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Monolithic mode-locked erbium-doped $LiNbO_3$ waveguide laser with dielectric multilayer mirror

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Abstract: We fabricated a diode-pumped mode-locked Ti-diffused Er-doped $LiNbO_3$ (Ti:Er:LN) laser with a SiO_2/TiO_2 dielectric multi-layered mirror. The lasing threshold power was 70 mW at 1484 nm, and the slope efficiency was 1.48%. Stable optical pulses with a width of 10.86 ps were measured by driving the phase modulator at 13.575 GHz.

Keywords: Er, $LiNbO_3$, mode-locking, laser

Classification: Optoelectronics, Lasers and quantum electronics, Ultrafast optics, Silicon photonics, Planar lightwave circuits

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1 Introduction

Optical short pulse sources play an important role in advanced high-speed optical communications and are a key technology for various applications. In particular, active mode-locked lasers can generate a transform-limited picosecond pulse train with a high repetition rate, and various applications have been demonstrated, such as transmitter pulse sources in optical-time-division multiplexing (OTDM) communication systems [1, 2]. However, semiconductor mode-locked lasers, for example, have undesired frequency chirping. Fiber lasers with long cavities exhibit small length perturbations due to mechanical vibrations or temperature changes, which tend to affect their output spectra or temporal waveforms [3]. On the other hand, Er-diffused $LiNbO_3$ is capable of low-chirp electro-optic modulation with optical amplification properties in communication bands around 1550 nm [4]. Some mode-locked lasers using this material have been demonstrated [5, 6]. However, in these reports, thermal diffusion was used for Er-doping, which takes more than 100 hours with a diffusion temperature of 1100°C. Not only does this process need a long time, but also the crystallinity of $LiNbO_3$ may be affected because this high diffusion temperature is close to the Curie temperature (1140°C). To solve this problem, we recently reported an amplifier and a reciprocating optical modulator using Er-doped $LiNbO_3$ (Er:LN) in which Er was doped during Czochralski crystal growth [7, 8]. In the present work, we formed a Ti-diffused optical waveguide in Er:LN (Ti:Er:LN) and used it as both a mode-locker and a gain medium to fabricate a mode-locked Ti:Er:LN laser. We investigated the lasing characteristics and the emitted pulses.

2 Device fabrication

We used a Z-cut Er (0.5 mol%)-doped $LiNbO_3$ 3-inch-diameter wafer as a substrate. First, we fabricated Ti-diffused optical waveguides in the Er:LN. A 95-nm-thick Ti film was deposited on the -Z face by electron-beam evaporation using a Ti metal source. Ti-diffusion was carried out at 1030°C for 7 hours with 250 ml/min of wet-O_2 gas flow. Second, a 600-nm-thick SiO_2 buffer layer and a traveling-wave electrode were formed on the waveguide. The electrode was formed by photolithography and electroplating gold to a thickness of approximately 10 μm on a 10-nm-thick Ti adhesion layer. Then, we diced the wafer into chips and polished both end facets of the waveguide. The waveguide length was 50 mm, which corresponds to a free spectral range (FSR) of 1.357 GHz. Next, a Fabry–Perot waveguide cavity was fabricated

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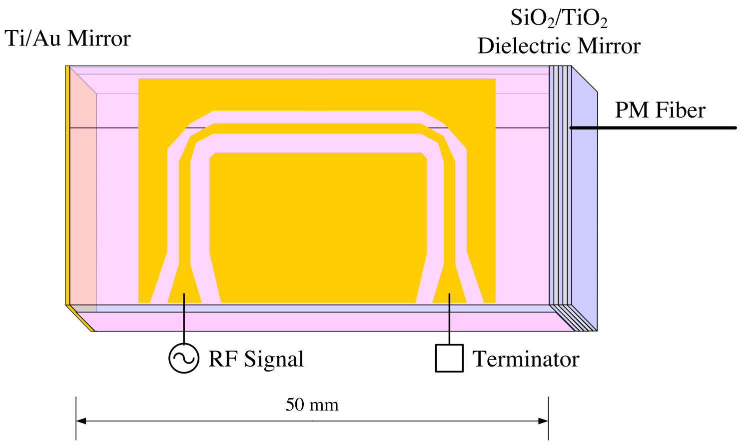

Fig. 1. Device configuration of mode-locked Ti:Er:LN laser.

by forming an RF-sputtered SiO_2/TiO_2 dielectric mirror and an evaporated Ti/Au mirror on the two end facets of the Ti:Er:LN waveguide. Five pairs of SiO_2/TiO_2 layers were formed. The thicknesses of the sputtered SiO_2 and TiO_2 layers were 306 nm and 193 nm, respectively, and the measured reflectivities of the SiO_2/TiO_2 stack at 1484 nm and 1602 nm were 1.9% and 77%, respectively. We finally attached and fixed a polarization maintaining fiber (PMF) to one end face of the waveguide by using UV-curing optical cement. Figure 1 shows the structure of the fabricated mode-locked Ti:Er:LN laser.

3 Experimental results

First, the basic properties of the waveguide were evaluated before fabricating the mirrors. The propagation loss of TM-mode light at 1602 nm was 1.56 dB/cm. The loss was mainly attributed to Er-ion absorption.

As for the gain characteristics, the propagation loss and coupling losses of the waveguide were fully compensated for with TM-mode pump light of 85 mW at 1484 nm.

