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Diode Pumped and Packaged 10GHz Harmonically Modelocked Ti:Er:LiNbO$_3$-Waveguide Laser for Soliton Transmission

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Abstract: Modelocked laser operation with a stabilized, packaged and diode pumped Ti:Er:LiNbO$_3$-waveguide laser has been demonstrated at 1561nm (TE) and 1575nm (TM) wavelength with 14% slope efficiency. Pulse widths of < 10ps at 10GHz pulse repetition rate have been measured.

Introduction

Modelocked lasers emitting in the third telecommunication window are promising sources for soliton transmission systems. In particular, (harmonically) active modelocked lasers are interesting due to their possibility to synchronize the pulse repetition rate to the high frequency system clock. Up to now both external cavity semiconductor lasers and Erbium-doped fibre lasers have demonstrated pulse repetition rates in the multi-gigahertz range. However, the pulses of semiconductor lasers are usually chirped and asymmetric [1]; fibre lasers have a low potential for miniaturization and problems with supermode competition noise [2]. On the other hand integrated optical modelocked lasers are rugged and can emit transform-limited pulses [3].

Erbium-doped LiNbO$_3$ is an attractive material for the realization of such soliton sources. It has excellent electrooptic properties, allows the incorporation of Er up to the solid solubility limit without fluorescence quenching and the fabrication of high quality Er-doped waveguides [4]. Using a monolithically integrated intracavity phase modulator as modelocker (FM-type modelocking) and a broadband Fabry Perot waveguide cavity fundamental and harmonic modelocking [3],[5] have already been demonstrated. However, the output power of these lasers was low and the emission wavelength (1531nm, 1602nm) was not matched to the third telecommunication window.

In this paper we report a diode pumped, pigtailed and packaged harmonically modelocked laser with a pulse repetition frequency up to 10GHz. The laser emits 10ps long pulses of more than 100mW peak power at 1562nm and 1575nm wavelength, respectively, depending on the polarization of the pump.

Device fabrication

Half (with respect to the X-direction) of the Z-cut (Y-propagation) LiNbO$_3$ substrate has been doped near the surface by indiffusion of 28nm of vacuum deposited Er at 1130°C during 125h. Subsequently, photolithographically delineated 7μm wide and 98nm thick Ti-stripes have been indiffused at 1060°C during 8h to form the 66.5mm long waveguide channels. Attenuation figures of the undoped channels down to 0.02dB/cm (TE) and 0.05 dB/cm (TM) have been measured at 1523nm wavelength, respectively. The FWHM-figures of the near field intensity distributions of the modes at 1545nm wavelength are 6.3μm × 4.5μm (width × depth; TE) and 4.6μm × 3.1μm (TM), respectively. Within experimental error the intensity distributions are identical for doped and undoped channels.

To avoid excess losses of the TM-mode an 0.6μm thick insulating SiO$_2$-buffer has been vacuum deposited onto the substrate surface prior to the electrode fabrication. The electrode structure of the intracavity travelling wave phase modulator (modelocker) is a symmetrical coplanar microstrip line with a gap to hotline width ratio of 0.75. First a thin electrode structure has been fabricated by photolithographic lift-off of a sandwich of 30nm sputtered Ti and 120nm sputtered Au. Subsequently, the Au-structure was electroplated up to a thickness of 6μm using as a cyanidic Au-electrolyte.

The laser cavity is comprised of a high reflector on the rear side and a pump input coupler of optimized output coupling for the signal (see e.g. [6]). Both mirrors consist of SiO_2/TiO_2-layers directly deposited onto the polished waveguide endfaces using O_2^+-ion assisted reactive evaporation. The rear mirror consists of 13 layers quarterwave at 765nm leading to about 98% reflectivity at both, pump and signal wavelengths. The output coupler constists of 14 layers quarterwave at 946nm leading to a minimurm reflectivity of about 7% at the pump wavelength ($\lambda \approx 1480$nm) and an output coupling of the signal of about 55%.

After characterization of the laser chip the pump input side of the cavity was pigtailed with the common branch of a fiberoptic wavelength division demultiplexer (WDM) to allow coupling of a pigtailed pump laser diode and extraction of the laser output in backward direction. The WDM has standard (9/125µm) fiber pigtails.

Finally, the pigtailed laser has been packaged including isolation, thermoelectric temperature control ($< \pm 0.01$K) and two cascaded 10/90% power splitters. A photograph of the packaged laser is shown in Fig. 1. FC/PC connection is provided for pump input, output to a data encoding modulator (90%), tap outputs (9% , 1%) for monitoring of modelocking stability and pulse peak power and to derive a control signal for feedback stabilization (controlled pumping).

