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Phase engineered wavelength conversion of ultra-short optical pulses in TI:PPLN waveguides

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ABSTRACT

A phase engineered all-optical wavelength converter for ultra-short pulses (down to 140 fs) in a Ti-diffused, periodically poled lithium niobate (Ti:PPLN) waveguide is proposed. The phase engineering, due to the phase conjugation between signal and idler (converted signal) pulses which takes place in the cascaded second harmonic generation and difference frequency generation (cSHG/DFG) based wavelength conversion, already leads to shorter idler pulses. The proposed device consists of an unpoled (passive) waveguide section beside of the PPLN waveguide section in order to compensate pulse broadening and phase distortion of the idler pulses induced by the wavelength conversion (in the PPLN section). For example numerical analysis shows that a 140 fs input signal pulse is only broadened by 1.6% in a device with a combination of 20 mm and 6 mm long periodically poled and unpoled waveguide sections. Thus, cSHG/DFG based wavelength converters of a bandwidth of several Tbits/s can be designed.

1. Introduction

All optical wavelength conversion is of great interest for dense wavelength division multiplexing (DWDM) networks [1]. If inherently combined with optical phase conjugation (OPC), it also enables by mid-span wavelength conversion in (long) fiber-optic links a compensation of nonlinear phase noise and dispersion induced signal distortions in the second half of the link; high bit-rate, ultra long-haul transmission has been demonstrated using this concept [2]. Among various wavelength conversion approaches nonlinear $\chi^{(2)}$ based difference frequency generation (DFG) in a lithium niobate ($LiNbO_3$, LN) waveguide proved to be very attractive [3]. It offers high efficiency, low noise (quantum limited) and high speed (fs response time) simultaneously and is inherently transparent for signal rate and format. In addition, quasi–phase matching (QPM) of DFG in a periodically poled lithium niobate waveguide (PPLN) of specific periodicity allows operating with any wavelength in the transparency range of the LN crystal. Mainly for practical reasons, a cascaded second harmonic generation (SHG) / DFG process (cSHG/DFG) is usually used [3]; it guarantees a spatial mode selective excitation of the (short wavelength) continuous wave (cw) pump by internal phase matched SHG of a cw fundamental wave. Fig. 1 schematically shows this cSHG/DFG-based wavelength conversion/OPC process.

cSHG/DFG (OPC) based wavelength conversion in PPLN waveguides has been intensively studied in recent years [e.g. 4,5]. It was shown that group velocity mismatch (GVM) and group velocity dispersion (GVD) lead to a temporal walk off and thereby to distortion and broadening of the interacting pulses. However, negligible pulse broadening for ~1.4 ps pulses was experimentally observed enabling all optical wavelength conversion of 40, 160 and 320 Gb/s signal data in the C-band [6–8]. It seems that similar to mid-span wavelength conversion with OPC in a (long) fiber link, the distributed wavelength conversion in the (short) PPLN waveguide yields a (partial) compensation of dispersion induced pulse distortions.

It should be emphasized that the acceptance bandwidth of a Ti:PPLN wavelength converter with homogeneous domain grating is more than sufficient even for ultra-short signal pulses for the cSHG/DFG approach studied here. This is in contrast to cSFG/DFG based wavelength converters with two pump waves [e.g. 9,10] where the signal pulses undergo two nonlinear processes (SFG and DFG) limiting strongly the acceptance bandwidth by the QPM conditions. Therefore, chirped domain gratings are used to broaden the bandwidth [9,10]. On the other hand, the cSFG/DFG approach allows a wavelength tuning of the idler (converted signal) even for a fixed signal wavelength, which is not possible for the cSHG/DFG approach. Here, the dispersion properties lead via the QPM condition to a narrow bandwidth of the SHG process in

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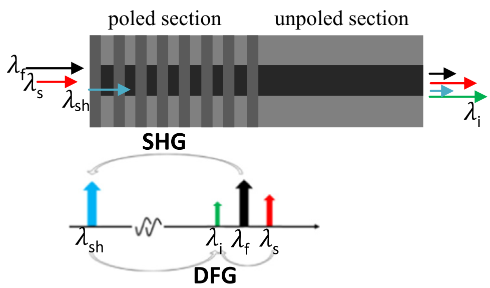

