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Integrated Photonics in $LiNbO_3$: Recent Developments

(Invited Paper)

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Abstract: Recent developments of integrated photonics in Lithium Niobate (LN) are reported. They include new waveguide structures such as low loss ridge guides and photonic crystal structures, a ring resonator gyroscope, an Erbium doped frequency shifted feedback laser for frequency domain ranging, nonlinear parametric devices for mid infrared (MIR) spectroscopy, and single photon pair sources for applications in quantum cryptography.

Keywords: integrated optics, photonics, lithium niobate

1. Introduction

Lithium Niobate (LN) has excellent electro-optical, acousto-optical, and nonlinear properties. It can be easily doped with laser-active ions and allows a simple fabrication of low-loss optical waveguides. Moreover, it can be periodically poled to tailor its nonlinear properties. Therefore, it is one of the most versatile materials for integrated photonics with numerous applications in optical communications, instrumentation and sensing.

In this contribution we will highlight the impressive progress of recent device development by reporting the latest results of selected examples [1]. They include new waveguide structures such as low loss ridge guides and photonic crystal structures, a ring resonator gyroscope, an Erbium doped frequency shifted feedback laser for frequency domain ranging, nonlinear parametric devices for mid infrared (MIR) spectroscopy, and single photon pair sources for applications in quantum cryptography.

2. Ridge Guides and Photonic Crystal Structures

Using the reliable, well-known technique of Ti-indiffusion, optical channel waveguides of very low propagation losses (~ 0.03 dB/cm at 1550 nm) can be fabricated in LN; they are used in most of the devices presented below. Ti:LN channel guides, however, are weakly guiding structures with relatively large waveguide cross-sections and, therefore, large mode distributions (typical: 3.4 µm x 4.7 µm at 1550 nm); this represents a limitation for the efficiency of electro-optical, nonlinear and laser devices. To improve the performance of such devices, we have developed new waveguide structures such as ridge guides and photonic crystal structures (Fig. 1).

Due to a strongly confined mode distribution, ridge guides can enhance the efficiency of electro-optical and nonlinear effects and lower the threshold of waveguide lasers. Therefore, we developed a chemical etching technique to fabricate high-quality mono-mode ridge guides in Ti:LN with a width between 4.5 µm and 7 µm and a height up to 8 µm [2]. Alternatively, the ridge can be fabricated first, followed by a Ti-indiffusion into the ridge only. Smooth surfaces and side walls result in low propagation losses (TE: 0.08 dB/cm; TM: 0.25 dB/cm) at 1550 nm wavelength.

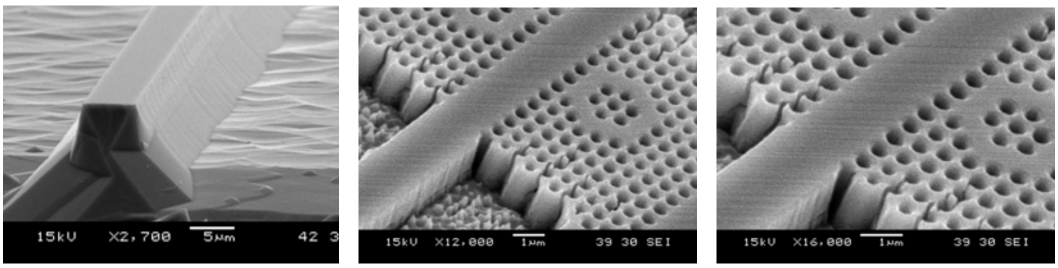

Figure 1. Ridge guide in Z-cut LN (left). Micrographs of a photonic crystal structure in proton exchanged LN observed with different magnifications of the SEM (middle and right).

For the same reason, the inductively coupled plasma (ICP)-reactive ion etching (RIE) technique was optimized to fabricate 1.5-μm-wide photonic crystal structures in a proton-exchanged surface layer of LN. The pore distance and diameter are 500 nm and 340 nm, respectively [3].

3. Ring Resonator Gyroscope

Ring resonators belong to the most basic structures of integrated optics and have a wide range of potential applications. They can be used as wavelength filter and (de-)multiplexer, but also as Sagnac-interferometer to measure rotation rates. Such sensors are attractive devices, which, in contrast to their mechanical counterparts, have no moving parts. Unlike ring resonators for wavelength filtering, rotation rate sensors usually require a much larger diameter; this is due to the Sagnac effect, in which a nonreciprocal phase shift is induced proportional to the area enclosed by the ring.