The pump light was launched into the waveguide through the dielectric

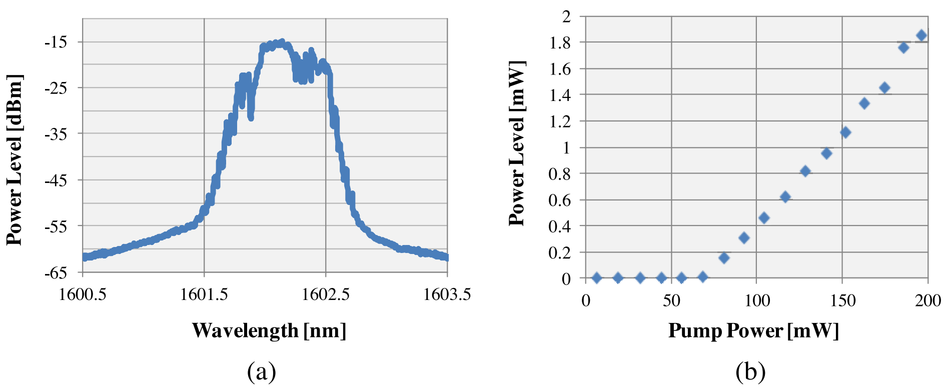

Fig. 2. (a) Optical spectrum of free running laser. (b) Power characteristic of mode-locked Ti:Er:LN laser.

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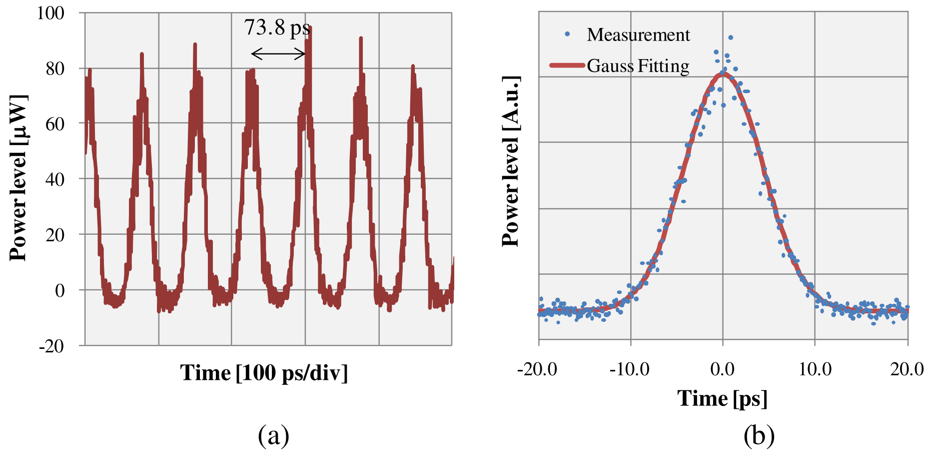

Fig. 3. (a) Pulse train and (b) Intensity autocorrelation of a pulse and its gauss fitting generated by mode-locked Ti:Er:LN laser driven at 13.575 GHz.

mirror to induce lasing, and laser light was emitted from the same end face. The spectrum and power characteristic are shown in Figure 2. From the spectrum of the free-running laser in Figure 2 (a), the laser emission was centered at 1602 nm. The pump power was set to about 70 mW. The slope efficiency of the mode-locked laser was 1.48%, as shown in Figure 2 (b).

We used a phase modulator to investigate the mode-locked laser operation. Stable mode-locking operation was achieved at 1.357 GHz, which corresponded to the fundamental of the longitudinal-mode frequency spacing. The RF power level was 26 dBm. We confirmed higher-order mode locking also at 2.718 GHz (second harmonic), 3.817 GHz (third harmonic), and so on. Stable pulses with the narrowest pulse width in this study were achieved at 13.575 GHz (10^{th} harmonic). Figure 3 (a) shows a pulse train measured with a sampling oscilloscope. The observed pulse repetition time was 73.8 ps. The pulse width measured with an autocorrelator was 10.86 ps, as shown in Figure 3 (b). Using these results, we calculated the time–bandwidth product to be 0.483. This value is close to the transform-limited product for a Gaussian pulse and indicates a pulse with a small chirp.

Compared with a previous report of a Ti:Er:$LiNbO_3$ mode-locked laser [5], we succeeded in producing pulses with higher repetition rate because the electrode was adapted to broadband modulation. Although the pulse width in this study was slightly broader, we could also acquire near Fourier-transform-limited pulses because of the narrower laser spectral width, which depended on the reflection bandwidth of the dielectric mirror.

4 Conclusions

We proposed a mode-locked Ti:Er:LN laser sandwiched by a dielectric multi-layered mirror and a Ti/Au mirror. Active mode-locking at a repetition frequency of up to 13.575 GHz was achieved. The narrowest pulse width obtained was 10.86 ps, and the emitted pulses were nearly transform-limited.

This mode-locked laser has a longer laser cavity length than mode-locked

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semiconductor lasers usually have; therefore, we can expect a pulsed laser with narrower pulse width and higher quality factor. Additionally, pulse generation with greater short-term stability is achievable. For semiconductor lasers, the external cavity structure allows the length of the optical cavity to be increased and introduces various advantages, but it also causes mechanical instability and increased cost.

Similarly, integrated optical devices are more compact and exhibit greater long-term stability compared with hybrid lasers, such as fiber ring lasers. Although the cavity length of fiber lasers is longer than that of Ti:Er:LN lasers, the long optical cavity length causes instability because of its sensitivity to external environmental changes. In addition, the fundamental mode of a fiber laser is generally about 1 MHz, so supermode noise appears in high-repetition-rate pulse generation.

We can see from the above that a mode-locked Ti:Er:LN laser has the advantage of stable pulse emission at multi-GHz repetition rates. Furthermore, $LiNbO_3$ modulators are suitable for integration and make it possible to generate chirp-free optical pulses.

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