguide. The transmitted light is collected by an optical fiber, discriminated from residual room light by a monochromator, and detected by a photomultiplier tube. This setup enabled measurement of the spectral response of the resonator for the temperature profiles produced along the waveguide, which result in thermally induced chirp profiles of the grating period. The FWHM of 40 MHz of the scanning narrow-linewidth laser is considered to de-convolute the measurement and obtain the correct line shape of the resonance, to which a Lorentzian curve is fitted to derive the FWHM linewidth. Although the temperature dependence of transition cross sections in laser systems can be significant [62,63], the absorption losses and the waveguide propagation losses remain approximately constant for the temperature range investigated here.

The experiments are complemented by calculations and simulations [42], see also [5,64–68].

3. RESULTS AND DISCUSSIONS

Although the spectral profiles are symmetric in the frequency domain [69], we choose the wavelength domain for investigation, as the wavelength range over which the analysis is carried out is small enough to result in negligible asymmetry of the spectral profiles. Under uniform heating of the sample, the dependence of wavelength shift of the resonance peak with temperature is approximately linear and amounts to 12.0 pm/K for $\sim 1028 \text{ nm}$, i.e., a relative wavelength shift of $\sim 1.2 \times 10^{-5} \text{ K}^{-1}$, which is in reasonable agreement with the values of $19 \pm 1 \text{ pm/K}$ [13] and 20 pm/K [70] reported for $\sim 1560\text{--}1590 \text{ nm}$, therefore corresponding to the same relative wavelength shift. From the shift of peak wavelength with temperature, we derive a change of refractive index with temperature of $dn/dT = 1.86 \times 10^{-5} \text{ K}^{-1}$. Since part of the shift is due to sample expansion, this value represents an upper limit to the refractive index change with temperature. The value is higher than the corresponding value of $0.83 \times 10^{-5} \text{ K}^{-1}$ in $\text{Y}_3\text{Al}_5\text{O}_{12}$ and the absolute of the two

values of $-0.43 \times 10^{-5} \text{ K}^{-1}$ and $-0.20 \times 10^{-5} \text{ K}^{-1}$ for the *c*- and *a*-axes, respectively, in YLiF₄ (see Ref. [71] and Refs. therein), but smaller than the value of $4.58 \times 10^{-5} \text{ K}^{-1}$ previously reported for amorphous Al₂O₃ [72].

The reflectivity profiles of grating 1 and grating 2 were simulated for the different values of linear chirp coefficient δ_{lin} . We obtain the reflectivity spectra of both gratings and the resulting Lorentzian-shaped resonance from the same simulation, enabling us to place the resonance within the reflection band of the gratings. The transmission spectrum is obtained by considering also the absorption and propagation losses. The resonance wavelength shifts linearly toward larger values for increasing values of δ_{lin} , which is a consequence of the linear increase in the accumulated phase shift. The reflection band changes drastically when the chirped profiles are imposed on the grating. This is a result of the change in the individual spectral responses provided by gratings 1 and 2. The spectral profile of the resonance is obtained experimentally for the temperature profiles produced. Each resonance peak is fitted by a Lorentzian function and both are simultaneously normalized such that the peak value of the Lorentzian function is unity.

The simulation results indicate that the resonance wavelength is mostly a result of the grating-period value at the phase-shift center, whereas the additional wavelength shift resulting from the grating chirp is small. Since the increase in grating period at the phase-shift center is proportional to δ_{lin} , the shift of resonance wavelength is a linear function of δ_{lin} . The measured values of resonance wavelength also exhibit a linear dependence on the estimated temperature at the phase-shift center.

The resonance linewidth is due to the outcoupling, propagation, and absorption losses. Imposing a chirp in the grating period changes the refractive index, the resonator length and, consequently, the round-trip time. All three losses depend on the refractive index. However, the change in refractive index is small, hence its effect is negligible. The propagation and absorption losses are defined per unit length, hence are independent of the resonator length. Moreover, for a temperature increase of a few degrees, they remain approximately constant. Consequently, their influence on the linewidth is also negligible. In contrast, the mirror reflectivities change significantly with a few degrees of temperature change, causing the linewidth to increase. The resonance linewidth changes approximately linearly as a function of grating reflectivities [42].

4. CONCLUSIONS

We have investigated the spectral response of a DFB rib waveguide resonator experimentally and by simulations. For uniform heating of the sample, the FWHM linewidth of the Lorentzian-shaped resonance remained unchanged. When a linear chirp profile was produced in the grating period, the FWHM linewidth increased. The outcoupling, propagation, and absorption losses are the parameters responsible for the FWHM linewidth of the resonance. We have demonstrated that the increase in the outcoupling losses is largely responsible for the increase in the FWHM linewidth of the resonance.

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