Fig. 1. Schematic diagram of the input and output waves in a proposed poled and unpoled sections of PPLN waveguide (top figure). The figure below shows a schematic diagram of cSHG/DFG-based wavelength conversion in the poled section of the waveguide. The cw fundamental wave (λ_f) generates its second harmonic (λ_{sh}) which serves as pump wave for the DFG-process with the signal. The resulting idler (λ_i) is the wavelength-shifted replica of short (Gaussian shaped) signal pulses (λ_s).

the homogeneous domain grating assumed. However, this is not a problem as no short pulses but a narrow line width cw wave is frequency doubled; therefore, chirped gratings to broaden the bandwidth of the SHG process [e.g. 11,12] are not necessary.

Is a design of an inherently dispersion compensated wavelength converter of nominally unlimited bandwidth possible? This question is theoretically investigated in this letter for cSHG/DFG (OPC) based wavelength conversion of 1.4 ps, 200 fs and 140 fs signal pulses in a standard Ti-indiffused PPLN waveguide. After introducing the mathematical methods in section II, the results are presented and discussed in Section 3. The evolution of signal and idler pulses along the waveguide is analyzed in detail by studying pulse widths and phase distributions. Based on the results, an engineered device is proposed to compensate idler pulse broadening and phase distortion as far as possible. This phase engineering by an unpoled (passive) waveguide section causes wavelength conversion of minimum distortion.

2. Device Modeling

The following coupled partial differential equations (Eqs. 1–4) describe the interacting waves and their evolution during cSHG/DFG inside a PPLN waveguide [4]. These equations have been obtained using the plane wave and the slowly varying envelope approximations. The latter can be applied if the bandwidth $\Delta\omega$ of the pulses to be investigated is significantly smaller than the carrier frequency ω_0, i. e. $\Delta\omega/\omega_0$ « 1. For our simulations we get $\Delta\omega/\omega_0$=0.0036 (0.036) using pulses of 1.4 ps (140 fs) width, respectively.

$$E(x, y, z, t) = \frac{1}{2}\sum_m A_m(z, t)F_m(x, y)\exp\left(j\omega t - j\beta_m z\right) + c.\,c$$

$$\frac{\partial A_f}{\partial z} + \beta_f' \frac{\partial A_f}{\partial t} - \frac{j\beta_f''}{2}\frac{\partial^2 A_f}{\partial t^2} = -j\kappa_{sh}^* A_f^* A_{sh} e^{-j\Delta_{sh} z} - \frac{\alpha_f}{2}A_f \tag{1}$$

$$\frac{\partial A_{sh}}{\partial z} + \beta_{sh}' \frac{\partial A_{sh}}{\partial t} - \frac{j\beta_{sh}''}{2}\frac{\partial^2 A_{sh}}{\partial t^2} = -j\kappa_{sh} A_f^* A_f e^{j\Delta_{sh} z} - j\frac{\omega_{sh}}{\omega_i}\kappa_{df}^* A_s A_i e^{j\Delta_{df} z} - \frac{\alpha_{sh}}{2}A_{sh} \tag{2}$$

$$\frac{\partial A_s}{\partial z} + \beta_s' \frac{\partial A_s}{\partial t} - \frac{j\beta_s''}{2}\frac{\partial^2 A_s}{\partial t^2} = -j\frac{\omega_s}{\omega_i}\kappa_{df} A_{sh} A_i^* e^{-j\Delta_{df} z} - \frac{\alpha_s}{2}A_s \tag{3}$$

$$\frac{\partial A_i}{\partial z} + \beta_i' \frac{\partial A_i}{\partial t} - \frac{j\beta_i''}{2}\frac{\partial^2 A_i}{\partial t^2} = -j\kappa_{df} A_{sh} A_s^* e^{-j\Delta_{df} z} - \frac{\alpha_i}{2}A_i \tag{4}$$

