1999 IEEE Technical Digest CLEO/Pacific Rim '99,Aug./Sept. 1999, Seoul/South Korea, paper FS1 (invited)

Waveguide Lasers and Nonlinear Devices in Lithium Niobate

W. Sohler

Angewandte Physik, Universität-GH Paderborn
Warburger Str. 100, D-33098 Paderborn, Germany
Phone: +49 5251 60-2712 / Fax +49 5251 60-3422
Email: sohler@physik.uni-paderborn.de

1. Introduction

During the last years a whole family of waveguide lasers has been developed in Er-diffusion doped $LiNbO_3$ substrates with conventional Ti-diffused channel guides [1]. More recently, various types of very efficient, quasi-phase-matched nonlinear frequency converters have been demonstrated in PPLN (periodically poled lithium niobate) also with Ti-diffused channel guides [2]. Moreover, periodic poling of Ti:Er:$LiNbO_3$ waveguides was achieved [2]. Using this technology the development of several attractive laser / nonlinear frequency converter combinations – integrated on the same substrate or even in the same waveguide structure – becomes possible. It is the aim of this contribution to briefly review the state of the art of Er-doped waveguide lasers and of quasi-phase-matched nonlinear devices. Moreover, concepts of laser/frequency converter combinations are discussed and latest results are reported.

2. Ti:Er:$LiNbO_3$ Waveguide Lasers

The most reliable and simplest technique to fabricate Er-doped waveguides in $LiNbO_3$ proved to be the indiffusion (e.g. 1130°C / 150 h) of a thin (e.g. 25 nm thickness) vacuum-deposited Er-layer followed by the standard waveguide fabrication process with an indiffusion of photolithographically defined, evaporated Ti-stripes of e.g. 100 nm thickness and 7 µm width. Using this technique single-mode channel guides of low scattering losses down to 0.1 dB/cm have been fabricated in $LiNbO_3$ surfaces with high erbium concentration. They are the basic structures of all the waveguide lasers discussed in the following.

Simple Fabry-Perot-type Ti:Er:$LiNbO_3$ waveguide lasers have been fabricated by coating the polished waveguide end-faces with dielectric SiO_2/TiO_2 multi-layer mirrors. The lasers have no special wavelength-controlling intracavity component; their emission wavelength is determined by the spectral properties of the cavity and by the waveguide amplifier gain spectrum. With a proper choice of the reflectivity of the output coupler, lasers of six different wavelengths have been developed: 1531, 1546, 1562, 1576, 1602, and 1611 nm. As an example, the threshold and the maximum slope efficiency of a 1562 nm device is 24 mW and 37 %, respectively, yielding a maximum cw output power of 63 mW at 210 mW pump power.

By replacing one of the dielectric mirrors with a grating reflector etched into the surface or defined in the waveguide core as a fixed photorefractive grating the laser emission wavelength is precisely determined and the linewidth is strongly reduced [3]. Even single frequency emission with a linewidth < 10 kHz has been observed.

By incorporating a high bandwidth phase modulator into the cavity of a Fabry-Perot-type laser above modelocking was achieved by a periodic phase modulation with (harmonics of) the optical round-trip frequency (e.g. 1 GHz) of the resonator. In this way short optical pulses of 5 ps to 10 ps halfwidth were generated with a repetition rate corresponding to the driving frequency. The fiber-pigtailed and packaged lasers have been successfully tested in high bitrate (5Gbit/s and 10 Gbit/s) optical transmission experiments.

By incorporating a folded Mach-Zehnder-type intensity modulator into the cavity electro-optically Q-switched Ti:Er:$LiNbO_3$ waveguide lasers have been developed. They are pumped by a cw semiconductor laser ($\lambda_p \approx 1480$ nm) and emit at $\lambda = 1562$ nm and at $\lambda = 1531$ nm, respectively. If Q-switched at 1 kHz repetition frequency, pulses of 4 – 5 ns halfwidth are generated with a peak power of up to 2 kW. This power level means a power density in the waveguide of about 10 GW cm^{-2}. Therefore, these lasers are ideal sources to study or to exploit nonlinear effects.

3. Quasi-Phase-Matched Nonlinear Frequency Converters

Using the electric field technique [4] up to 8 cm long $LiNbO_3$ substrates with Ti-indiffused optical waveguides have been periodically poled with periodicities around 17 µm and 32 µm. The short period waveguides were designed as single-mode channels around $\lambda = 1550$ nm for near-infrared (NIR) nonlinear interactions; the long period guides were single-mode channels around $\lambda = 3400$ nm to allow mid-infrared (MIR) nonlinear interactions. The propagation losses of the fundamental waveguide modes can be as low as 0.03 dB/cm in the MIR.

The short period waveguides of 5 cm length were tested as second harmonic generators using a tunable, single-frequency semiconductor laser as pump source [2]. A normalized efficiency of 442 % W^{-1} was achieved – considerably exceeding the 270 % W^{-1} reported for proton exchanged guides. The same Ti:$LiNbO_3$ guides were investigated as wavelength converters in the 1.5 µm band using a Ti:sapphire laser as pump source

(λ_p = 779.5 nm) and the tunable semiconductor laser as signal source. A normalized conversion efficiency of 318 % W^{-1} was obtained [2].

