Status and Prospects of Lithium Niobate Integrated Optics

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***Abstract*—Status and prospects of $LiNbO_3$ (LN) integrated optics will be reviewed with emphasis on waveguide lasers, nonlinear frequency converters, single photon devices and their respective applications. Moreover, a new platform for LN-based nanophotonics will be introduced.**

Keywords-integrated optics; lithium niobate; waveguide laser; frequency converter; photon pair source; quantum memory.

I. INTRODUCTION

Among the different materials used for integrated optics since a long time, ferroelectric Lithium Niobate ($LiNbO_3$, LN) offers a unique combination of excellent electro-optical, acousto-optical, and nonlinear properties. Moreover, it can be easily doped with laser-active ions and enables a simple fabrication of low-loss optical waveguides by doping with transition metals or by ion-exchange processes. Meanwhile, integrated LN devices find wide commercial applications e.g. as high-bandwidth electro-optical modulators for the optical internet or as phase modulators for signal processing in all-optical gyroscopes.

The status of LN integrated optics will be reviewed emphasizing new waveguide structures, devices and applications in the last years. In particular, the large potential of waveguide lasers, of nonlinear frequency converters and ultra-fast all-optical signal processing devices and of single photon sources and quantum memories will be discussed. Finally, Lithium-Niobate-On-Insulator (LNOI) will be introduced as a promising new platform for LN-based integrated optics and nanophotonics.

II. WAVEGUIDE LASERS

LN can be easily doped with laser-active (rare earth) ions by several methods; in particular, a simple diffusion technique proved to be very successful. Based on this technique, a whole family of Er-doped waveguide lasers of excellent quality has been developed emitting in the wavelength range 1530 nm < λ < 1603 nm. Free running lasers of the Fabry-Pérot type, harmonically mode-locked lasers (5 ps / 10 GHz), Q-switched lasers (4 ns / 1 kHz / 1 kW), Distributed Bragg Reflector- (DBR-) and Distributed Feedback- (DFB-)lasers, self-frequency doubling devices, ring and acousto-optically tuneable lasers have been reported [1]. They all are optically in-band pumped by λ = 1480 nm radiation.

Recently, also Tm-doped waveguide lasers have attracted increased attention [2]. By exploiting the $^3F_4 \rightarrow {}^3H_6$ transition, their emission wavelength is within the band 1650 nm < λ < 1900 nm. Such lasers will find applications in spectroscopy, medicine, remote sensing and material processing. As example, a Ti:Tm:LN waveguide laser of very low threshold and long emission wavelength will be reported [3]. The simple Fabry-Perot type laser - without any wavelength selective component in the cavity - is in-band pumped at 1650 nm and emits near 1890 nm (Fig. 1). This is the longest emission wavelength from a Tm:LN laser reported so far. The strong relaxation oscillations can easily be suppressed by feedback controlled pumping.

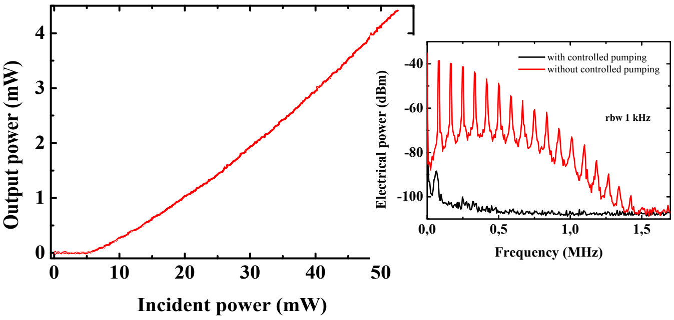

Figure 1. Left: Power characteristics of a Ti:Tm:$LiNbO_3$ waveguide laser: output power (TE) at 1890 nm emission wavelength versus incident pump power (TE) at 1650 nm. Right: Relaxation oscillations, displayed as RF-spectrum of the photodiode current without (red) and with (black) feedback controlled optical pumping (here: 14 mW pump power) [3].

III. SECOND ORDER NONLINEAR DEVICES

It was the quasi phase matching (QPM) concept, realized by periodic poling of LN waveguides with periodicities from ~ 30 µm down to < 1 µm, which enabled an enormous broadening of the wavelength range accessible for nonlinear frequency converters and all-optical signal processing devices. They all rely on three-wave nonlinear interactions, determined by energy conservation and QPM.

As examples, nonlinear wavelength converters in the mid-infrared (MIR), near-infrared (NIR) and visible spectral ranges will be presented with most interesting applications in absorption spectroscopy, optical communications and stellar interferometry. To introduce just one example, special modules with Ti:PPLN waveguides have been developed for nonlinear wavelength conversion from the NIR to the MIR and back again by sum frequency (SFG) and difference frequency generation (DFG) (Fig. 2) [4]. Using these modules, free space optical communication in an atmospheric window was demonstrated at 3.8 µm wavelength. Using the same approach, also MIR absorption spectroscopy of methane was investigated in the wavelength range 3.26 µm < λ < 3.42 µm.