We recently demonstrated the first ring resonator fabricated in LN for rotation rate sensing with a diameter of 60 mm [4]. It consists of a low-loss Ti:LN waveguide ring cavity and a straight waveguide tangential to the ring forming a directional coupler. Both ends of the straight guide were connected to optical fibers. The whole substrate was glued to a copper base plate, which was temperature-stabilized by a thermoelectric cooler/heater, and packaged in an aluminum housing. In this way, light can be coupled into the resonator propagating clockwise or counter-clockwise. By slightly tuning the laser frequency (around 1530 nm wavelength), we measured a resonator finesse of 8.4 in both modes of operation, corresponding to a cavity Q of $2.2x10^6$ (Fig. 2, left).

To measure the Sagnac-effect induced frequency shift of the cavity resonance towards higher (lower) frequencies for clockwise (counter-clockwise) operation, we operated the ring resonator in both directions simultaneously using a narrow line width laser. The frequency was modulated around a cavity resonance to allow a sophisticated signal processing technique with two lock-in amplifiers (Fig. 2, middle). In this way, the mid-frequency of the laser could be locked to a cavity resonance of the non-rotating ring.

Consequently, if rotated, the transmitted intensities for light propagating clockwise and counter-clockwise changed in opposite directions. Therefore, the difference signal was proportional to the rotation rate; a corresponding result is shown in Fig. 2 on the right as a function of time (integration time: 30 ms). The noise equivalent rotation rate for an integration time of 1s is 0.01 rad/s - still far away from the theoretical limit of 0.09 rad/h.

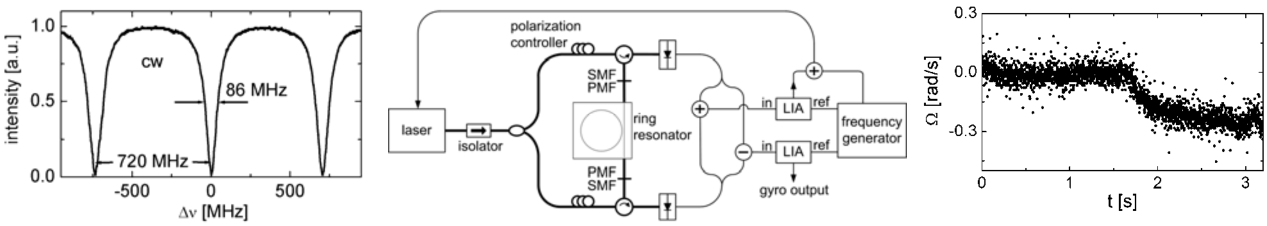

Figure 2. Measured cavity resonances for clockwise operation (left). Schematical experimental setup for gyroscope signal processsing (middle) with PMF: polarization maintaining fiber, SMF: single mode fiber, LIA: Lock-in amplifier. Gyro output versus time with the ring resonator at rest and with constant rotation rate of -0.24 rad/s (right).

4. Frequency Shifted Feedback (FSF-) Laser

$Er:LiNbO_3$ is an excellent laser material for integrated optics. It can be easily fabricated in the surface layer of a $LiNbO_3$ substrate by indiffusion of a thin vacuum-deposited Er layer. Afterwards, optical waveguides can be defined in the laser-active surface layer by the standard indiffusion technique of Ti-stripes. If optically pumped by 1480 nm radiation, a wavelength-dependent gain results of up to 2 dB/cm in the wavelength range of 1530 to 1611 nm.

Using such Er-diffusion doped substrates, an acousto-optically tuneable frequency shifted feedback (FSF-) laser was developed. It consists of an integrated acousto-optical wavelength filter, incorporated in the amplifier section, and of dielectric end face mirrors defining the waveguide resonator. The wavelength filter is composed of two polarization splitters and an acousto-optical polarization converter in between; the converter has a tapered directional coupler for guided surface acoustic waves (SAW) (Fig. 4, left). The transmitted wavelength is selected by the frequency of the SAW (~ 170 MHz) inducing an acousto-optical polarization conversion. As this process is determined by phase matching, a narrow filter bandwidth of about 1 nm results, depending on the interaction length. Due to the interaction with a running SAW, a frequency shift of about 170 MHz is imposed on the optical wave each time it passes the acousto-optical filter. Therefore, after each round trip, the frequency of the intracavity laser field is shifted by two times the SAW frequency. The result is a relatively broad line width of the laser emission of about 180 pm (pump power dependent). The output power is very stable with time.