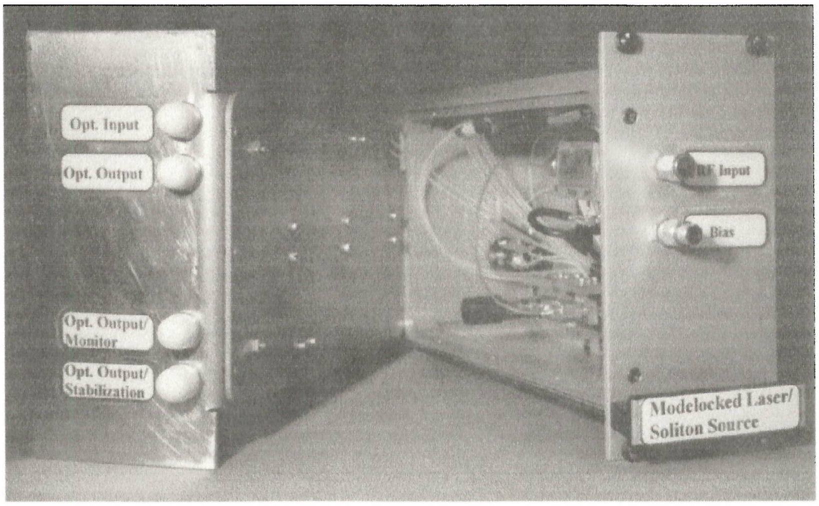

Fig. 1: Photograph of the pigtailed, packaged, and thermoelectrically temperature controlled modelocked laser.

Experimental results

The modelocked Er-doped laser has been investigated in terms of axial mode structure, power characteristics, pulse width, spectrum and time bandwidth product for modelocking different harmonics (2nd, 5th and 10th) of the axial mode frequency spacing. To drive the modelocker the rf-signal from a highly stable generator was boosted using a narrow band low noise amplifier and then fed via a bias tee to the travelling wave electrodes of the intracavity phase modulator. The electrodes are terminated AC-coupled by a 50Ω load.

To pump the $Ti:Er:LiNbO_3$-waveguide laser a high power (up to 150mW from the laser pigtail) laser diode of about 1480nm center wavelength and 12nm spectral width has been used. The pump power was launched through the WDM into the modelocked laser. Up to 140mW of incident pump power were available at the common branch of the WDM.

In Fig. 2 the power characteristics of the Er-laser is shown for TM(π)-polarized emission at 1575nm and TE(σ)-polarized emission at 1561nm wavelength, respectively. The polarization and wavelength of the emission can be adjusted by the pump polarization. With $\pi(\sigma)$-polarized pumping the Er-laser emits at 1575(1562)nm $\pi(\sigma)$-polarized. Threshold pump power and slope efficiencies are 56mW(65mW) and

14.4%(13.2%) for π(σ)-polarized emission, respectively. Both, slope efficiency and output power are more than an order of magnitude better than previously reported results [3],[5].

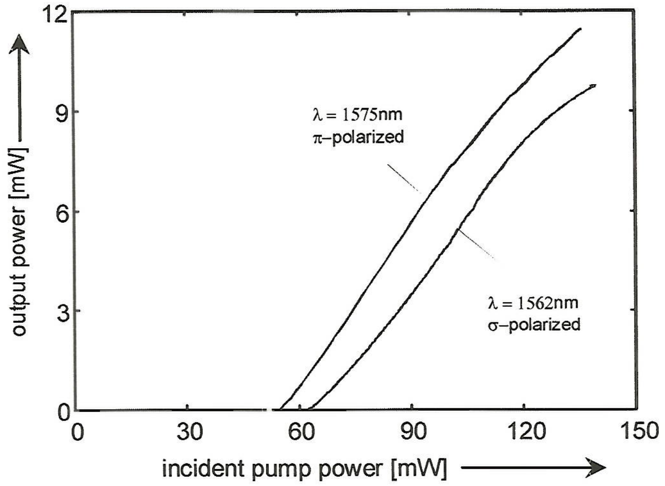

Fig. 2: Output power versus pump power incident at the common branch of the f/o WDM-coupler for both, π- and σ-polarized emission. The polarization dependent emission wavelength is indicated.

To suppress relaxation spiking of the laser during modelocking 9% of the laser output were detected and the detector signal fed to a specially designed control circuit. This circuit generates and superimposes a correction component to the injection current of the pump laser diode to suppress relaxation oscillations by controlled pumping. Up to 42dB reduction of the spectral power density at the dominant peak of the noise spectrum around 450 kHz has been achieved leading to a relative intensity noise (RIN) of the laser of -82.3dB/Hz for 3.5dBm of DC-electrical power (detector signal into 50Ω). At frequencies above 100MHz the laser output is almost shot noise limited.

