Phase control of double-pass cascaded SHG/DFG wavelength conversion in Ti:PPLN channel waveguides

Rahman Nouroozi,* Hubertus Suche, Ansgar Hellwig, Raimund Ricken, Viktor Quiring, and Wolfgang Sohler

Angewandte Physik,Universität Paderborn,Warburger Strasse 100,Paderborn 33098, Germany
**rahman.nouroozi@uni-paderborn.de*

Abstract: The efficiency of wavelength conversion by cascaded second harmonic generation / difference frequency generation (cSHG/DFG) in Ti:PPLN waveguides can be considerably improved by using a double-pass configuration. However, due to the wavelength dependent phase change by the dielectric folding mirror phase compensation is required to maintain an optimum power transfer. We experimentally investigated three different approaches and improved the wavelength conversion efficiency up to 9 dB in comparison with the single-pass configuration.

OCIS codes: (160.3730) Lithium Niobate; (130.3120) Integrated optics, devices; (190.4360) Nonlinear optics, devices; (130.3405) Wavelength conversion, devices.

References and links

1. G. Schreiber, H. Suche, Y. L. Lee, W. Grundkötter, V. Quiring, R. Ricken, and W. Sohler, "Efficient cascaded difference frequency conversion in periodically poled Ti:LiNbO3 waveguides using pulsed and cw pumping," Appl. Phys. B **73**, 501–504 (2001).
2. H. Hu, H. Suche, R. Ludwig, B. Huettl, C. Schmidt-Langhorst, R. Nouroozi, W. Sohler, and C. Schubert, "Polarization insensitive all-optical wavelength conversion of 320 Gb/s RZ-DQPSK data signals," in *Proceedings of Optical Fiber Communication Conference (OFC) 2009*, (San Diego, March 2009), paper OThS6.
3. A. Galvanauskas, K. K. Wong, K. El-Hadi, M. Hofer, M. E. Fermann, D. Harter, M. H. Chou, and M. M. Fejer, "Amplification in the 1.2-1.7 µm communication window using OPA in PPLN waveguides," Electron. Lett. **35**(9), 731–733 (1999).
4. G. Imeshev, M. Proctor, and M. M. Fejer, "Phase correction in double-pass quasi-phase-matched second-harmonic generation with a wedged crystal," Opt. Lett. **23**(3), 165–167 (1998).
5. C.-W. Hsu, and C. C. Yang, "Using a grating structure for phase compensation in achieving an efficient round-trip optical parametric process in periodically poled lithium niobate with an incomplete quasi-phase-matching period," Opt. Lett. **24**(8), 540–542 (1999).
6. Y.-C. Huang, K.-W. Chang, Y.-H. Chen, A.-C. Chiang, T.-C. Lin, and B.-C. Wong, "A high-efficiency nonlinear frequency converter with a built-in amplitude modulator," J. Lightwave Technol. **20**(7), 1165–1172 (2002).
7. J. Buck, and R. Trebino, *Nonlinear Optics* (Wiley-VCH, 2006).

1. Introduction

Guided-wave, quasi-phase-matched (QPM) second order ($\chi^{(2)}$) nonlinear optical frequency conversion in periodically poled lithium niobate (PPLN) [1] is an efficient way, e.g., to avoid contention in reconfigurable optical communication networks by wavelength conversion of data channels. As the nonlinear optical approach of wavelength conversion is inherently coherent there is no loss of information even with phase sensitive encoding formats like differential quaternary phase-shift keying (DQPSK) [2]. Moreover, only a low amount of quantum limited excess noise is added to the converted signal by spontaneous parametric fluorescence and optical parametric gain can even be utilized to improve the conversion efficiency [3].

The efficiency of nonlinear conversion processes can be drastically improved by increasing the interaction length, provided the waveguide is homogeneous enough to maintain QPM over its whole length. An alternative to a long waveguide which is difficult to prepare

#127948 - $15.00 USD Received 3 May 2010; revised 11 Jun 2010; accepted 14 Jun 2010; published 17 Jun 2010

could be the use of a folded structure where the interacting waves are reflected back into the same waveguide to double the interaction length.

