Internal fluorescence induced refreshment of thermally fixed photorefractive grating in Ti:Fe:Er:LiNbO$_3$ for stable laser emission

B.K. Das, W. Sohler and V. Dierolf

It is shown that thermally fixed photorefractive gratings fabricated for waveguide lasers in Ti:Fe:Er:LiNbO$_3$ can be refreshed and stabilised by the upconverted green fluorescence from Er^{3+} ions. Spectral properties of such refreshed gratings are found to be superior and are excellent for a single-frequency laser emission.

Introduction: Integrated optical distributed Bragg reflector (DBR) and distributed feedback (DFB) lasers have been realised in Er-doped LiNbO$_3$ making use of thermally fixed photorefractive gratings fabricated either in a Ti:Fe:LiNbO$_3$ or in a Ti:Fe:Er:LiNbO$_3$ waveguide section [1–4]. These lasers are attractive for fibre-optic dense wavelength division multiplexed (DWDM) systems and interferometric instrumentation. To produce a thermally fixed grating, a periodic modulation of the Fe^{2+}/Fe^{3+} concentration that is established through interferometric light illumination, is compensated at elevated temperatures ($T \sim 180°C$) by a H^+ grating that is frozen at room temperatures [5]. Unfortunately, the produced fixed H^+ gratings are compensated over time by electrons through dark conductivity [2, 6] and therefore they require constant surface illumination with blue/green light for stable operation.

To get around this problem, we have investigated the effect of the characteristic green luminescence of Er under IR excitation on thermally fixed photorefractive Bragg gratings in Ti:Fe:Er:LiNbO$_3$ waveguides. We have previously reported that the upconverted green luminescence in a DFB-DBR coupled cavity laser (with a pre-refreshed grating) can stabilise the grating response by countering the electron tunnelling [4]. In this Letter we show that the H^+ grating can be refreshed, stabilised and simultaneously used for single-frequency laser emission ($\lambda_L \sim 1.55$ μm) under the excitation of laser light ($\lambda_p \sim 1.48$ μm). Gratings refreshed this way have superior properties compared those refreshed by homogeneous illumination in terms of spectral response and stability.

Experiment description: For our studies we have used a DFB-laser/amplifier device as shown in Fig. 1. This device is fabricated in the surface of an X-cut LiNbO$_3$ crystal with a Ti-indiffused waveguide aligned parallel to the z-axis. It comprises an 18 mm-long thermally fixed photorefractive grating ($\Lambda \sim 355$ nm, $\lambda_B = 1561.25$ nm, $R = 95\%$, FWHM = 125 pm, when developed conventionally with full strength) in an Fe/Er co-doped section (DFB-laser) and a 32 mm-long section doped by Er only (amplifier). Fabrication of this device has been described in detail elsewhere [3].

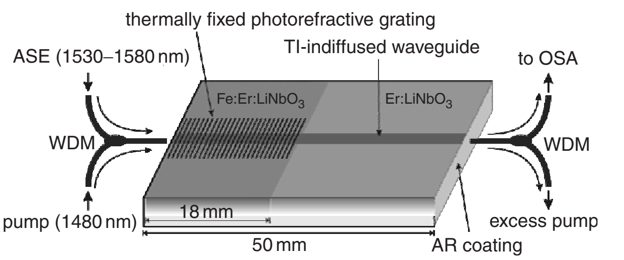

Fig. 1 *Experimental setup for thermally fixed photorefractive grating stabilisation by green luminescence and transmission characteristics measurement*

OSA: optical spectrum analyser; WDM: wavelength division (de-)multiplexer; ASE: amplified spontaneous emission; AR: antireflection

The pump light ($\lambda_P = 1480$ nm, $P = 100$ mW) was launched to the waveguide from the grating side (see Fig. 1). Two fibre-optic wavelength (de-)multiplexers (WDMs) allowed us to couple the amplified spontaneous emission (ASE) from an erbium-doped fibre amplifier (EDFA) and extract transmitted ASE from the device, respectively. The ASE was used as a broadband light source ($\lambda_S = 1530$–1580 nm) for measuring the transmission characteristics of the grating refreshed by the internal green luminescence.

For laser operation experiments, we modified the setup. A broadband dielectric mirror ($R > 90\%$, $\lambda = 1480$–1600 nm) was glued on the right-hand side end-face of the device. This way we have a DFB-DBR coupled cavity laser with a low threshold pump power level [4]. A WDM allowed us again to couple the pump light and extract the laser emission at the grating side.

Results and discussion: Fig. 2 shows the transmission characteristics of gratings ($R > 50\%$) that were refreshed by homogenous blue light illumination and by guided green luminescence created by the guided pump laser light ($P = 100$ mW, $\lambda_P = 1480$ nm). The inset shows the refreshment dynamics due to the green luminescence. It is evident that the grating response (FWHM = 35 pm, $R = 55\%$) refreshed by the guided green luminescence is significantly narrower than that obtained by homogeneous illumination with a blue Ar laser (FWHM = 90 pm, $R = 53\%$), although their peak reflectivities are almost the same. The grating transmission characteristics calculated by the coupled mode theory shows good agreement with the grating response that is refreshed by green luminescence. Although the detail of this improvement is not yet clear, we suspect that the near perfect performance of the grating is related to the strong overlap of the refreshed region and the mode profile of the fundamental mode ($\lambda \sim 1.55$ μm). This will reduce the influence from inhomogeneities across the waveguides compared to uniform refreshed gratings. The inhomogeneities can be due to non-ideal interference patterns used in the grating writing or the Ti^{4+}-concentration and composition dependence of the thermal expansion [7] that will lead at room temperature to a non-uniformity of the grating that are produced at elevated temperature uniformly.

