# Nonlinear Effects in PPLN Waveguide Resonators

R. Geiss, R. Schiek*, T. Pertsch, A. Chipouline, O. Egorov, F. Lederer, W. Sohler**, and A. Tünnermann***

Friedrich-Schiller-Universität Jena, Max-Wien-Platz 1, 07743, Jena, Germany
* University of Applied Sciences Regensburg, Prüfeninger Str. 58, 93049 Regensburg, Germany
** Applied Physics, Universität Paderborn, 33095 Paderborn, Germany
*** Fraunhofer Institute for Applied Optics and Precision Engineering, Albert-Einstein-Strasse 7, 07745 Jena, Germany
reinhard.geiss@uni-jena.de

**Abstract:** Bistability in Ti:PPLN waveguide resonators was tested experimentally. Power dependent spectra were measured and compared with theory. Parameters necessary for bistable operation have shown to be accessible via temperature and wavelength tuning.

**Keywords:** nonlinear optics, all-optical devices, waveguide resonators, bistabilty, lithium niobate

## 1. Introduction

Discrete systems, such as coupled pendulums, molecular chains, and waveguide arrays share numerous interesting features. Recently significant attention has been paid to experimental and theoretical studies of nonlinearly localized modes in arrays of evanescently coupled waveguides [1] or interacting microcavities [2]. These modes are referred to as discrete solitons and differ considerably from there continuous counterparts.

The interaction of light with the nonlinear medium can be enhanced by light confinement between two mirrors, which reduces power requirements. However, the dissipative nature and thus inevitable optical losses of such resonators require energy compensation by means of, for example, an external optical pump. The simultaneous presence of loss compensation, feedback and internal nonlinearity causes bistability of the optical states. In addition to the fundamental relevance of bistabile resonant nonlinear systems the topic opens up potential applications on the way towards fast all-optical signal processing.

Currently most investigations were concentrated on extensive theoretical modelling of nonlinear discrete cavity soliton dynamics in arrays of coupled waveguide resonators [3,4]. However, experimental studies in this particular field have not yet been reported.

Preparatory investigations of a single-waveguide resonator capable of showing optical bistability are presented in this work.

## 2. Basic theory

In order to estimate the influence of different system parameters on the systems performance detailed theoretical investigations have been performed. Starting point are the coupled-mode equations, which describe the propagation of the slowly varying envelope of forward (+) and backward (-) propagating fields in the waveguide taking into account quadratic nonlinearities [3]. The evolution equations for the amplitudes $u$ and $v$ of Fundamental (FH) and Second Harmonic (SH) field read as:

$$\left(\pm i\frac{\partial}{\partial z}+\frac{i}{v_{\mathrm{FH}}}\frac{\partial}{\partial t}\right)u^{\pm}+\chi_{\mathrm{eff}}^{(2)}u^{\pm *}v^{\pm}\exp(\mp i\Delta\beta z)=0, \qquad (1)$$

$$\left(\pm i\frac{\partial}{\partial z}+\frac{i}{v_{\mathrm{SH}}}\frac{\partial}{\partial t}\right)v^{\pm}+\chi_{\mathrm{eff}}^{(2)}u^{\pm 2}\exp(\pm i\Delta\beta z)=0, \qquad (2)$$

where $v_{\mathrm{FH,SH}}$ are the group velocities of the respective fields and $\Delta\beta$ is the phase mismatch.

This system can be described within the framework of a mean-field approximation in the vicinity of a single longitudinal resonance. Thus a high finesse resonator, resonant for both FH- and SH-fields is assumed. The resonator is formed by a single-mode waveguide with dielectric mirrors at the end facets. Losses are compensated by an external driving field at the FH. The cavity has to be short compared to the interaction length of the nonlinear process. Hence, all processes take place during numerous roundtrips and can be regarded as genuine cavity effects[3].

In the stationary limit of the coupled evolution equations for the transmitted FH and SH fields in mean-field approximation a cubic nonlinearity is mimicked by a quadratic one. This effect can be understood as a $\chi^{(2)}$ cascading phenomenon resulting in a change of the refractive index depending on the sign of the phase mismatch. Those nonlinear changes of the effective refractive index result in a shift of the resonances for sufficiently high intensities inside the resonator. Therefore a detuned system in the linear limit becomes resonant again for strong input fields giving rise to a bistable response. The amplitude of the input beam needed for optical bistability depends on various system parameters. Looking for the theoretical minimum pumping power a parameter plane between mono- and bistable response has been identified. These findings led to a set of design parameters for the actual waveguide sample.

## 3. Results of the experimental investigations

In this work nonlinear effects in resonators formed in Periodically Poled Lithium Niobate (PPLN) have been the object of investigation. Therefore, according to results from previous theoretical analyses, waveguides were fabricated on 15 mm long $Z$-cut $\mathrm{LiNbO_3}$ wafers by indiffusion of 7 µm wide Ti stripes of 90 nm thickness into the substrate. Maximum losses of 0.4 dB/cm for the fundamental field were achieved. For efficient SHG phase matching a uniform quasi-phase-matching grating with a period of 16.6 µm was generated by electric field poling. The resonator was formed by depositing dielectric mirrors at the sample facets resulting in reflectivities of $R_{FH}$=98.8% for the FH and $R_{SH}$=97.4% for the SH field respectively, leading to a doubly resonant system.

