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Tunable wavelength conversion of picosecond pulses based on cascaded sum- and difference-frequency generation in quasi-phase-matched $LiNbO_3$ waveguides

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ABSTRACT

Tunable wavelength conversion for picosecond pulses is proposed and demonstrated exploiting cascaded sum- and difference-frequency generation in quasi-phase-matched $LiNbO_3$ waveguides. The influences of initial pulse widths and injected pulse powers on the conversion efficiency and converted pulse width are theoretically analyzed. Arbitrarily tunable wavelength conversion is performed for the signal pulse with the temporal width of 1.57 ps and repetition rate of 40 GHz. Approximately −18.9 dB conversion efficiency and 25 nm variable region of the input signal are achieved under the lower launched signal power. The results imply that simultaneous wavelength conversion and pulse compression can be potentially obtained by using the pulsed control wave or designing longer waveguides.

1. Introduction

All-optical wavelength converters are expected to be potential components in future dense wavelength division multiplexed (DWDM) networks to realize wavelength routing and information processing in optical domain [1]. Compared with the several demonstrated schemes, wavelength converters exploiting second-order nonlinear interactions in quasi-phase-matched $LiNbO_3$ waveguides can meet the requirements of the realistic DWDM networks, which can perform with broad wavelength conversion span, strict transparency for any bit rate and data format, no intrinsic frequency chirp and without excess noise accumulation [2,3]. Simultaneous multiwavelength conversion [3,4], spectral inversion, and parametric amplification [5] are also remarkable properties in the second-order nonlinear processes. Three types of second-order nonlinear interactions, direct difference-frequency generation (DFG), cascaded second-harmonic generation (SHG) and difference-frequency generation (cSHG/DFG) [6], and cascaded sum- and difference-frequency generation (cSFG/DFG) [7], have been employed in quasi-phase-matched (QPM) $LiNbO_3$ waveguides to achieve wavelength conversion. In direct DFG-based wavelength conversion, a pump wave at a wavelength of 700–800 nm is required to realize high conversion efficiency, thus causing the difficulties in simultaneously coupling the 780 nm pump and 1.55 μm band signals into the fundamental mode of the waveguide. By adopting cSHG/DFG interactions in QPM periodically poled $LiNbO_3$ (PPLN) waveguides, difficulties in coupling are conveniently overcome by arranging all incident signals within the 1.55 μm band and cSHG/DFG-based wavelength conversion has shown impressive performance. As the pump wavelength is given, the converted wavelength will change following the variations of the signal wavelength. Thus, wavelength conversion occurs within a fixed wavelength span. If the pump wavelength can be varied, the converted wavelength corresponding to the idler wave will be tuned accordingly. Unfortunately, the response bandwidth for the pump wavelength is much narrower and is determined by the precisely phase-matched condition for SHG via the structure parameters of the PPLN waveguide [8]. Tunable operation, however, is essential for wavelength converters to enhance the flexibility of the DWDM network management by facilitating reconfigurable dynamic wavelength routing. Ishizuki et al. [9] and Schreiber et al. [10] have experimentally demonstrated wavelength conversion based on the cSHG/DFG scheme employing pulsed pumping. In their configuration, the wavelength conversion only occurs within a fixed wavelength span and tunable wavelength conversion cannot be performed. Variable output signals converted from a given input signal have recently been demonstrated with the input signal carried by the pump wave in the cSHG/DFG process [11]. However, the wavelength of the injected signal cannot be varied greatly unless the pump wave holds a wide response bandwidth. Xu and Chen [12] have presented a cSFG/DFG-based wavelength conversion in a MgO-doped $LiNbO_3$ quasi-phase-matched waveguide for continuous wave (CW) signals, showing impressive performance. Using cSFG/DFG, a 10 GHz, 5 ps pulse stream has been wavelength converted with the wavelength-shifting range of 15 nm. But the input pulse stream is also fixed at a certain wavelength (1554.82 nm) [13]. Yamazaki et al. [14] have demonstrated widely tunable

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multichannel wavelength conversion by employing a multiple wavelength quasi-phase-matched $LiNbO_3$ waveguide, leading to complicated device structures and difficulties in the fabrication of the waveguides. Chen et al. [15] have also achieved all-optical variable-in variable-out wavelength conversion by broadening the pump response band via changes of the device temperature and pump wavelength.