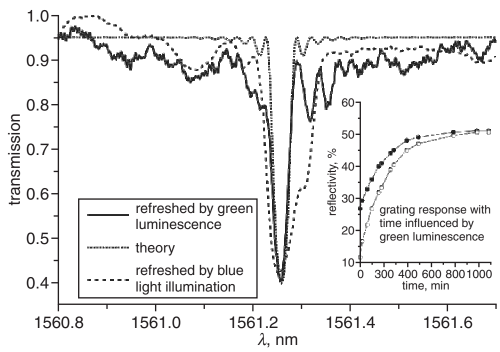

Fig. 2 *Transmission characteristics of 18 mm-long grating in Ti:Fe:Er:LiNbO$_3$ waveguide for TE-polarised light with 10 pm wavelength resolution*

Inset: Grating stabilisation dynamics in presence of green luminescence created by pump laser ($\lambda_P = 1480$ nm, $P = 115$ mW, TE-polarised) for two different initial conditions

We further observed improved stability for the gratings that have been refreshed just within the waveguide region by the green luminescence or by 488 nm laser light that is coupled into the waveguide. The reason may be inferred by the different effective dark conductivity of the electrons in the grating region. After the grating refreshment, the concentrations of Fe^{2+} and Fe^{3+} are redistributed and it is known that the dark conductivity of the electrons depends on the ratio $\gamma = c_{Fe^{2+}}/c_{Fe^{3+}}$ [8]. For uniform illumination, the value of γ is constant in the guiding region and its surroundings when the grating is refreshed, whereas γ is higher in the guiding region compared to its surroundings when the grating is refreshed just within the waveguide. In other words, the waveguide region is depleted of trapped carriers reducing the dark conductivity and hence the stability of the thermally fixed H^+ grating.

To test if the self-refreshment and stabilisation of the photorefractive grating persists under laser conditions, we studied an integrated laser device with a DFB-DBR coupled cavity configuration [4]. For this we launched the pump laser light ($P = 115$ mW, $\lambda_P = 1480$ nm) when the ion grating was completely compensated by electrons. The laser sets in ($\lambda_L = 1561.25$ nm) approximately after 1 h when the grating reflectivity $R > 20\%$. After a few hours of operation the laser output power reached its maximum value and continued with single-frequency laser emission with constant output power (see Fig. 3). Although we have studied the effect of green luminescence on DFB-DBR coupled cavity laser operation only, we strongly believe that it will be equally effective for a pure DFB laser. For a DBR laser, on the other hand, we expect that selfrefreshment will be less efficient since only guided green luminescence is present in the Er-free grating section.

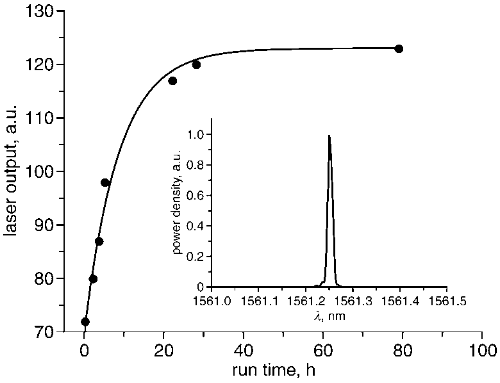

Fig. 3 *DFB-DBR coupled cavity laser stabilisation dynamics with pump laser light ($\lambda_p = 1480$ nm, $P = 115$ mW, TE-polarised)*

Inset: Single-frequency TE-polarised laser emission was measured with optical spectrum analyser (resolution: < 10 pm)

Conclusions: We have shown that thermally fixed photorefractive Bragg gratings in Ti:Fe:Er:$LiNbO_3$ waveguides exhibit an internal refreshing and stabilisation mechanism due to the upconverted Er emission. The FWHM of such grating is extremely narrow, e.g. 35 pm ($\sim$3.7 GHz), making them attractive for narrowband integrated optical lasers in ultra-dense wavelength multiplexing systems in modern fibre-optic communication. Our results show that the spatial distribution of the refreshing light influenced the grating stability by a non-uniform Fe^{2+}/Fe^{3+} distribution. We are confident that a thermally fixed photorefractive grating can be refreshed almost permanently if all the parameters, including fabrication parameters, are optimised properly. In this regard we plan to analyse the defect distribution inside the thermally fixed photorefractive grating by performing a detailed spectroscopic study.

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B.K. Das and V. Dierolf (*Department of Physics, Center for Optical Technologies, Lehigh University, 16 Memorial Drive East, Bethlehem, PA 18015, USA*)

E-mail: vod2@lehigh.edu

W. Sohler (*Department of Applied Physics, University of Paderborn, Warburger Str. 100, Paderborn 33098, Germany*)

B.K. Das: Also at (*Department of Applied Physics, University of Paderborn, Warburger Str. 100, Paderborn 33098, Germany*)

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