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Waveguide lasers and nonlinear frequency converters in lithium niobate

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ABSTRACT

A whole family of waveguide lasers (fixed frequency, acoustooptically tunable, modelocked, Q-switched) has been developed in Er-diffusion doped $LiNbO_3$ substrates. By periodically poling the Ti:Er:$LiNbO_3$ waveguides quasi-phase-matched nonlinear interactions can be achieved in the same structure. In this way the development of self-frequency doubling lasers, of laser / difference frequency generator combinations, and of optical parametric oscillators with intracavity pump laser becomes possible.

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 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 recently [2]. In this way the development of several attractive laser / nonlinear frequency converter combinations – integrated on the same substrate, eventually in the same waveguide structure – is rendered possible. It is the aim of this contribution to briefly review the laser development, to present the results of new nonlinear frequency converters, and to discuss concepts of laser / frequency converter combinations.

2. Ti:Er:$LiNbO_3$ WAVEGUIDE LASERS

In the following the Er-diffusion technique is sketched and several important types of waveguide lasers are presented. They have the potential to be combined with nonlinear frequency converters on the same substrate.

2.1 Erbium diffusion doped Ti:$LiNbO_3$ waveguides

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 [3]. They are the basic structures of all the waveguide lasers discussed in the following.

2.2 Basic laser structures

Simple Fabry-Perot-type Ti:Er:$LiNbO_3$ waveguide lasers have been fabricated (see Fig. 1); they represent the basis for any further laser development. The cavity has been defined 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. E.g. the threshold and the maximum slope efficiency of a 1562 nm device was 24 mW and 37 %, respectively, yielding a maximum cw output power of 63 mW at 210 mW pump power [4].

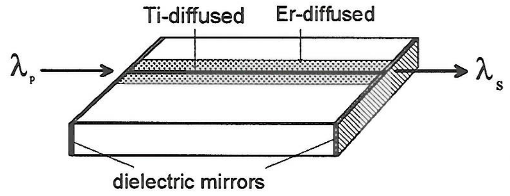

Fig. 1: Schematic structure of Ti:Er:$LiNbO_3$ waveguide lasers with Fabry-Perot-type cavity defined by dielectric end-face mirrors.

2.3 Distributed Bragg reflector (DBR-) lasers

By replacing one of the dielectric mirrors (see Fig. 1) with a grating reflector etched into the surface [5] or defined in the waveguide core as a fixed photorefractive grating [6] the laser emission wavelength is precisely determined and the linewidth is strongly reduced. Even single frequency emission with a linewidth < 100 kHz has been observed. Laser diode pumped ($\lambda_p \approx 1480$ nm), fiber-pigtailed and packaged devices have been developed; they emit e.g. 5 mW cw output power at $\lambda = 1532$ nm with 110 mW launched pump power.

2.4 Modelocked lasers

By incorporating a high bandwidth phase modulator into the cavity of a Fabry-Perot-type laser as described above (see Fig. 1) modelocking can be achieved by a periodic phase modulation with (harmonics of) the optical round-trip frequency (e.g. 1 GHz) of the resonator. The result is the emission of short optical pulses of 5 ps to 10 ps halfwidth with a repetition rate corresponding to the driving frequency. As an example, Fig. 2 presents the average output power (left) of a laser diode ($\lambda_p \approx 1480$ nm) pumped, harmonically modelocked Ti:Er:$LiNbO_3$ waveguide laser with the output pulses (right) as measured by a second harmonic autocorrelator [7]. The pulse peak power exceeds 100 mW. The fiber-pigtailed and packaged lasers have been successfully tested in high bitrate optical transmission experiments.

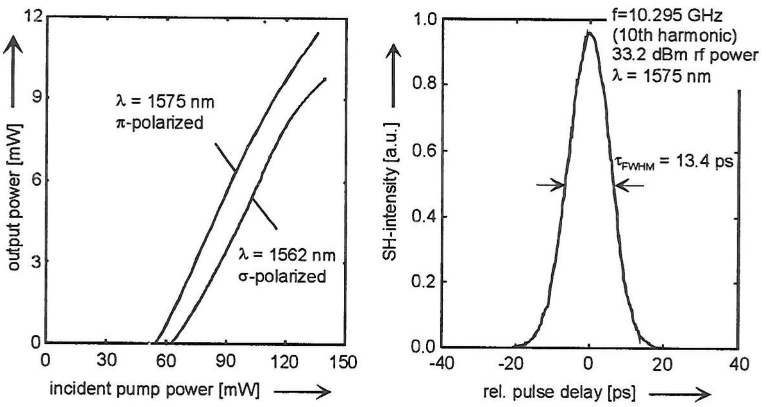

Fig. 2: Left: Power characteristic as average output power versus incident pump power ($\lambda_p \approx 1480$ nm) of a harmonically modelocked Ti:Er:LiNbO$_3$ waveguide laser with pump polarization-dependent emission wavelength. Right: Output pulse shape as measured by a second harmonic autocorrelator.