In this paper, a theoretical model is developed for the pulsed wavelength conversion including group velocity dispersion and walk-off effect arising from group velocity mismatch. The evolutions of the optical pulses are simulated based on the developed theoretical model and the influences of initial pulse widths and injected pulse powers on the conversion efficiency and converted pulse width are theoretically analyzed. Arbitrarily tunable wavelength conversion of picosecond pulses based on cSFG/DFG is proposed and demonstrated instead of one of pump waves with a pulsed signal in SFG process. The wavelength dynamic range of the input signal is significantly broadened through the proper changes of the pump and control wavelengths, and the tunable operation is hence not restricted by the pump response in the conventional cSFG/DFG scheme. Wavelength conversion with lower injected signal powers between picosecond pulses rather than CW waves is concentrated on in the proposed scheme, and our proposed scheme approaches the practical applications much more since the wavelengths usually carry the data streams (i.e. pulses) in the practical optical communication systems. The results imply that simultaneous wavelength conversion and pulse compression can be potentially obtained by using the pulsed control wave or designing longer waveguides.

2. Theoretical model

The frequency relationships in cSFG/DFG-based wavelength converters are schematically shown in Fig. 1. The wavelength conversion process can be briefly described as follows: A pump wave (wavelength λ_p) of frequency ω_p and signal pulse (wavelength λ_s) of frequency ω_s, whose wavelengths are both located in the 1.55 μm band, are simultaneously launched into the PPLN waveguide. Propagating along the waveguide, the signal pulse will interact with the pump wave through SFG effect under the perfectly phase-matched condition and the sum-frequency (SF) pulse (wavelength λ_{sf}) of frequency ω_{sf} is generated. Meanwhile, following the growth of the sum-frequency pulse, an injected control wave is mixed with the generated sum-frequency pulse in the

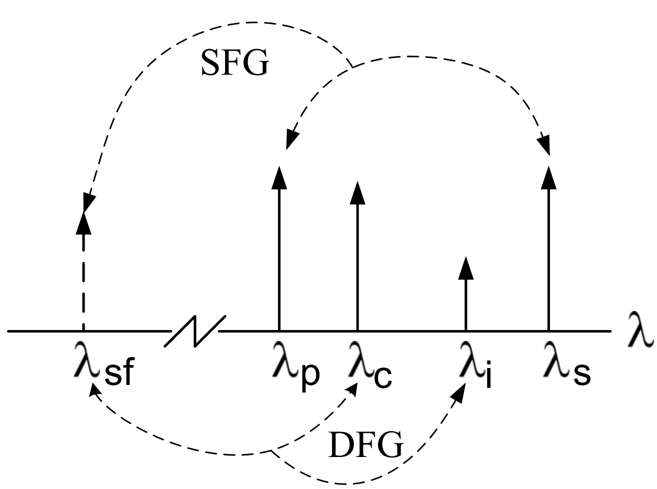

Fig. 1. Schematic diagram of frequency relationships in wavelength conversion with the cascaded SFG and DFG processes in PPLN waveguides.

same waveguide to realize DFG process under QPM condition. As a result, the idler pulse (wavelength λ_i) corresponding to the frequency of $\omega_i = \omega_p + \omega_s - \omega_c$ is brought out. Consequently, the information carried by λ_s is completely copied onto the wavelength λ_i and the wavelength λ_i satisfies the following relationship

$$\frac{1}{\lambda_i} = \frac{1}{\lambda_p} + \frac{1}{\lambda_s} - \frac{1}{\lambda_c} \tag{1}$$

The expression (1) reflects that for a fixed signal pulse λ_s variable converted pulse λ_i can be obtained by the adjustment of control wave, and for the variable input signal pulse the variable output converted pulse can also be generated by accordingly changing the pump and the control pulse wavelengths to meet the exactly phase-matched condition for SFG and QPM for DFG. Of course, the SFG process can probably occur between the pump and the control waves and the DFG process then takes place between the signal and the generated SF wave. These processes, however, are not taken into account in the numerical simulations and experiments because no matter how the pump and the control wavelengths change wavelength conversion can only happen with a fixed wavelength spacing. As a result, flexibly tunable wavelength conversion cannot be successfully achieved.

