Proc. Photonics 2004, Cochin/India, December 2004,
p. 141, paper FBR P44 (invited)

Erbium-doped Lithium Niobate waveguide lasers: recent progress

W. Sohler, D. Dey, B. Das, S. Reza, H. Suche, and R. Ricken
Department of Applied Physics, Faculty of Science, University of Paderborn,
Warburger Str. 100, 33098 Paderborn, Germany

ABSTRACT

Erbium diffusion doping of $LiNbO_3$ (e.g. 30 nm / 1130 °C / 150 hrs) is the preferred method to fabricate an excellent laser material for integrated optics. After Er-doping single mode channel waveguides are defined by the standard indiffusion technique of Ti-stripes. By optical pumping at $\lambda = 1480$ nm a wavelenth dependent gain of up to 2 dB/cm is achieved (1530 nm < λ < 1610 nm). Different types of narrow linewidth **Distributed Bragg Reflector (DBR-) and Distributed FeedBack (DFB-) lasers** will be presented. They are based on photorefractive gratings holographically defined in Ti/Fe- and in Ti/Fe/Er-codoped waveguide sections. Single frequency emission at several wavelengths within the Er-gain band around $\lambda \sim 1550$ nm and an output power of up to 8 mW have been achieved. The range for continuous tuning of **acoustooptically tunable lasers** could be extended to 47 nm (1530 nm < λ < 1577 nm). The emission linewidth has been reduced to 12 pm. Moreover, a tunable frequency shifted feedback laser with a variety of remarkable properties has been developed. As one application optical frequency domain ranging will be presented with a resolution better than 1 mm. The concept of **ring lasers** in Er:$LiNbO_3$ is introduced with their potential to be used as optical gyro. First experimental results are reported; by pumping the ring of 60 mm diameter with a laser diode ($\lambda = 1480$ nm) clockwise and counter-clockwise lasing at $\lambda = 1603$ nm has been achieved with an output power up to 150 µW.

Keywords: Erbium, Lithium Niobate, integrated optics, waveguide laser, DBR- and DFB-laser, acoustooptically tunable laser, frequency shifted feedback laser, ring laser, optical gyro.

1. INTRODUCTION

During the last years there was a considerable interest in rare-earth doped $LiNbO_3$ waveguide lasers. In particular, a whole family of Er-doped waveguide lasers of excellent quality has been developed for the wavelength range 1530 nm < λ < 1610 nm. Free running lasers of the Fabry Pérot type, harmonically mode-locked lasers (5 ps / 10 GHz), Q-switched lasers (4 ns / 1 kHz / 1 kW), Distributed Bragg Reflector- (DBR-) lasers, self-frequency doubling devices, and acoustooptically tunable lasers have been reported [1,2].

Er:$LiNbO_3$ is an excellent laser material for integrated optics. It can be easily fabricated as surface layer in congruent $LiNbO_3$ substrates by an indiffusion of vacuum-deposited thin Er layers (e.g. 30nm / 1130 °C / 150 hrs). Afterwards, single mode channel waveguides are defined by the standard indiffusion technique of Ti-stripes. If optically pumped by $\lambda = 1480$ nm radiation a wavelenth dependent gain of up to 2 dB/cm results (1530 nm < λ < 1610 nm).

Additional doping by Fe allows to define holographically waveguide gratings of excellent quality. Reflectivities > 95 % and a spectral halfwidth of the grating characteristic of < 60 pm enabled the development of narrow linewidth integrated optical DBR- [3], Distributed Feedback- (DFB) [4], and coupled DBR-DFB-lasers [5].

Acoustooptically tunable lasers have been significantly improved during the last time. As an example, a 47 nm tuning range has been demonstrated [6]. Moreover, a tunable frequency shifted feedback laser with avariety of remarkable properties has been developed recently [7].

The first ring laser in Er:$LiNbO_3$ was demonstrated a few months ago using a Ti-indiffused waveguide structure [8]. Due to its large diameter of 60 mm it has a great potential to be used as compact laser gyro.