2.5 Q-switched lasers

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 [8]. 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. The devices have been packaged and fiber-coupled; they are tested in laser ranging experiments.

3. QUASI-PHASE-MATCHED NONLINEAR FREQUENCY CONVERTERS

We developed periodically poled, long, low loss Ti:LiNbO$_3$ channel guides for nonlinear interactions in the near- and mid-infrared, characterized the waveguides by second harmonic generation (SHG), and investigated their performance as difference frequency generators in different spectral ranges.

3.1 Periodically poled Ti:LiNbO$_3$ waveguides

Using the electric field technique [9,10] up to 5 cm long LiNbO$_3$ substrates with titanium-indiffused optical waveguides have been periodically poled with periodicities around 17 μm and 32 μm (see Fig. 3, left). 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 0.15 dB/cm.

3.2 Second harmonic generator

The short period waveguides were tested as second harmonic generators using a tunable, single-frequency semiconductor laser as pump source [2]. Fig. 3 presents on the right an example of a measured characteristic compared with a calculated one. Both curves are nearly identical demonstrating the excellent homogeneity of the periodically poled waveguide. Its high quality also resulted in a normalized efficiency of 442 % W^{-1} – considerably exceeding the 270 % W^{-1} reported for proton exchanged guides [11].

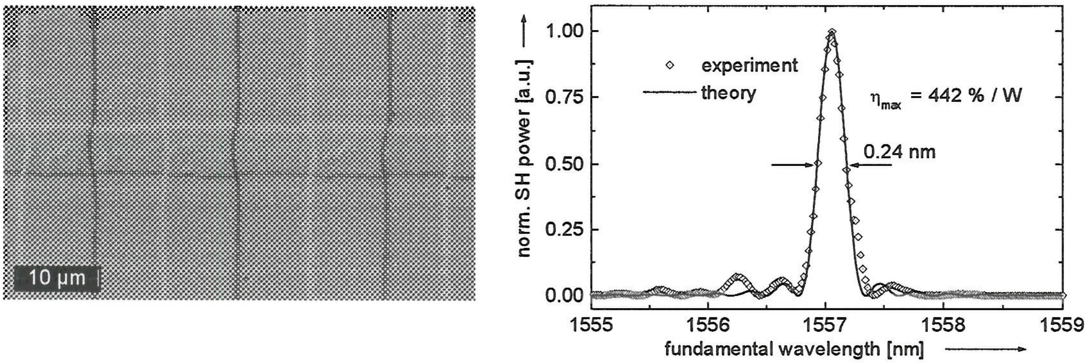

Fig. 3: Left: Chemically etched surface of a periodically poled $LiNbO_3$ substrate with Ti-indiffused channel guide. The periodicity is 17.3 µm. Right: Characteristics of a periodically poled, 50 mm long second harmonic (SH) generator plotted as normalized SH-power versus the fundamental wavelength. η_{max} is the normalized conversion efficiency at the phase match wavelength.

3.3 Near-infrared difference frequency generator

The same periodically poled 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. One example of a measured result is given in Fig. 4 for a coupled pump power of 260 µW and a coupled signal power of 1.1 mW. Despite these low power levels 930 nW of idler power could be generated at the difference frequency in the case of phase matching, resulting in a normalized conversion efficiency of 318 % W^{-1} [2]. The smaller figure in comparison with the SHG-result is explained by a reduced overlap of the three interacting waves (somewhat away from degeneracy).

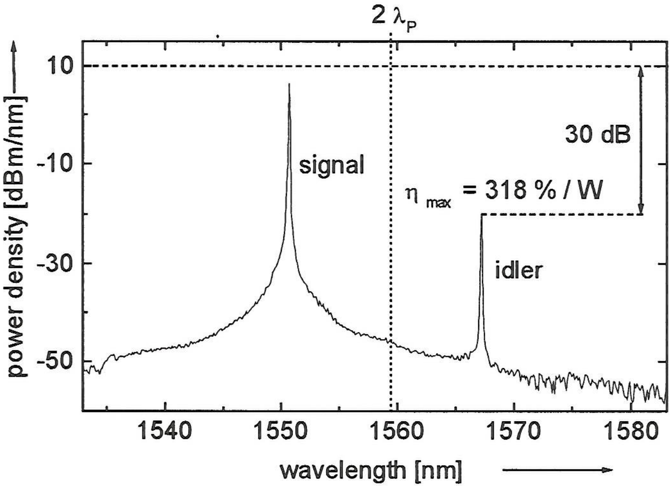

Fig. 4: Characteristic of a periodically poled, 50 mm long NIR-DFG-generator plotted as signal and idler spectral power density versus the wavelength (spectral resolution: 0.1 nm).