Theoretical models have been developed for DFG-based wavelength conversion, which can be categorized to describe CW cSHG/DFG [16], cSFG/DFG [7], and pulsed cSHG/DFG-based [9] wavelength conversion. The CW cSHG/DFG and cSFG/DFG models focus on the conversion efficiency and bandwidth, and cannot explain the walk-off effect and the variations of the output converted pulses. The pulsed cSHG/DFG model is established by assuming the exactly phase-matched condition to be met for all of the frequency components within the broad frequency range, and the tunable behaviors cannot be analyzed and discussed. In fact, although the QPM condition is satisfied at the central frequencies of the picosecond optical pulses propagating in the PPLN waveguide, a phase mismatch will possibly occur within broad frequency ranges corresponding to the picosecond optical pulses. Moreover, interactions among the pulses under the case of group-velocity mismatch will lead to walk-off effect and pulse distortion. The phase mismatch, the group-velocity mismatch, and the group-velocity dispersion in the cascaded SFG and DFG processes are considered in the following theoretical model. With the proposed model pulse evolutions along the waveguide and the compression and broadening of the output pulses can be simulated and analyzed. To realize the SFG effect in the PPLN waveguide, the pump wavelength must be kept away from the QPM wavelength of the SHG process. Hence, the SHG process is ignored in the theoretical model.

The slowly varying amplitudes A_p, A_s, A_c, A_{sf}, and A_i of the pump, signal, control, SF, and idler pulses in the PPLN waveguide are governed by [17]

$$\frac{\partial A_p}{\partial z} + \beta_p' \frac{\partial A_p}{\partial t} - i\frac{\beta_p''}{2}\frac{\partial^2 A_p}{\partial t^2} = i\omega_p \kappa_{sf} A_s^* A_{sf} \exp(i\Delta\beta_{sf} z) \tag{2}$$

$$\frac{\partial A_s}{\partial z} + \beta_s' \frac{\partial A_s}{\partial t} - i\frac{\beta_s''}{2}\frac{\partial^2 A_s}{\partial t^2} = i\omega_s \kappa_{sf} A_p^* A_{sf} \exp(i\Delta\beta_{sf} z) \tag{3}$$

$$\begin{aligned}\frac{\partial A_{sf}}{\partial z} + \beta_{sf}' \frac{\partial A_{sf}}{\partial t} - i\frac{\beta_{sf}''}{2}\frac{\partial^2 A_{sf}}{\partial t^2} &= i\omega_{sf} \kappa_{sf} A_p A_s \exp(i\Delta\beta_{sf} z) \\ &\quad + i\omega_{sf}\kappa_{df} A_c A_i \exp(-i\Delta\beta_{df} z)\end{aligned} \tag{4}$$

$$\frac{\partial A_c}{\partial z} + \beta_c' \frac{\partial A_c}{\partial t} - i\frac{\beta_c''}{2}\frac{\partial^2 A_c}{\partial t^2} = i\omega_c \kappa_{df} A_i^* A_{sf} \exp(i\Delta\beta_{df} z) \tag{5}$$

$$\frac{\partial A_i}{\partial z} + \beta_i' \frac{\partial A_i}{\partial t} - i\frac{\beta_i''}{2}\frac{\partial^2 A_i}{\partial t^2} = i\omega_i \kappa_{df} A_c^* A_{sf} \exp(i\Delta\beta_{df} z) \tag{6}$$

$$\beta_m' = \left.\frac{\partial \beta_m(\omega)}{\partial \omega}\right|_{\omega=\omega_m} \quad m = p, s, sf, c, i \tag{7}$$