It is the aim of this contribution to report the latest progress in the field of Ti:Er:$LiNbO_3$ waveguide lasers. In particular, we will summarize the different types of integrated lasers with grating resonator structures, acoustooptically tunable lasers and ring laser structures. Moreover, the potential of combining lasers and nonlinear waveguide devices in periodically poled lithium niobate (PPLN) will be outlined.

2. DBR- AND DFB-LASERS

Several types of narrow linewidth lasers with optical feedback by photorefractive gratings have been developed: distributed Bragg reflector- (DBR-), distributed feedback- (DFB-), and DBR-/DFB-coupled cavity lasers with Ti:Er:$LiNbO_3$ single mode waveguide. They have one or two photorefractive gratings in Fe-doped waveguide sections.

Two types of DBR-lasers have been demonstrated. One has a cavity consisting of one Bragg-grating, a gain section, and a multi-layer dielectric mirror deposited on the opposite waveguide end face. The other DBR-cavity consists of two gratings in Ti:Fe:$LiNbO_3$ waveguide sections on both sides of the Er-doped waveguide (see Fig., left) [3]. Single-frequency operation could be achieved in the latter case at various wavelengths in the Er-band (1530nm < λ < 1575nm) with up to 1.12mW output power (see Fig. 1, right).

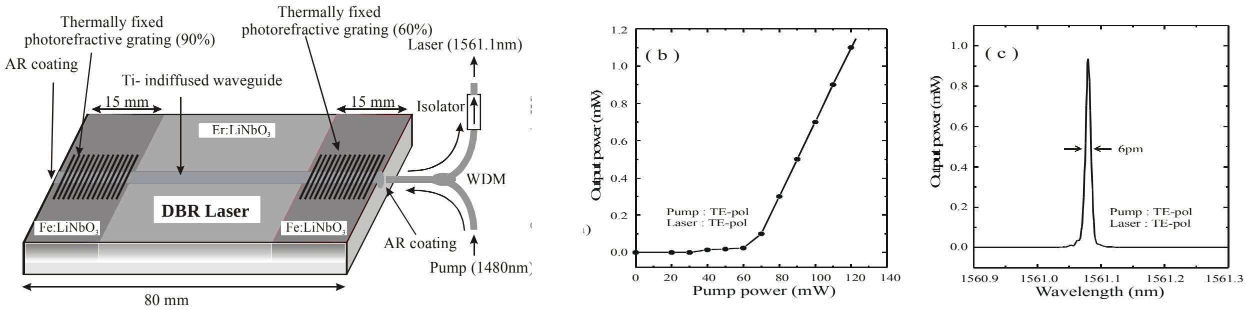

Figure 1: Schematic structure of a DBR-laser with a cavity comprised of two thermally fixed photorefractive gratings (left); Laser power characteristics and emission spectrum (right).

The DFB-laser has a thermally fixed photorefractive grating in a Ti:Fe:Er:$LiNbO_3$ waveguide section; the laser is combined with an integrated optical amplifier on the same substrate [4]. The threshold of the DFB-laser, which emits two narrow lines simultaneously, is significantly higher than the threshold of the DBR-lasers.

Moreover, an attractive DBR/DFB coupled cavity laser has been developed [5]. Its cavity consists of a photorefractive Bragg grating in the Ti:Fe:Er:$LiNbO_3$ waveguide section close to one end face of the sample, a Ti:Er:$LiNbO_3$ gain section and a broadband multi-layer dielectric mirror of high reflectivity on the other end face. Single-frequency operation has been achieved with an output power of up to 8 mW.