The experiments were performed with a Tuneable Laser Source at wavelengths around 1560 nm. The output power was modulated with an acousto-optic modulator yielding a 125 kHz pulse train of 130 ns pulses. Subsequently the signal was amplified up to a maximum peak power of 5 W using an Erbium Doped Fiber Amplifier and then coupled into the sample.

Typical spectra for the output FH and SH at an input power of 1.04 W consisted of narrowly spaced Fabry-Perot resonances - see Fig.1.

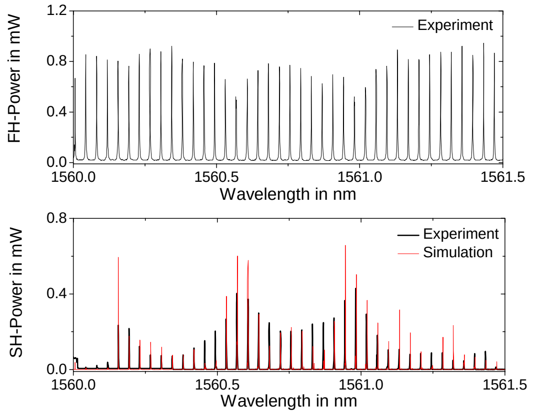

Fig.1 Output spectra for FH (upper) and SH (lower).

Certain resonances exhibited broadening and asymmetric deformation (tilting) of the original Lorentzian shape as the input power was increased (Fig.2a, b). For resonance wavelengths below the phase matching wavelength of 1561.05 nm a tilt towards smaller wavelengths was observed. Tilting in the opposite direction occurred for resonances above phase matching.

The broadening and tilting strongly depends on the relative position of the three system resonances – the FH and SH cavity resonances, and the periodic poling resonance (phase matching condition). It has been demonstrated that all parameters necessary to tune the relative positions of these resonances are accessible in the experimental setup via temperature and wavelength tuning.

In accordance with theory the observed effect of resonance broadening and shifting is related to a change of sign of the nonlinear phase shift induced by cascaded second order nonlinearities. This is an essential requirement for the observation of optical bistability.

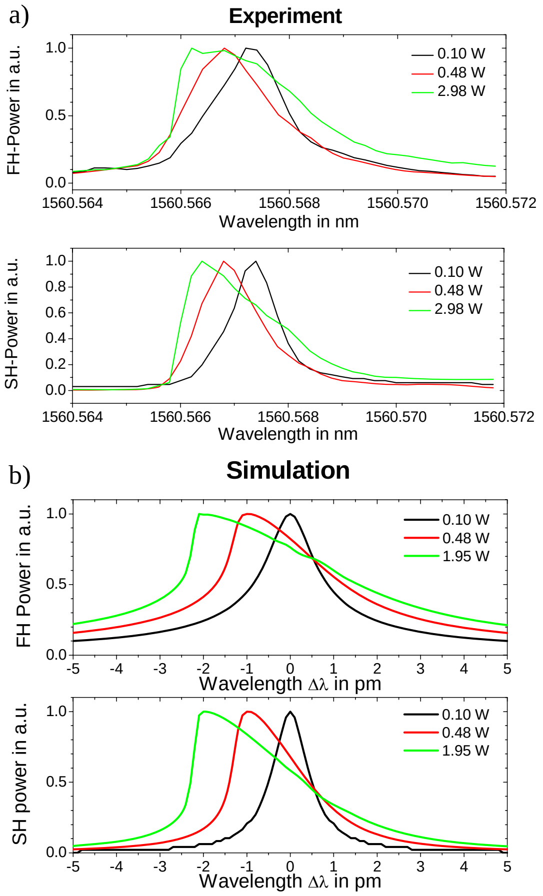

Fig.2 a) Experimentally obtained single resonance shape for different input power levels; b) numerical simulation of the resonance shapes.

## 4. Summary and Outlook

The accessibility of parameters necessary for a bistable system response has been demonstrated in the performed experiments. According to the theoretical expectations peculiarities of bistability such as resonance spectrum broadening and tilting have been observed in a waveguide resonator formed in a $LiNbO_3$ crystal at telecom wavelengths. Switching and fast memory operation based on bistability are subject of ongoing experiments.

## 5. References

[1] R. Iwanow, R. Schiek, G. I. Stegeman, T. Pertsch, F. Lederer, Y. Min, and W. Sohler, Phys. Rev. Lett. 93, 113902 (2004).

[2] D. N. Christodoulides and N. K. Efremidis, Opt. Lett. 27, 568-570 (2002).

[3] O. Egorov, U. Peschel, and F. Lederer, Phys. Rev. E 71, 056612 (2005).

[4] O. Egorov, F. Lederer, and Y. S. Kivshar, Opt. Express 15, 4149-4158 (2007).