

10-GHz Mode-Locked Ti:Er:LiNbO₃ Waveguide Laser

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Abstract: Mode-locked laser operation with a stabilized, packaged and diode-pumped Ti:Er:LiNbO₃ waveguide laser has been demonstrated at 1561-nm (TE) and 1575-nm (TM) wavelength with 14% slope efficiency. Pulse widths of < 10 ps at 10-GHz pulse repetition rate have been measured.

Introduction: Mode-locked lasers emitting in the third telecommunication window are promising sources for (soliton) transmission systems. Of particular interest are (harmonically) active mode-locked lasers due to their possibility to synchronize the pulse repetition rate to the high frequency system clock.

Lithium niobate is an attractive material to develop integrated solid state lasers. 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. Using a monolithically integrated intracavity phase modulator as mode locker (FM-type mode locking) and a broadband Fabry Perot waveguide cavity fundamental and harmonic mode locking have already been demonstrated [1],[2]. 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 mode-locked laser with a pulse repetition frequency up to 10 GHz. The laser emits 10-ps-long pulses of more than 100-mW peak power at 1562-nm and 1575-nm wavelength, respectively, depending on the polarization of the pump.

Device fabrication: Half (with respect to the X-direction) of the Z-cut (Y-propagation) LiNbO₃ substrate has been doped near the surface by indiffusion of 28 nm of vacuum-deposited Er at 1130°C during 125 h. Subsequently, photolithographically delineated 7- μ m-wide and 98-nm-thick Ti-stripes have been indiffused at 1060°C during 8h to form the 66.5mm long waveguide channels (see Fig. 1).

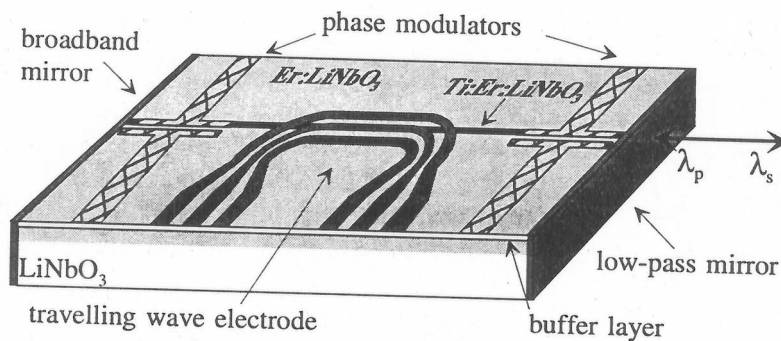


Fig. 1: Mode-locked Ti:Er:LiNbO₃ waveguide laser. (New laser design with two phase modulators)

To avoid excess losses of the TM-mode an 0.6- μ m-thick insulating SiO₂ buffer layer has been vacuum deposited onto the substrate surface prior to the electrode fabrication. The electrode structure of the intracavity travelling wave phase modulator (mode locker) is a symmetrical coplanar microstrip line with a gap to hotline width ratio of 0.75. It has been fabricated by photolithographic lift-off of a sandwich of 30-nm sputtered Ti and 120-nm sputtered Au as a first step. Subsequently, the Au-structure was electroplated up to a thickness of 6 μ m using a cyanidic Au-electrolyte.

The laser cavity is comprised of a broadband high reflector on the rear side to achieve double-pass pumping and of a pump input coupler of optimized output coupling for the signal on the front face (see e.g. [3]). Both mirrors consist of a stack of 13 and 14 SiO₂/TiO₂-layers, respectively, directly deposited onto the polished waveguide endfaces using O₂⁺-ion assisted reactive evaporation.

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 pigtailed. Finally, the pigtailed laser has been packaged including isolation, thermo-electric temperature control ($< \pm 0.01\text{K}$) and two cascaded 10/90% power splitters. FC/PC connection is provided for the pump input, for the laser output (90%), for monitoring of mode-locking stability (1%) and to derive a control signal for the pump feedback stabilization (9%).

Experimental results: The mode-locked Er-doped laser has been investigated in terms of power characteristics, pulse width, spectrum and time-bandwidth product for mode locking at different harmonics (2nd, 5th and 10th) of the axial mode frequency spacing. To drive the mode locker 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 50-Ω load.

To pump the Ti:Er:LiNbO₃-waveguide laser a high-power (up to 150 mW from the laser pigtail) laser diode of about 1480-nm center-wavelength and 12-nm spectral width has been used. The pump power was launched through the WDM into the mode-locked laser. Up to 140 mW of incident pump power were available at the common branch of the WDM. 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 56 mW (65 mW) and 14.4%(13.2%) for $\pi(\sigma)$ -polarized emission, respectively. Both, slope efficiency and output power are more than an order of magnitude better than previously reported results [1],[2].