3. ACOUSTOOPTICALLY TUNABLE LASERS

3.1 Narrow linewidth laser

A diode-pumped packaged acousto-optically tunable integrated Ti:Er:$LiNbO_3$ waveguide laser was reported by Schäfer et al. [9] in 1997. It could be tuned (not continuously) over 31 nm in the wavelength range 1530 nm <λ <1610 nm with an emission linewidth of 0.3 nm. Recently, an improved version of the laser has been developed (see Fig. 2). The laser

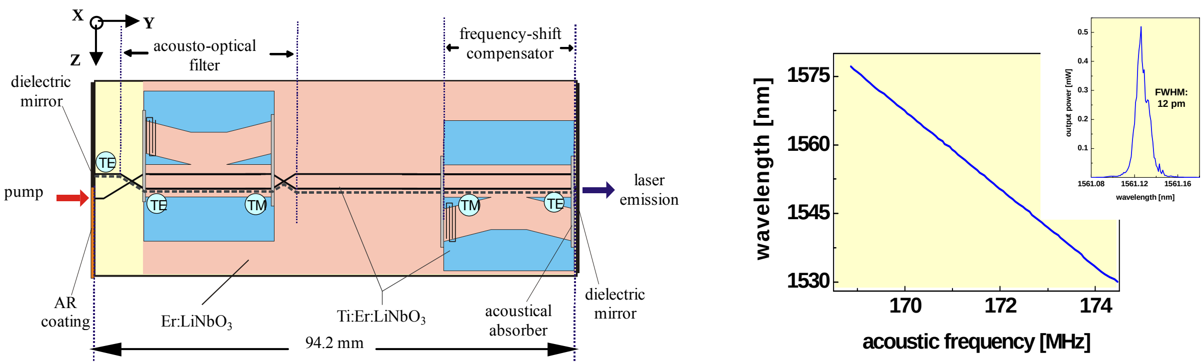

Figure 2: Schematic diagram of the acoustooptically tunable laser (left) and its tuning characteristic with emission wavelength versus frequency of acoustooptical filter and frequency shift compensator (right). Inset: emission spectrum.

consists of an integrated acoustooptical filter incorporated in the Er-doped amplifier section, an acoustooptical frequency-shift compensator and dielectric end face mirrors defining the waveguide resonator. Its tuning range could be extended to 47 nm with a linewidth smaller than 12 pm, if appropriate operating conditions are adjusted. [6].

3.2 Frequency-Shifted Feedback (FSF-)Laser

By switching off the intracavity frequency-shift compensator of the device sketched above the laser properties change significantly. During each round-trip a frequency shift is imposed on the optical field inside the resonator, which is twice the acoustical frequency of about 170 MHz. The result is a smaller but very stable output power and an increased linewidth of the laser emission (see Fig. 3). It should consist of a comb of narrow lines of constant frequency spacing, which changes with time, as previously obversed with a bulk laser [10].

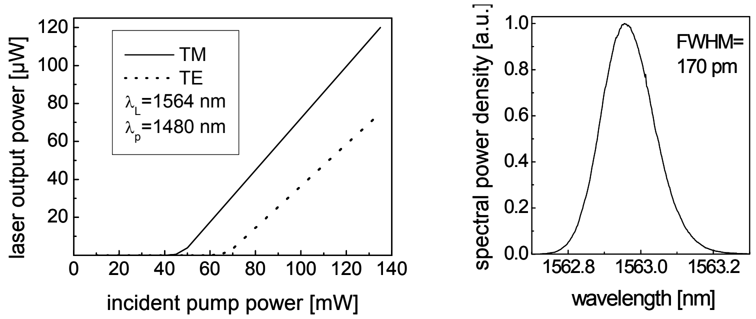

Figure 3: Power characteristics (left) and emission spectrum in TM-polarization (right) of the integrated FSF-laser.

The unique spectral properties of frequency shifted feedback lasers have been studied by several groups investigating bulk devices [10,11]. A detailed characterization of the dynamic spectral properties of the integrated optical frequency shifted feedback laser is still to be done.

With bulk lasers a variety of attractive applications has already been demonstrated such as chromatic dispersion and polarization mode dispersion measurement in fibers as well as optical frequency domain ranging [12]. Similar experiments have just been performed using the integrated FSF-laser as source in a michelson interferometer setup (see Fig. 4, left). As the frequency comb of the laser emission changes with time, a superposition of the two beams propagating through the two arms of the interferometer yields a beat frequency, which depends on the optical path difference of the two arms. This can be exploited for optical ranging; if the first order beat frequency is used by measuring the difference frequency of two neighbouring lines, a resolution of < 1 mm can be achieved (see Fig. 4, right).