f, sh, s and i denote the fundamental, second harmonic, signal and idler fields, respectively. A_m (as a function of time t and position z) represents the slowly varying complex amplitude of the electric field m (m=f, sh, s, i); $F_m(x,y)$ describes the field distribution of mode m within the waveguide cross section. β_m' ($\partial\beta_m/\partial\omega$ at $\omega = \omega_m$) stands for reciprocal group velocities and β_m'' ($\partial^2\beta_m/\partial\omega^2$ at $\omega = \omega_m$) for group velocity dispersions. β_m are the propagation constants. κ_{sh} and κ_{df} are the coupling coefficients of SHG and DFG processes, and we assume $\kappa_{sh} \approx \kappa_{df}$ for the case of $\omega_f \approx \omega_s$. Λ is the period of the domain inverted grating for QPM. Finally, Δ_{sh} and Δ_{df} represent the deviations from SHG and DFG quasi phase mismatching conditions, respectively. All the calculations in this paper are done with $\Delta_{sh}=\Delta_{df}=0$ ($\Delta_{sh} = \beta_{sh} - 2\beta_f - \frac{2\pi}{\Lambda}$ & $\Delta_{df} = \beta_{sh} - \beta_s - \beta_i - \frac{2\pi}{\Lambda}$) assuming perfect quasi phase matching. The launched fundamental and, consequently, the internally generated pump waves are assumed to be continuous waves (cw); therefore, β_f', β_{sh}', β_f'' and β_{sh}'' are negligible. The signal wave is assumed to be a Gaussian pulse at the beginning of the waveguide (z=0):

$$A_s(0, t) = \sqrt{P_{s0}}\,exp\left(\frac{-(1 - jC)t^2}{2\,T_{s0}^2}\right) \tag{5}$$

where P_{s0} is the peak power and T_{s0} is related to the Full Width at Half Maximum (FWHM) of the initial signal pulse by the relation $\tau_{s0} = 2\sqrt{ln(2)}\;T_{s0}$. The parameter C is the frequency chirping factor which is zero in our simulation except where otherwise noted. The (slowly varying) phase evolution with position and time along the waveguide can be written as:

$$\varphi_m(z, t) = tan^{-1}\left(\frac{Im\left(A_m(z, t)\right)}{Re\left(A_m(z, t)\right)}\right) = \frac{C(z)}{2\,T_{s0}}t^2 \tag{6}$$

The coupled Eqs. (1)–(4) cannot be solved analytically. The Split Step Fourier method [13] with parameters listed in Table 1 for the specific waveguide investigated [8] is used to solve them numerically. The refractive index, the group velocity and group velocity dispersion are taken from [14].

It is important to mention that for cSHG/DFG-based wavelength conversion within the C-band, the QPM determined bandwidth for the fundamental wave of the SHG process is relatively narrow (about a nm) [15]. On the other hand, due to the dispersion properties of LN, the bandwidth for the signal wave is broad enough to cover the whole C-band [8]. Here the wavelength of 1551 nm is chosen for the signal wave to enable a comparison with published experimental data [8].

Table 1
Simulation parameters.

Parameter	Value
P_{s0}	100 mW
P_{i0}	0 mW
λ_f	1.546 μm
λ_s	1.551 μm
τ_{s0}	1.4 ps, 200 fs, 140 fs
$\alpha_f=\alpha_s=\alpha_i$	0.15 dB/cm
α_{sh}	0.3 dB/cm
$\kappa_{sh} \approx \kappa_{df}$	0.55 $1/\mathrm{cmW}^{1/2}$
$\beta_f \approx \beta_s \approx \beta_i$	8.723 1/μm
β_{sh}	17.825 1/μm
$\beta_s' \approx \beta_i'$	7.34 ns/m
β_s''	110 $\mathrm{ps^2/km}$
β_i''	113 $\mathrm{ps^2/km}$
Λ	16.6 μm