However, a steady energy transfer requires a well defined phase relationship between the interacting waves. In a cascaded $\chi^{(2)}$ process like cascaded second harmonic generation/difference frequency generation (cSHG/DFG; Fig. 1, left), this phase relationship has to be maintained after reflection by the end face mirror for the second pass through the waveguide (see Fig. 1, right). As the mirror induces wavelength dependent phase shifts, a compensating phase control is required (see chapters 2 and 3). In cSHG/DFG the pump wave for the DFG process is generated internally by SHG of the fundamental wave, $\lambda_{sh} = \lambda_f/2$. Due to QPM a selective excitation of a single spatial pump mode is guaranteed. The converted wave, the idler, is generated via DFG with $1/\lambda_i = 1/\lambda_{sh} - 1/\lambda_s$.

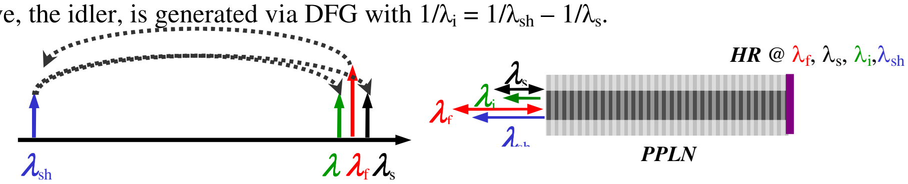

Fig. 1. Left: cSHG/DFG operation principle with fundamental (λ_f), second harmonic (λ_{sh}), signal (λ_s) and idler (λ_i) wavelengths. Right: Double-pass configuration with a broadband dielectric mirror deposited on the PPLN waveguide end face.

Phase control schemes have already been reported in the literature for the SHG process alone. For a bulk optical approach Imeshev et al. have used a wedged periodically poled crystal and adjusted the propagation length between mirror and nonlinear crystal for phase control by a lateral shift of the crystal [4]. Hsu and Yang have used a Bragg grating to compensate the relative phase change of the propagating waves in a Ti:PPLN waveguide by reflection [5]. Huang et al. used electro-optic phase compensation in an unpoled dispersive section of a waveguide [6].

In this paper we report, for the first time, phase control for cSHG/DFG in a folded double-pass Ti:PPLN waveguide configuration with a broad band dielectric mirror on one end face of the guide. To adjust the phase relationship between the interacting waves after reflection we have investigated three different approaches which will be discussed in detail in chapter 3.

2. Phase problem in double-pass configuration

In $\chi^{(2)}$ nonlinear processes the phase relation between the induced nonlinear polarization and the interacting waves determines the direction of the energy transfer. Due to the dispersive properties of a dielectric mirror, not only the reflectance magnitude but also the reflectance phase is wavelength dependent. As a result in nonlinear optics the phase relation between waves interacting via the nonlinear polarization can drastically change after reflection from such a dielectric mirror. This can lead to a depletion of the converted wave during the second pass rather than a continuation of the conversion process performed during the first pass through the waveguide.

In the slowly varying envelope approximation [7] the interaction of the 4 waves in a cSHG/DFG process, fundamental, SH, signal, and idler waves, is described by a first order coupled differential equation system of the complex amplitudes $A_f = |A_f|\exp(i\varphi_f)$ for fundamental, $A_{sh} = |A_{sh}|\exp(i\varphi_{sh})$ for SH, $A_s = |A_s|\exp(i\varphi_s)$ for signal, and $A_i = |A_i|\exp(i\varphi_i)$ for the generated idler wave, respectively. To provide a steady conversion from the fundamental to the SH wave the phase relation, $\varphi_{sh} - 2\varphi_f = \pi/2$, has to be maintained. Simultaneously, to provide steady depletion of the SH (pump) wave and growth of signal and idler waves the phase relation, $\varphi_{sh} - \varphi_s - \varphi_i = \pi/2$, has to be maintained. For signal and idler wavelengths not too far away from degeneracy both conditions can be simultaneously achieved to a good approximation. If these conditions can be maintained after reflection simulations predict an almost exponential increase of signal and idler with the interaction length sufficient fundamental power assumed (see Fig. 2, left). For a coupled fundamental power level of 200

#127948 - $15.00 USD Received 3 May 2010; revised 11 Jun 2010; accepted 14 Jun 2010; published 17 Jun 2010

mW and a device length of 35 mm the calculated wavelength conversion efficiency of the double-pass configuration surpasses that of the single pass version by ~10 dB (see Fig. 2, right). This is, however, only true if the phase relation between the interacting waves for optimum energy transfer can be maintained after reflection.