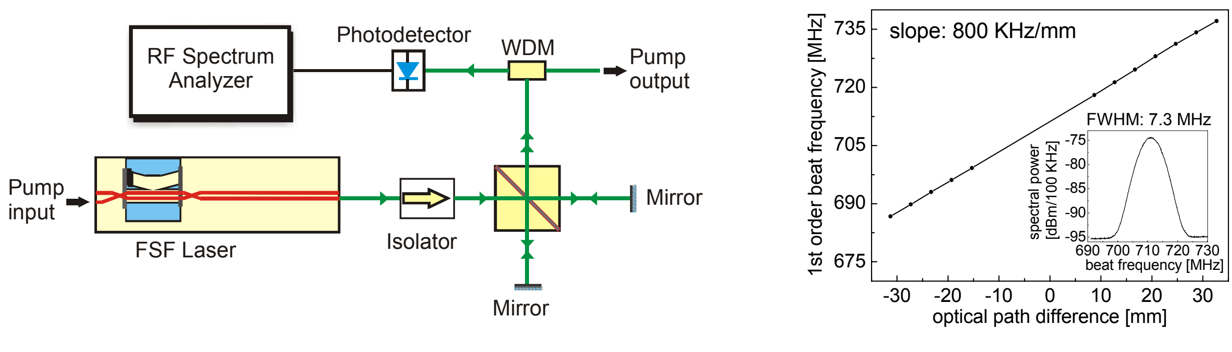

Figure 4: Optical frequency ranging with the integrated FSF-laser: schematical experimental setup (left) and 1st order beat frequency, measured with the RF-spectrum analyzer, as function of the optical path difference in the michelson interferometer (right).

4. RING LASERS

Recently, the first integrated optical ring laser has been demonstrated, fabricated in an Er-doped $LiNbO_3$ substrate [ ]. Its structure is shown in Fig. 5. It consists of the Er-doped ring and two straight waveguides tangential to the ring forming two directional couplers. One serves as pump coupler allowing to couple the pump light (λ = 1480 nm) clockwise and counter-clockwise into the ring. The other one serves as laser output coupler allowing to observe the guided spontaneous fluorescence and the laser emission, if threshold is surpassed, propagating in both directions. The absorption of the pump light in the ring can be observed indirectly via the green upconversion light excited by a three step excitation of the Er-ions (see Fig. 5).

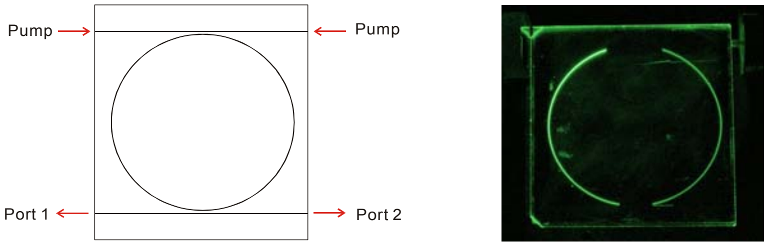

Figure 5: Structure of the ring laser of 30 mm radius (left) and photograph of the Er-doped waveguide ring emitting green up-conversion light (right).

To reduce the laser threshold a new version has just been fabricated with one straight waveguide only; in this way the resonator losses have been lowered as only one directional coupler is used. Pump and laser light are separated or combined externally by appropriate fiber optical wavelength division multiplex (WDM-)devices. Lasing sets in at about 70 mW pump power (λ_p = 1480 nm) coupled into the straight channel guide from one side only. As the coupling efficiency of the directional coupler is about 40 %, laser threshold corresponds to about 28 mW pump power coupled into the ring. Due to the weak spectral dependence of the coupling efficiency of the directional coupler relatively high losses are thus induced in the ring resonator at the laser wavelength (λ = 1610 nm). An optimization of the directional coupler(s) with a high coupling efficiency at the pump wavelength, but a low efficiency at the laser wavelength has still to be done.