Results of modelocking are shown in Fig.3 for the 10th harmonic and π-polarized emission. With 33.2dBm of rf-power a pulse width of 9.5ps (FWHM) has been determined by deconvolution of the autocorrelation trace assuming a Gaussian pulse shape. Together with the spectral width of 0.59nm a time bandwidth product of 0.68 results.

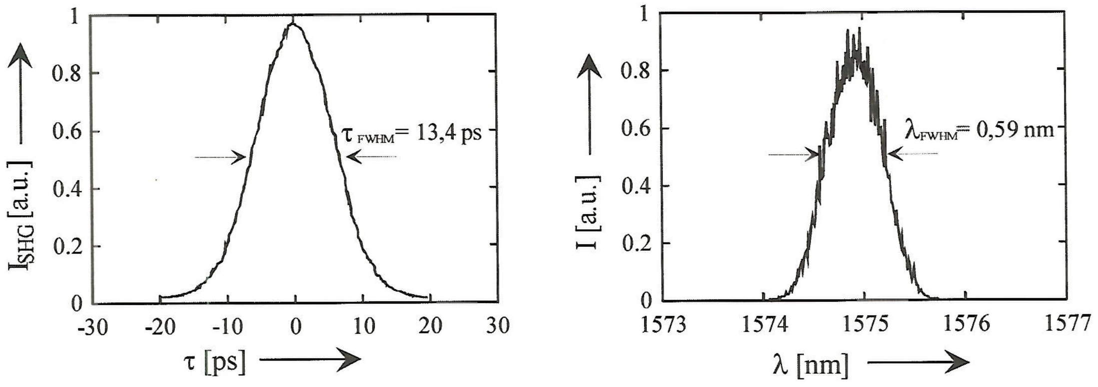

Fig. 3: Autocorrelation trace as function of the relative pulse delay (left) and spectral power density versus wavelength (right) for modelocking at the 10th harmonic (10.295GHz) in π-polarized emission with 33.2 dBm rf-power.

For σ-polarized emission at 1562nm wavelength 5th harmonic modelocking has been obtained at 4.971GHz. Time bandwidth products down to 0.45 have been achieved, but, as a result of the much higher halfwave voltage and the much lower phase modulation index the stability of the pulses was worse compared to the π-polarized case.

First Bit Error Rates have been measured with a pulse repetition rate of 2GHz. The driving frequency was limited by the bit error measurement set up. A $LiNbO_3$ intensity modulator with an extenction ratio of 23dB was used for the digital encoding. In Fig.4 the Eye-diagram at 2GHz is shown. With a pseudo random bit pattern of 2^7-1 length a Bit Error Rate of $1.9 \cdot 10^{-9}$ within half an hour was detected.

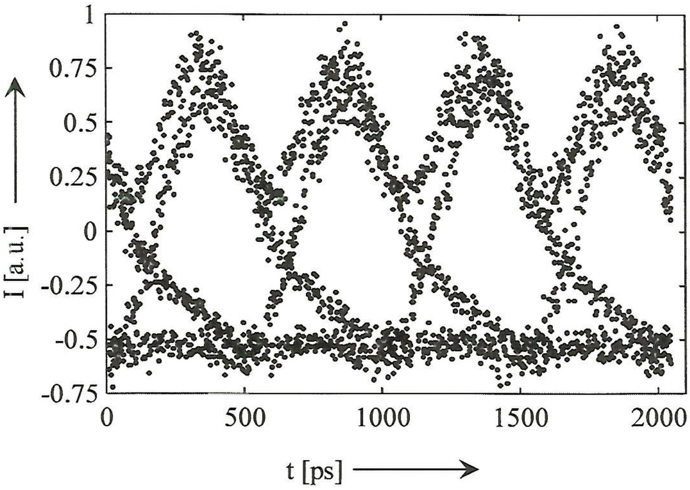

Fig. 4: Eye-diagram of the modulated pulse train at 2GHz

Conclusions

We have demonstrated a harmonically modelocked Ti:Er:$LiNbO_3$-waveguide laser of drastically improved performance compared to former results. Output power and slope efficiency have been improved by more than an order of magnitude. The emission wavelength is now suitable for applications in the third telecommunication window. By feedback controlled pumping the RIN of the laser could be reduced by 42dB. A Bit Error Rate of 10^{-9} at 2nd harmonic modelocking within half an hour has been achieved. By optimization of the travelling wave electrode design it should be possible to increase the pulse repetition rate of 10GHz even further.

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