The laser's highly resolved output spectrum consists of a comb of narrow lines of constant frequency spacing (corresponding to the free spectral range of the laser cavity) (Fig. 4, right). This comb changes its frequencies as a whole with the enormous chirp rate of 2.4×10^{17} Hz/s. Therefore, the device is ideally suited for frequency domain ranging using a Michelson-interferometer. We have demonstrated a spatial resolution of about 1.6 µm/kHz [5, 6].

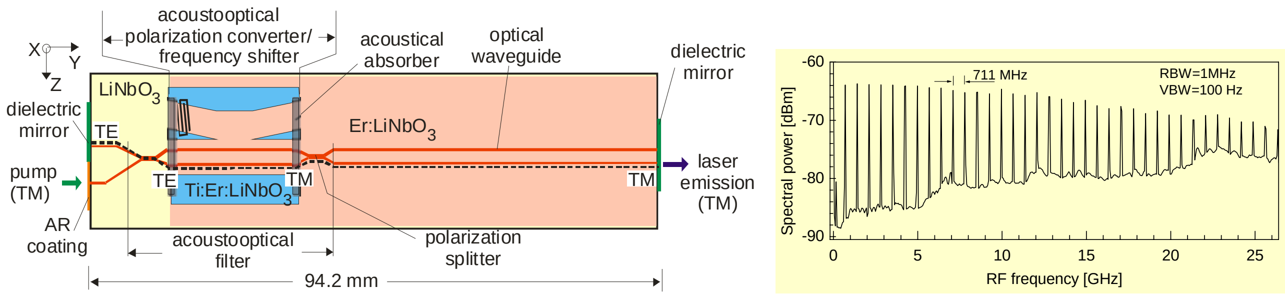

Figure 3. Schematic diagram of the frequency shifted feedback (FSF) laser with intracavity acoustooptical filter and Ti-indiffused optical waveguide structure in Er:$LiNbO_3$ (left). RF spectrum of the output of the FSF laser measured with a fast photodiode (right). The discrete frequency components result from the beating of the different lines of the moving frequency comb with a separation of 711 MHz (equal to the laser cavity FSR). RBW: Resolution Bandwidth, VBW: Video Bandwidth of the RF spectrum analyzer.

5. Nonlinear Optical Parametric Devices for MIR-Spectroscopy

There has also been a considerable worldwide progress of the development of integrated, tuneable, nonlinear parametric devices for efficient wavelength conversion. All-optical signal processing in the near infrared (NIR) mainly for fiber optical communications and absorption spectroscopy in the mid-infrared (MIR) mainly for environmental analysis are the most important applications. The common feature of all devices is the use of waveguides in PPLN-substrates exploiting the largest nonlinear coefficient d_{33} and quasi-phase matching. Due to the mode confinement in long, narrow channel guides a high wavelength conversion efficiency can be expected, up to several orders of magnitude larger than for bulk optical devices. For MIR-spectroscopy in the wavelength range 2700 nm < $\lambda_{s,i}$ < 3500 nm tuneable integrated optical parametric generators (OPG) and oscillators (OPO) [7], as well as difference frequency generators (DFG) have been developed. As an example we report here our latest results on DFG for methane absorption spectroscopy.

Ti:PPLN channel waveguides of 20 µm width and 90 mm length with poling periods around 27µm were fabricated to develop the MIR-source. A fiber-Bragg-grating stabilized laser diode at 1.064 µm acts as pump source, and a tuneable external cavity laser (ECL) as signal source. The mid-infrared idler wavelength can be tuned from 3.3 µm to 3.6 µm by changing the signal wavelength and the device temperature to maintain phase matching. At fixed temperature tuning around the phase match wavelength over a few nanometers is possible as well (see also Fig. 4 right). Up to 180 µW of idler power could be generated with 160 mW (20 mW) signal (pump) power.

The experimental set up to investigate absorption of methane/air gas mixtures in a 39.5 cm long cell is shown in Fig. 4 on the left. Two mercury cadmium telluride photo-detectors were used in combination with two lock-in amplifiers to measure the MIR input and output power levels. The data processing was done with a computer. As example, spectra measured at different methane concentration levels in air (1 atm total pressure) are shown in Fig. 4 on the right. The demonstrated sensitivity of the present measurement set up is well below the mbar level [8].