The long period waveguides were used as MIR-difference frequency generators mixing the radiation of a tunable extended cavity semiconductor laser (1500 nm < λ_p < 1580 nm) and of a mid-infrared He-Ne laser (λ_s = 3391 nm) to generate radiation of a wavelength around λ_i = 2800 nm (see Fig. 1). With a 80 mm long waveguide a pump power normalized frequency conversion efficiency of η_{norm} = 105 % W^{-1} was achieved, more than one order of magnitude higher than recently reported data.

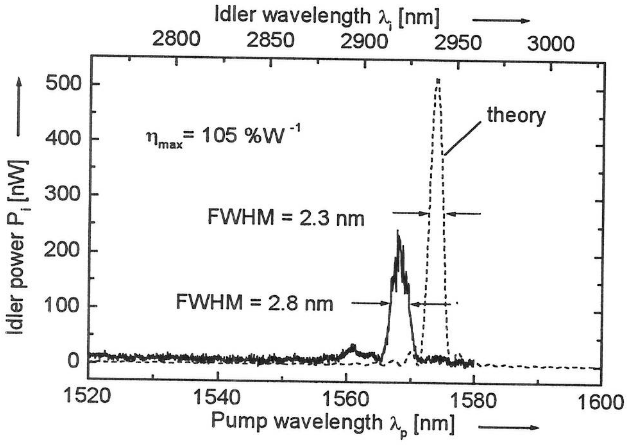

Fig. 1: Idler power versus pump wavelength generated in a 20 µm wide Ti:LiNbO$_3$ waveguide with a QPM period of 31.4 µm. Theoretical response is calculated with the experimental data: 2 mW pump power, 110 µW signal power (λ_s = 3391 nm), 80 mm interaction length and attenuations of 0.03 dB cm^{-1} for signal and idler and of 0.1 dB cm^{-1} for pump.

Waveguides of the same type as described above were used to develop a MIR optical parametric oscillator (OPO) with an extremely low threshold of 15 mW only. As a consequence, the OPO can be operated with a cw tunable, extended cavity semiconductor laser, amplified by an Erbium Doped Fiber Amplifier (EDFA).

4. Optical Amplifier/ and Laser/Frequency Converter Combinations

Very recently a successful periodic poling also of Ti:Er:LiNbO$_3$ waveguides could be demonstrated [2]. This key result allows the realization of several attractive concepts for combinations of integrated optical amplifiers and lasers with nonlinear frequency converters.

The most straightforward device is a Fabry-Perot-type laser fabricated in a periodically domain inverted Er-doped substrate. If the periodicity is appropriately chosen, quasi-phase-matched second harmonic generation of the intracavity laser field is achieved. A high conversion efficiency can be expected, if the resonator is carefully designed to optimize the enhancement of the laser field. Very recently, the first self-frequency doubling waveguide laser of this kind has been demonstrated [5]. The non-optimized device simultaneously emits at the fundamental (λ_f = 1531 nm) and second harmonic wavelength (λ_{SH} = 765,5 nm) up to 2.5 mW and 2.7 µW, respectively.

The same principle can be applied to fabricate an amplifying difference frequency generator in a periodically poled Ti:Er:LiNbO$_3$ waveguide. By pumping the erbium-ions a wavelength-dependent single-pass amplification up to 2 dB/cm can be obtained in the wavelength range 1530 nm < λ < 1610 nm. This should boost the output power of both signal and idler of a near-infrared difference frequency generator.

Even more attractive is the concept of a mid-infrared optical parametric oscillator with an intracavity Ti:Er:LiNbO$_3$ laser as pump source. The structure must be doubly (or triply) resonant at the laser wavelength and at the signal or (and) the idler wavelength. The laser wavelength can be fixed by a grating mirror. The MIR output of the OPO can be tuned via the temperature or by an electro-optical tuning of the grating response.

5. Conclusions

The recent development of Ti:Er:LiNbO$_3$ waveguide lasers and of quasi-phase-matched Ti:LiNbO$_3$ nonlinear frequency converters represents a great challenge to develop new miniaturized, tunable, efficient, all-solid-state sources of coherent radiation by a monolithic integration of lasers and frequency converters in the same substrate or even in the same waveguide structure. First promising results have been achieved.

References:

1. Baumann et al., IEEE J. Select. Topics Quantum Electron., **2** (2), pp. 355-366 (1996)
2. D. Hofmann/G. Schreiber et al., ECIO '99, Torino/Italy (accepted)
3. Ch. Becker et al., Opt. Lett., **23** (15), pp. 1194-1196 (1998)
4. L.E. Myers, W.R. Bosenberg, IEEE J. Quantum Electron., **33** (10), pp. 1663-1672 (1997)
5. G. Schreiber et al., CLEO/Europe 1999 Focus Meetings (LASER '99), Munich/Germany (submitted)