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All-Optical Signal Processing Devices with (Periodically Poled) Lithium Niobate Waveguides

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Abstract: Integrated optical Lithium Niobate devices for all-optical signal processing in the 1.5 µm wavelength range are reviewed. Besides nonlinear devices with periodically poled waveguides tunable Ti:Er:$LiNbO_3$ waveguide lasers are presented. Novel waveguide structures are reported.

OCIS codes: (130.3730) Lithium niobate; (190.4410) Nonlinear optics, parametric processes;

1. Introduction

During the last years a variety of efficient integrated optical devices for ultra-fast all-optical signal processing in the 1.5-µm wavelength range has been developed. By exploiting quasi phase matched second order nonlinear interactions in Ti-indiffused or proton exchanged waveguides in periodically poled Lithium Niobate (Ti:PPLN, pe:PPLN) wavelength conversion, dispersion compensation, parametric amplification, λ-selective time division multiplexing, phase- and polarization-switching as well as spatial switching have been demonstrated [1]. Moreover, a whole family of Er-doped waveguide lasers has been developed in LN emitting in the wavelength range $1530 \text{ nm} < \lambda < 1603$ nm [2]. In particular, the new integrated frequency shifted feedback lasers are attractive devices for all-optical signal processing and allow e.g. optical frequency domain ranging with high accuracy. To improve the performance of nonlinear and laser devices, new waveguide structures such as ridge guides, photonic crystal guides and bent PPLN structures have been developed.

It is the aim of this contribution to review the state of the art of integrated nonlinear and laser devices in LN for all-optical signal processing. Applications in the field of optical communications and metrology are emphasized.

2. Novel waveguide structures

Due to small mode distributions ridge guides can enhance the efficiency of nonlinear effects and lower the threshold of waveguide lasers. Therefore, we developed a chemical etching technique to fabricate high quality monomode ridge guides in Ti:LN with a width between 4.5 µm and 7 µm and a height up to 8 µm (Fig. 1, left) [3]. Smooth surfaces and side walls have been obtained by adding some ethanol into the HF/HNO_3 etchant resulting in low propagation losses (TE: 0.3 dB/cm; TM: 0.9 dB/cm) at 1.55 µm wavelength.

For the same reason an inductively coupled plasma (ICP)-reactive ion etching (RIE) technique was developed to fabricate 1.5 µm wide photonic crystal waveguides with pore distance and diameter of 500 nm and 340 nm, respectively, with first promising results (Fig. 1, middle) [4].

The efficiency of nonlinear devices also strongly depends on the interaction length, which should be as long as possible. Therefore, Ti:PPLN structures with a 180° bend of a radius of curvature from 20 mm to 36 mm and an overall length up to 180 mm have been developed. As the domains preferentially grow with boundaries parallel to the main crystallographic axes, their orientation had to be changed abruptly three times by 60° (Fig. 1, right). On the other hand, the domain periodicity has to be continuously adapted to get perfect quasi phase matching along the whole interaction length.

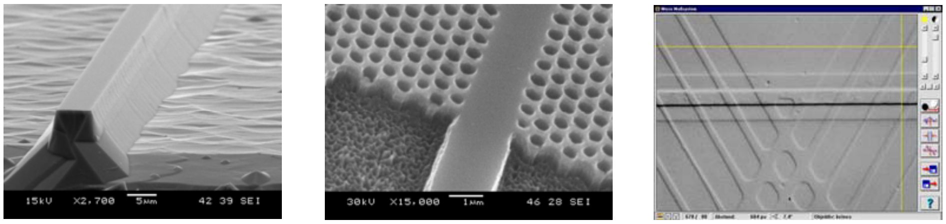

Fig. 1: SEM micrographs of a chemically etched ridge guide in Ti:PPLN (left) and of a pe:LN photonic crystal waveguide (middle). Selectively etched surface of a bent Ti:PPLN waveguide section, where the domain orientation changes by 60°; domain periodicity Λ ~ 17 µm (right).