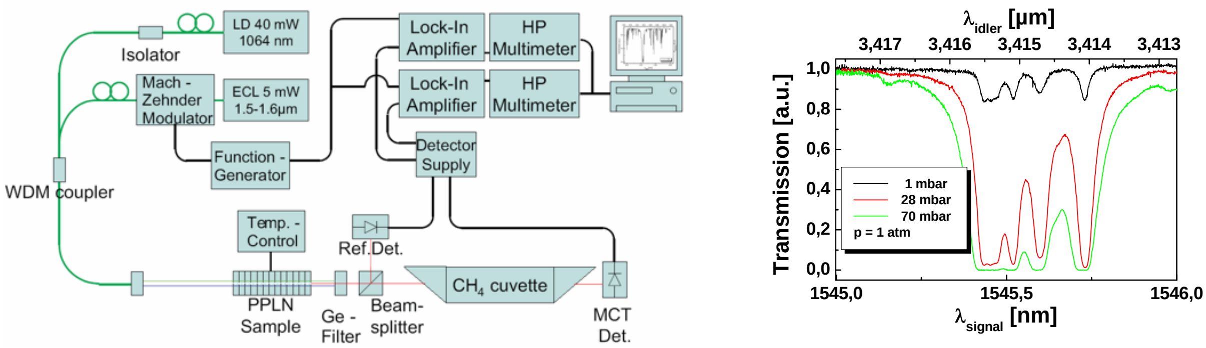

Figure 4. Experimental set-up (left) to measure the absorption by methane at different methane partial pressures in air (1 atm total pressure) with an integrated optical difference frequency generator as tuneable MIR source around 3.4 µm wavelength (right).

6. Single Photon Pair Sources

For quantum cryptography and quantum information technology in general, integrated photonic LN and PPLN devices become more and more important. They offer the best performance for the generation and manipulation of single photons. For example, integrated sources of single photon pairs are, in principle, optical parametric generators with proton exchanged or Ti indiffused waveguides in PPLN; however, they are operated at very low pump power levels.

We have developed Ti:PPLN waveguides for single photon pair generation in the wavelength range from 1530 to 1570 nm. The wavelength and polarization of the pump, the PPLN periodicity and waveguide dispersion determine the wavelength of both signal and idler photons via energy conservation and phase matching. As type II phase matching was exploited both generated photons have orthogonal polarizations. The PPLN periodicity is around 9 µm, the waveguide width 7 µm. As an example: pumping at 755 nm wavelength yields photon pairs with 1490 nm (signal) and 1535 nm (idler) wavelength, respectively. The device is typically pumped with 10 mW power only. The resulting power of the signal and idler photons is in the pW range.

Fig. 5 shows experimental results clearly demonstrating that photon pairs have been generated by measuring the arrival time difference of the individual photons of orthogonal polarizations. Avalanche photo diodes operated in the Geiger mode have been used to detect the photons.

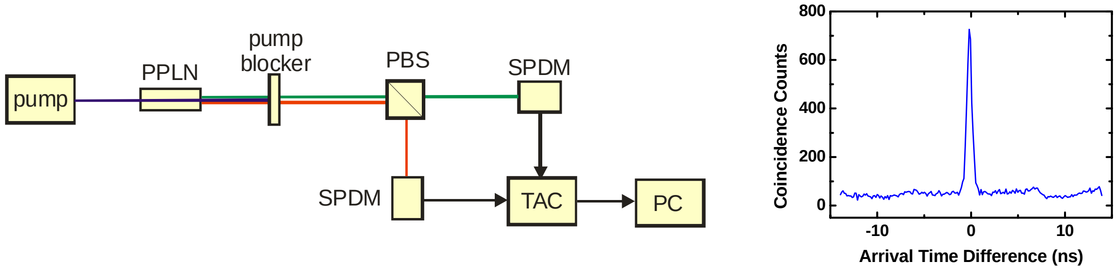

Figure 5. Experimental set-up for the generation and detection of orthogonally polarized photon pairs (left). PBS: polarization beam splitter, SPDM: single-photon detection module, TAC: time-to-amplitude converter, PC: personal computer. Result of a correlation measurement showing the number of detected photon pairs (“coincidence counts”) versus arrival time difference (right).

7. Conclusion

The impressive progress of recent device development in LN was highlighted by reporting latest results of selected examples. They include low loss ridge guides and photonic crystal structures, a ring resonator gyroscope, an Erbium doped frequency shifted feedback laser for frequency domain ranging, nonlinear parametric devices for mid infrared (MIR) spectroscopy, and single photon pair sources for applications in quantum cryptography.

It remains a great challenge to develop photonic optical circuits of even higher functionality and complexity by combining several (many) different devices on a single chip of Lithium Niobate, a substrate material for integrated photonics of enormous versatility.

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