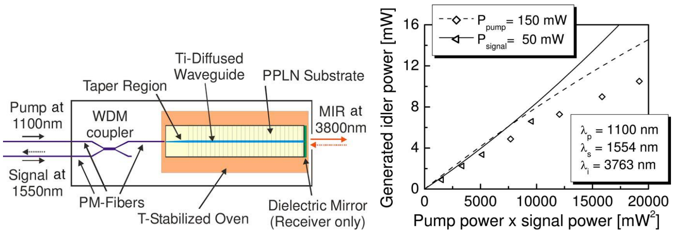

Figure 2. Left: Scheme of the transmitter and receiver modules for MIR generation via DFG. The receiver module has an additional dielectric mirror for the pump to enable copropagating DFG of MIR and pump radiation from right to left. Right: Measured output power of the transmitter module (symbols), depending on pump and signal power levels coupled to the waveguide. The curves represent corresponding calculations [4].

IV. SINGLE PHOTON (PAIR) SOURCES AND QUANTUM MEMORIES

Periodically poled LN (PPLN) waveguides enabled the development of a variety of single photon (pair) sources for applications such as quantum key distribution (QKD) [5]. The principle is to exploit spontaneous parametric down conversion (SPDC) to generate a pair of (entangled) photons. Energy of pump photons and periodicity Λ of the ferroelectric domains determine energy and bandwidth of the two generated photons. As example, special sources are currently developed for quantum repeaters; the wavelength of one photon matches an absorption line of a rare-earth doped crystal or waveguide (e.g. 880 nm for Nd) used as quantum memory, while the wavelength of the other is in a telecom band (e.g. 1345 nm).

Several rare earth-doped waveguides have been developed during the last years not only for laser applications, but also for photon echo-based quantum memories. To be specific, special Er-doped waveguides have been fabricated (Fig. 3, left) to demonstrate e.g. stimulated photon echoes in the ensemble of Er-ions. More recently, Tm-doped channel waveguides have been developed (Fig. 3, right) and used to demonstrate single photon storage and retrieval [6].

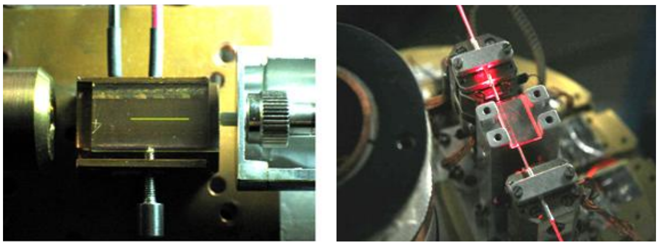

Figure 3. Left: Ti:Er:LN waveguide (λ_{memory} = 1531 nm). Right: Ti:Tm:LN waveguide (λ_{memory} = 795.5 nm) [6].

V. LITHIUM NIOBATE ON INSULATOR (LNOI) PLATFORM, NANOPHOTONIC WAVEGUIDES AND DEVICES

Recently, a novel platform for LN waveguides of high refractive index contrast was demonstrated [7]. Similar to the fabrication of Silicon-On-Insulator (SOI), an ion-implantation based "smart cut" process is used, followed by crystal-bonding, to fabricate a single crystalline LN film on a PECVD-deposited SiO_2-layer on a LN substrate. Therefore, the new wafer-scale platform is called LNOI (Fig. 3). Similar to SOI, it enables the development of "photonic wires", and of ultra-compact integrated devices and circuits [7]. However, - in contrast to SOI – the excellent electro-optic, acousto-optic and nonlinear optical properties of LN can be exploited. Moreover, also LNOI can be doped with rare-earth ions to get a laser active material.

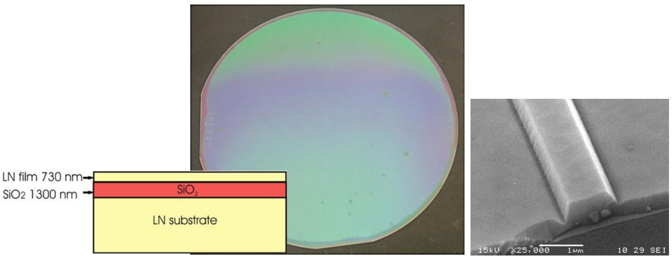

Figure 4. Schematic cross-section (left) and photograph (middle) of a LNOI-wafer of 3`` diameter. Right: SEM micrograph of a LNOI "photonic wire" of 1 µm top width and 730 nm thickness [7].

VI. CONCLUSIONS

Status and prospects of LN integrated optics have been reviewed emphasizing the most promising fields and applications. Though impressive results have been achieved, there are still a large number of laser-active ions with numerous electronic transitions to be investigated as amplifiers, lasers and even quantum memories in LN waveguides. The enormous wavelength flexibility of nonlinear wavelength converters will enable additional attractive applications. And the field of integrated quantum optics just started to grow at an enormous rate. It might be that LNOI serves as an attractive platform to develop nanophotonic devices and to combine them in integrated circuits for a large bunch of applications.

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