3.4 Mid-infrared difference frequency generator

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 the difference frequency (idler) radiation of a wavelength around λ_i = 2800 nm. Using an EDFA (Erbium Doped Fiber Amplifier) to boost the coupled pump power up to 7 mW, an idler power of 350 nW was generated at phase matching with 70 μW coupled signal power of the He-Ne laser [2]. This result means a pump power normalized frequency conversion efficiency of the 50 mm long device of $\eta_{norm} = 71\ \%\ W^{-1}$, which is more than three orders of magnitude higher than recently reported data [12].

3.5 Mid-infrared parametric fluorescence generator

Waveguides of the same type as described above were used to demonstrate the single-pass generation of stimulated parametric fluorescence. A Ti:Er:$LiNbO_3$ Q-switched waveguide laser as presented in section 2 was applied as pump source delivering about 5 ns long pulses at 1562 nm wavelength; the peak power coupled to the periodically poled waveguide was about 500 W. As a result signal and idler pulses were generated simultaneously with estimated peak power levels of about 10 mW at 2930 nm and 3300 nm, respectively. Wavelength tuning was possible by adjusting the device temperature or the pump wavelength.

3.6 Optical parametric oscillators

All the results presented in this section demonstrate the great potential of periodically poled Ti:$LiNbO_3$ channel guides for the development of near- and mid-infrared optical parametric oscillators of excellent properties. In particular, due to the inherent low waveguide losses, devices of very low threshold will be feasible. Calculations predict a pump threshold of 12 mW and 55 mW for near- and mid-infrared doubly resonant oscillators, respectively.

4. CONCEPTS FOR LASER / FREQUENCY CONVERTER COMBINATIONS

Very recently a successful periodic poling also of Ti:Er:$LiNbO_3$ waveguides could be demonstrated [2]. This key experiment will lead to the realization of several attractive concepts for combinations of integrated optical lasers and nonlinear frequency converters on the same substrate.

4.1 Self-frequency doubling laser

The most straightforward device will be a Fabry-Perot-type laser fabricated in a periodically domain inverted erbium-doped substrate (see Fig. 5). If the periodicity is appropriately chosen, 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. Even a doubly resonant device (at λ_s and λ_{SH}) should be possible.

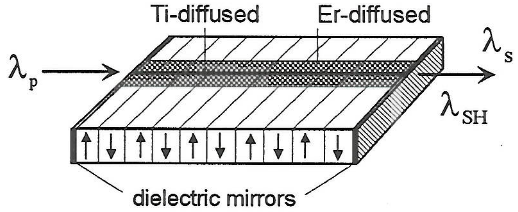

Fig. 5: Schematic structure of the self-frequency doubling waveguide laser. λ_p, λ_s and $\lambda_{SH} = \lambda_s/2$ are the pump, signal (laser) and second harmonic wavelengths, respectively.

4.2 Amplifying difference frequency generator

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 [13]. This should boost the output power of both signal and idler of a near-infrared difference frequency generator (see also Fig. 4). In this way also the conversion efficiency (idler output with respect to the signal input) will be increased considerably.

4.3 Mid-infrared optical parametric oscillator with intracavity pump

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 design of such a device is similar to that sketched in Fig. 5. The difference is that a mid-infrared waveguide with a corresponding periodicity of the microdomains is used; moreover, 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. An example of a calculated tuning characteristic of the optical parametric oscillator is shown in Fig. 6.

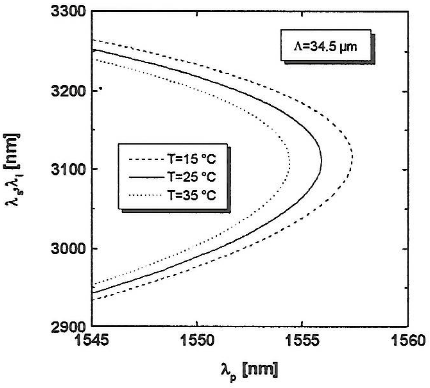

Fig. 6: Calculated tuning characteristic of a mid-IR optical parametric oscillator plotted as signal and idler wavelengths versus pump wavelength. Parameter is the device temperature.

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. This will be the goal of our work in the next future.

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