3. All-optical wavelength converters

All-optical wavelength conversion based on quasi phase matched quadratic nonlinear interactions in Ti:PPLN channel guides offers a large tuning range, quantum-limited noise and ultra-fast response. Second Harmonic Generation (SHG), Difference Frequency Generation (DFG), cascaded SHG and DFG (cSHG/DFG), Sum Frequency Generation (SFG), and cascaded SFG and DFG (cSFG/DFG) have been exploited for efficient λ-conversion.

As an example, Fig. 2 presents on the left a scheme of a fully fiber connected optical subsystem with a Ti:PPLN channel guide as core component for polarization-independent wavelength conversion by **cSHG/DFG**. This device was the key component in a 21.4 Gbit/s (per channel) differential quadrature phase-shift keying (DQPSK) transmission experiment with 22 WDM channels over more than 10000 km [5]; it was used in the middle of the span for compensation of chromatic dispersion and nonlinear impairments. Figure 2 shows on the right the output spectrum of the converter of about –9 dB conversion efficiency.

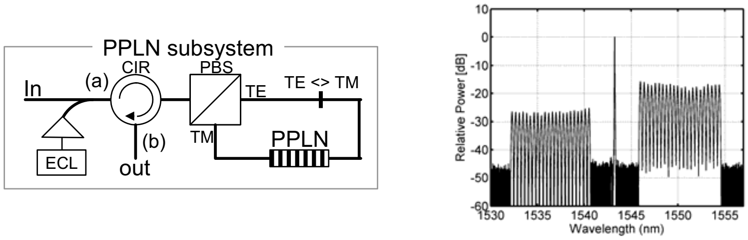

Fig. 2: Schematical setup of the polarization independent wavelength converter with Ti:PPLN channel guide (left). Output spectrum of the converter during multi-channel conversion by cSHG/DFG (right).

Even optically tunable λ-conversion could be demonstrated by exploiting **cSFG/DFG** using two independent pump waves [6]. The first enables efficient SFG of a high bit rate signal, followed by DFG with the second pump. Tuning of the wavelength of the second pump results in tuning of the idler wavelength. A conversion efficiency from the (transmitted) signal to the generated idler of –4.7 dB was achieved with pump power levels of ~275 mW.

4. Optical parametric amplifiers

Cascaded difference frequency generation (cSHG/DFG) is always accompanied by optical parametric amplification (OPA) of the signal. Theory predicts that a small signal gain higher than 30 dB can be achieved, high quality waveguides of sufficient length, negligible photorefractive effects and sufficient pump power assumed. As an example Fig. 4 presents on the left the calculated small signal gain versus the interaction length, 300 mW pump power assumed. In the middle of Fig. 4 the gain in 80 mm and 160 mm long Ti:PPLN channel guides is shown as function of the wavelength for three different domain periodicities. It is most attractive that the center wavelength of the OPA characteristics with a spectral width of 50-70 nm can be adjusted by the period of the microdomain structure alone.

Experimentally, a cw-gain of up to 4 dB was achieved in an 8.3 cm long waveguide with 765 mW coupled pump power (λ = 1558 nm). In a pulsed mode of operation (100 ns; 1 MHz) a gain of 12 dB was observed at 1.3 W peak power (see Fig. 4 on the right). The measured gain is still considerably smaller than the predicted one. Currently, additional experiments are performed in long bent Ti:PPLN waveguides, in waveguide resonators and in periodically poled ridge guides.

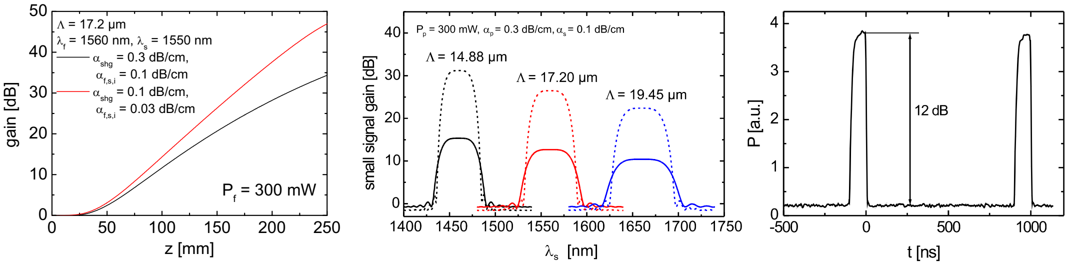

Fig. 4: Calculated small signal gain as function of the interaction length (left). Amplifier characteristics as gain versus wavelength for three different periodicities of the microdomain structure of Ti:PPLN channel guides of 80 mm (solid line) and 160 mm (dashed line) length (middle). Experimentally observed gain of 12 dB (right).