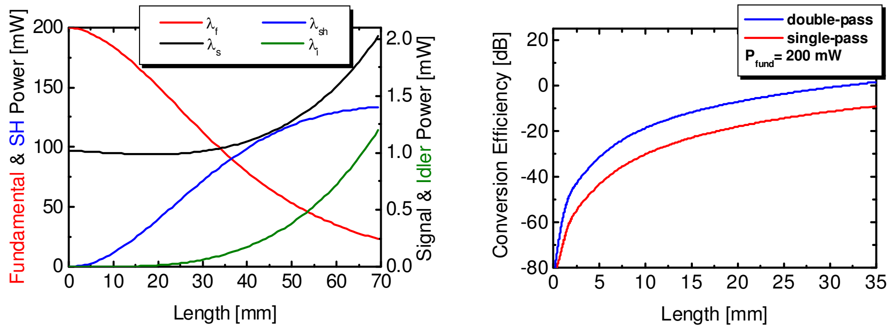

Fig. 2. Left: Simulated evolution of cSHG/DFG: power levels versus interaction length for 200 mW of coupled fundamental power. Right: Comparison of calculated cSHG/DFG conversion efficiencies in single- and double-pass devices for 200mW of coupled fundamental power versus device length.

In Fig. 3; the calculated wavelength dependent phase shifts modulo 2π of an optimized broadband dielectric mirror for fundamental ($\Delta\varphi_f$), signal ($\Delta\varphi_s$), and idler ($\Delta\varphi_i$) waves with wavelengths in the C-band and the SH ($\Delta\varphi_{sh}$) wave around 775 nm are shown. In both ranges, the wavelength dependence is almost linear but with different slopes.

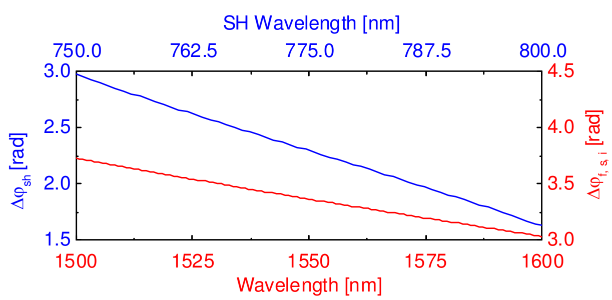

Fig. 3. Calculated phase shifts $\Delta\varphi_{f,\ s,\ i}$ and $\Delta\varphi_{sh}$ for fundamental, signal, idler, and second harmonic waves induced by an optimized broadband dielectric mirror versus wavelength in the ~1550 nm (lower scale) and ~775 nm (upper scale) range, respectively.

To maintain a steady energy transfer of SHG and DFG after reflection, the change of the phase differences by reflection $\Delta\varphi_{SHG} = \Delta\varphi_{sh} - 2\Delta\varphi_f$ and $\Delta\ \varphi_{DFG} = \Delta\varphi_{sh} - \Delta\varphi_s - \Delta\varphi_i$ have to be compensated. As signal and idler wavelengths are located symmetrically with respect to the fundamental wavelength, $2\Delta\varphi_f \approx \Delta\varphi_s + \Delta\varphi_i$ results. Therefore, a phase compensation $\Delta\varphi_{comp}$ can indeed be achieved for both processes, SHG and DFG, simultaneously. The following conditions have to be fulfilled:

$$\Delta\phi_{SHG} + \Delta\phi_{comp} \sim \Delta\phi_{DFG} + \Delta\phi_{comp} = m2\pi \ with\ m = 0,1,2,3,\ ....$$

3. Phase control schemes

In this chapter three phase compensation schemes are introduced and experimentally investigated to control the phase relation of the interacting waves after reflection (section 3.1 and 3.2).