The laser emission was observed via both outputs of the straight channel investigating in this way the clockwise and counter-clockwise propagation in the ring; both power characteristics look very similar. The small slope efficiency is a consequence of the non optimized laser design (see Fig. 6, left). The laser emits several lines with a spectral fine structure, centered around λ = 1603 nm (see Fig. 6, right). As the ring laser is operated without any wavelength selective intracavity components its emission wavelength corresponds to electronic transitions of lowest energy difference from the $^4I_{13/2}$ to the $^4I_{15/2}$ manifolds of Er^{3+} in $LiNbO_3$. For these energy levels population inversion is obtained at lowest pump power; this mode of operation is similar to that of a standard 4-level laser-system. Thus the long wavelength emission of this laser is understood; however, its spectral structure is not.

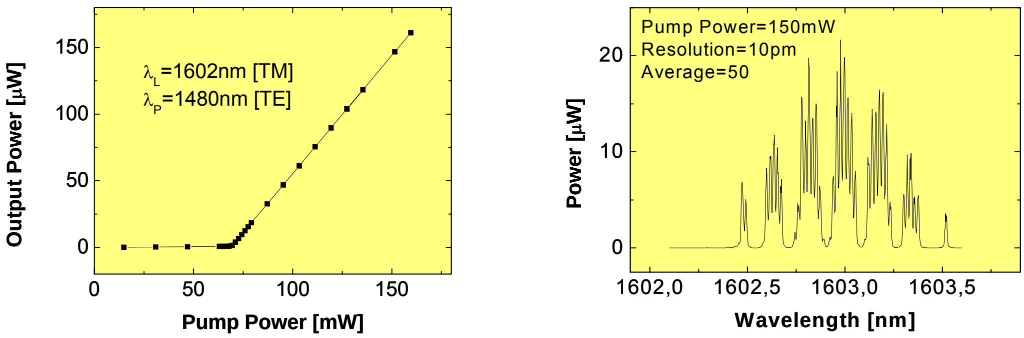

Figure 6: Power characteristics (left) and emission spectrum in TM-polarization (right) of the integrated $Ti:Er:LiNbO_3$ ring laser.

5. CONCLUSIONS

DBR- and DFB-lasers increase the potential of $LiNbO_3$ integrated optics significantly; a DFB-laser can be incorporated everywhere in an optical circuit. Acoustooptically tunable lasers promise single frequency emission and mode-hop free continuous tuning. As frequency shifted feedback devices attractive applications become possible. The ring laser might allow the development of compact optical gyroscopes of high performance. Moreover, if fabricated in a PPLN substrate a laser can be combined with a nonlinear device in the same waveguide enabling e. g. the development of self-frequency doubling lasers or of parametric oscillators with integrated pump.

REFERENCES

[1] C. Becker et. al., *IEEE J. Select. Topics Quantum Electronics,* **6,** 101 (2000)
[2] I. Baumann et. al., *IEEE J. Select. Topics Quantum Electronics,* **2**, 355 (1996)
[3] B. K. Das et. al., *Appl. Phys. B,* **73**, 439 (2001)
[4] B. K. Das et. al., *Appl. Phys. Lett.,* **82**, 1515 (2003)
[5] B. K. Das et. al., *Opt. Lett.,* **29**, 165 (2004)
[6] S. Reza et. al., *CLEO-Europe,* paper – CL1-5-THU, (2003)
[7] S. Reza et. al., *ECIO, Proceedings*, 167 (2003)
[8] W. Sohler et al., *Techn. Digest OECC`04,* paper 14F4-1, 568 (2004)
[9] K. Schäfer et. al., *IEEE J. Quantum Electron.,* **33**, 1636 (1997)
[10] K. Kasahara et. al., *IEEE J. Quantum Electron.,* **34,** 190 (2003)
[11] M. Stellpflug et. al., *Opt. Ex.,* **11**, 2060 (2003)
[12] K. Nakamura et. al., *IEEE J. Quantum Electron.,* **36**, 305 (2000)