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Recent Progress in Integrated Rare-Earth Doped $LiNbO_3$ Waveguide Lasers

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I) 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 emitting at wavelengths around 1550 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 of $LiNbO_3$ 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 ë = 1.48 ìm radiation a wavelenth dependent gain of up to 2 dB/cm results around ë = 1550 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 example, a 80 nm tuning range has been demonstrated meanwhile [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 weeks ago using a Ti-indiffused waveguide structure. Such a ring laser 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.

II) 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. 1a). Single-frequency operation could be achieved in the latter case at various wavelengths in the Er-band (1530nm < ë < 1575nm) with up to 1.12mW output power (see Figs. 1b and 1c).

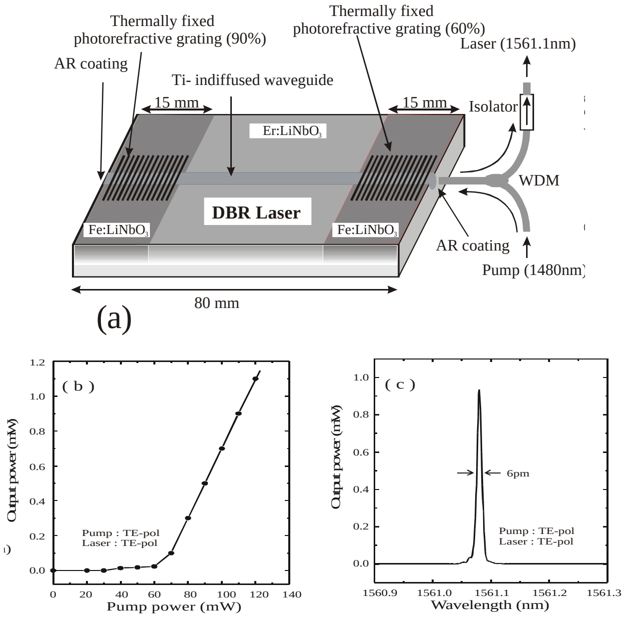

Fig. 1: *(a) Schematic structure of a DBR-laser with a cavity comprised of two thermally fixed photorefractive gratings. (b) Power characteristics. (c) Emission spectrum.*

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. 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. 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.

III) Acoustooptically Tunable Lasers

1. Narrow Linewidth Laser

A diode-pumped packaged acousto-optically tunable integrated Ti:Er:$LiNbO_3$ waveguide laser was reported by Schäfer et. al. [8] in 1997. It could be tuned (not continuously) over 31 nm in the wavelength range 1530 nm $<\lambda<$ 1610 nm with an emission linewidth of 0.3 nm. Recently, an improved version of the laser has been developed with a modified design (see Fig. 2); its tuning range is extended to 47 nm with a linewidth smaller than 12 pm if appropriate operating conditions are adjusted. The laser 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.

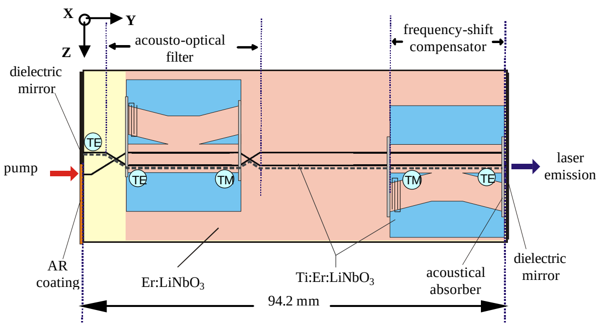

Fig. 2: *Schematic diagram of the acoustooptically tunable laser. A TM polarized pump leads to a TE polarized laser output.*

2. Frequency-Shifted Feedback 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 [9].

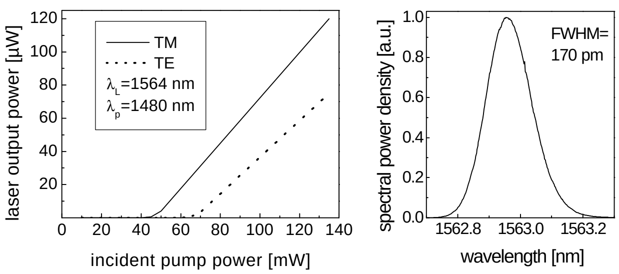

Fig. 3: *Power characteristics (left) and emission spectrum (TM) (right).*

The unique spectral properties of frequency shifted feedback lasers have been studied by several groups investigating bulk devices [9,10]. 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 [11].

IV) Ring Lasers

Recently, the first integrated optical ring laser has been demonstrated, fabricated in an Er-doped substrate. Its structure is shown in Fig. 4. 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 (ë = 1.48 ìm) 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. 4).

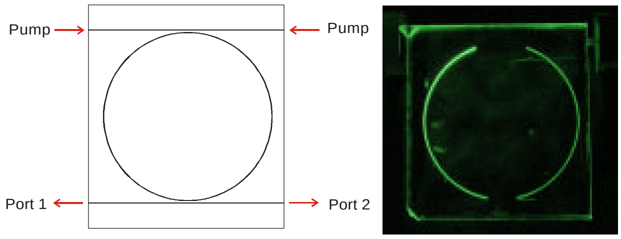

Fig. 4: *Structure of the ring laser of 30 mm radius (left) and photograph of the Er-doped waveguide ring emitting green upconversion light (right).*

Lasing sets in at about 80 mW pump power coupled into the upper straight channel guide from the right (see Fig. 4). Due to the moderate efficiency of the pump directional coupler a dielectric mirror of 98 % reflectivity was placed at the left output of the channel yielding also counter-clockwise pumping of the ring. The laser emission was observed via both outputs of the lower straight channel. The free running laser (without any wavelength selective intracavity component) emitted several narrow lines centered around ë = 1.61 ìm.

V) 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.

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