5. Wavelength selective time division multiplexers and all-optical switches

Further examples of ultra-fast nonlinear optical signal processing have been demonstrated. Using **cSHG/DFG** all-optical de-multiplexing of 10 Gbit/s OTDM-channels from a 4*10 Gbit/s data stream with simultaneous λ-conversion was investigated [7]. As another example wavelength selective OTDM-channel dropping was shown exploiting **SFG** [8]. Moreover, **cSFG/DFG** was used to get all-optical phase, polarisation and space switching [9]. At high pump power levels a signal is first depleted by SFG and then regenerated by DFG with a π-phase shift with respect to the input wave. This process is wavelength selective due to phase matching. cSFG/DFG was exploited in a polarisation interferometer using a Ti:PPLN waveguide as polarisation and wavelength selective phase switch. By controlling the input polarisation of pump and signal a polarisation rotation of the signal was achieved with a pump power of 1120 mW. Using a polarisation beam splitter at the output, wavelength selective spatial switching of a signal at $\lambda = 1554$ nm could be demonstrated with an extinction ratio of -20.2 dB.

6. Tunable frequency shifted feedback (FSF-) lasers

Er-diffusion doping enables the development of a variety of different types of waveguide lasers with excellent properties for the wavelength range 1530 nm < λ < 1603 nm [2]. Among them are mode-locked lasers (5 ps / 10 GHz), Q-switched lasers (4 ns / 1 kHz / 1 kW), (electro-optically tunable) Distributed Bragg Reflector- (DBR-) and Distributed Feedback- (DFB-) lasers, self-frequency doubling devices, acousto-optically tunable lasers and ring lasers as potential optical gyroscopes.

In particular, acousto-optically tunable frequency shifted feedback (FSF-) lasers proved to be important devices for all-optical signal processing. Fig. 6 shows on the left a schematic diagram of our integrated laser. In the middle the measured emission spectrum is presented; it has a linewidth of 180 pm. Under the envelope a comb of cavity modes shifts with time with the enormous rate of $2.4 \cdot 10^{17}$ Hz/s as schematically shown on the right. It is this property, which enabled the high accuracy of frequency domain ranging of 2.5 μm, as recently demonstrated for the first time with an integrated optical device by measuring the beat signals of an interferometer output.

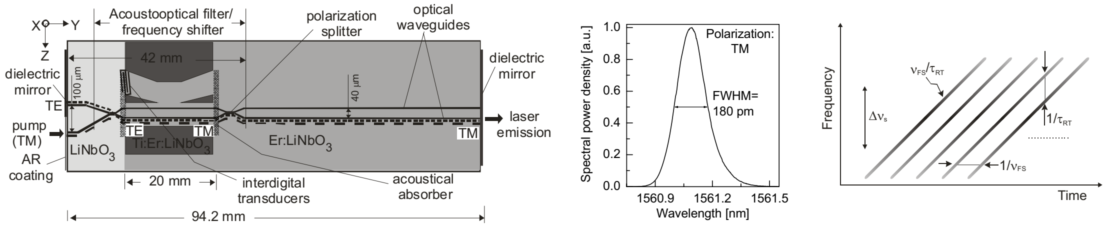

Fig. 5: Scheme of an integrated acousto-optically tunable FSF-laser (left) with a measured emission spectrum (middle). Schematic representation of the instantaneous frequency comb as function of time (right).

7. Conclusions

A variety of integrated optical Lithium Niobate devices for all-optical signal processing (wavelength converters, parametric amplifiers, time division multiplexers, all-optical switches and tunable frequency shifted feedback lasers) have been reviewed. The development of improved and new devices using novel waveguide structures (ridge and photonic crystal waveguides, bent and ring structures) is continued.

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