To suppress relaxation spiking of the laser during mode locking 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 -42 dB 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 -82.3 dB/Hz for 3.5 dBm of DC-electrical power (detector signal into 50 Ω). At frequencies above 100 MHz the laser output is almost shot noise limited.

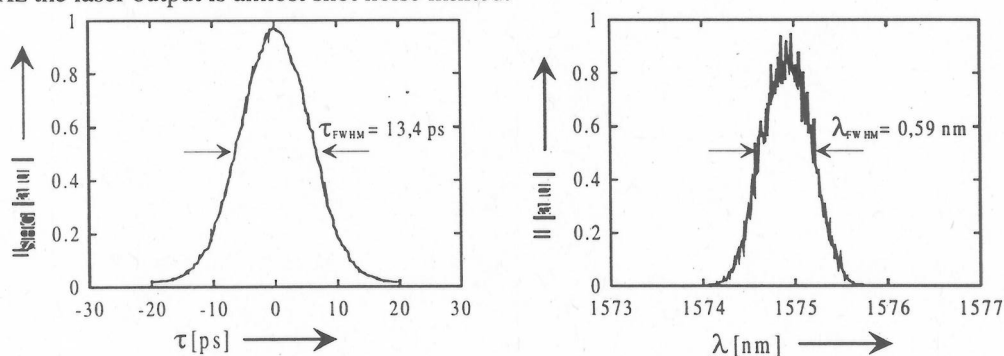


Fig. 2: Autocorrelation trace as function of the relative pulse delay (left) and spectral power density versus wavelength (right) for mode locking at the 10th harmonic (10.295 GHz) in π -polarized emission with 33.2-dBm rf-power.

Results obtained with mode-locked operation are shown in Fig. 2 for the 10th harmonic and π -polarized emission. With 33.2 dBm of rf-power a pulse width of 9.5 ps (FWHM) has been determined by deconvolution of the autocorrelation trace assuming a Gaussian pulse shape. Together with the spectral width of 0.59 nm a time bandwidth product of 0.68 results.

First Bit Error Rates (BER) have been measured with a pulse repetition rate of 2 GHz. The driving frequency was limited by the bit error measurement set up. A LiNbO₃ intensity modulator with an extinction ratio of 23 dB was used for the digital encoding. With a pseudo random bit pattern of 2^7-1 length a BER of $1.9 \cdot 10^{-9}$ was detected during half an hour. To achieve this result, the RF-drive frequency had to be detuned about 500 kHz from the frequency of minimum time-bandwidth product.

This detuning was necessary to reduce high-frequency noise detected at the optimum locking frequency. This noise is well known for harmonical mode locking as beat noise of supermodes [4]. Therefore, we developed an improved laser design with two additional phase modulators, indicated in Fig. 1. By active spatial averaging of the standing wave intensity pattern of the supermodes the beat noise is reduced. With this laser design we measured the spectral power density at the lowest beat noise component. In Fig. 3 the results are shown for 5th harmonic mode locking at optimum locking frequency (time-bandwidth product = 0.49). With 2 MHz push-pull phase modulation the noise maximum is reduced by -24 dB.

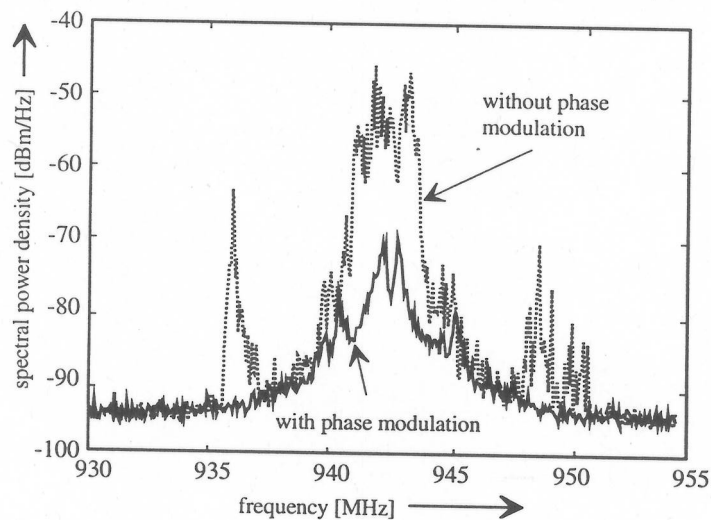


Fig. 3: Electrical spectral power density at the lowest beat noise component at 5th harmonic mode locking and σ -polarized emission with (solid line) and without (dashed line) phase modulation

Conclusions: We have demonstrated a harmonically mode-locked Ti:Er:LiNbO₃ 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. By feedback controlled pumping the RIN of the laser could be reduced by -42dB. A Bit Error Rate of 10^{-9} at 2nd harmonic mode locking during half an hour has been achieved. With an improved laser design it was possible to reduce the high-frequency beat noise by -24 dB.

References:

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