Figure 4 shows the experimental setup to investigate wavelength conversion by double-pass cSHG/DFG with the different phase control schemes. A tuneable external cavity laser (ECL) was used as fundamental source; a fixed wavelength distributed feedback laser (DFB) served as signal source. Polarization controlled (PC) signal and fundamental waves were combined by a 3 dB coupler and boosted by an erbium doped fiber amplifier (EDFA). The light was butt coupled to the temperature stabilized double-pass waveguide. The wavelength conversion spectra were recorded in backward direction using a circulator and an optical spectrum analyzer (OSA).

In addition, due to the small transmittance of the end face mirror(s), also single-pass wavelength conversion spectra could be measured in forward direction.

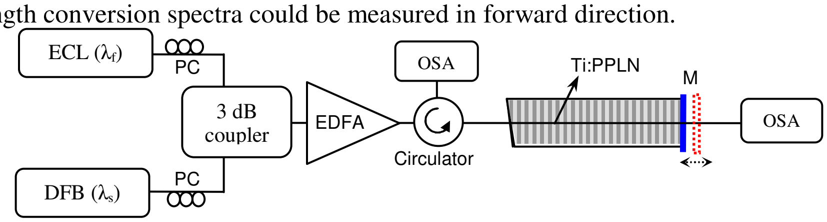

Fig. 4. Experimental setup to investigate double-pass cSHG/DFG: ECL - external cavity laser; DFB – distributed feedback laser; PC – fiber optical polarization controller; EDFA - erbium doped fiber amplifier; OSA – optical spectrum analyser; M – dielectric mirrors, deposited on waveguide end face and movable, respectively.

3.1 Phase control with dichroic mirrors of adjustable spacing

Phase control can be achieved by reflecting the different waves with two sequential dichroic mirrors: The first one, which is directly deposited on the polished waveguide end face, was designed to highly reflect the SH wave (~98%) and to transmit only ~2% of the fundamental, signal, and idler waves (Fig. 5, blue graph). The second mirror is an external one and its separation from the first one can be adjusted; it is a broadband high reflector of more than 98% reflectance for fundamental, signal, and idler waves but of high transmittance for the SH-wave (Fig. 5, red graph).

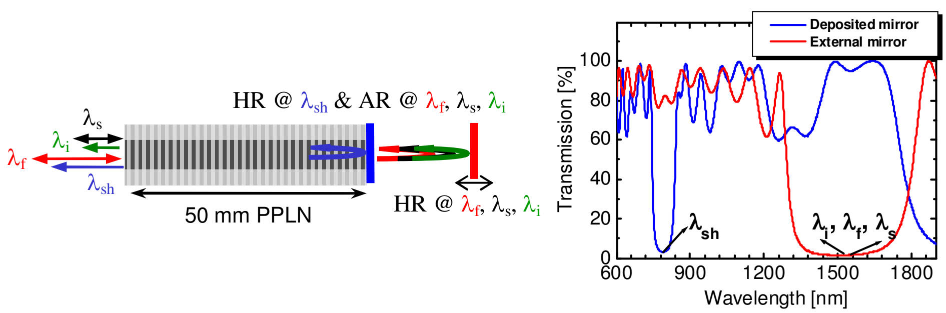

Fig. 5. Left: Double pass-configuration using two dichroic mirrors. AR – anti reflection coated; HR – high reflection coated. Right: Measured transmission versus wavelength of the mirror deposited on the waveguide end face (blue) and of the external moveable mirror (red).

By controlling the separation Δz of the external mirror to the waveguide end face within half a fundamental wavelength, the phase relationship between the reflected SH wave and the fundamental, signal, and idler waves can be adjusted by $\Delta\varphi_{comp} = 2\pi(2\Delta z)/\lambda_f$, leading to maximum power transfer from the fundamental to SH, signal, and idler waves. As long as the mirror separation Δz is smaller than a wavelength, the coupling loss back into the waveguide is negligible; therefore, $\Delta z < 1$ µm was adjusted.

Using this scheme an improvement of cSHG/DFG-based wavelength conversion of 7.5 dB has been achieved in comparison to the single-pass configuration for the same device of 50 mm length. In Fig. 6 the experimental results for SHG (left diagram) together with the cSHG/DFG wavelength conversion spectra (right diagram) are shown. The improvement of 7.5 dB agrees reasonably well with the theoretically predicted 10 dB for an effective interaction length of 35 mm derived from the single-pass SHG characteristics.

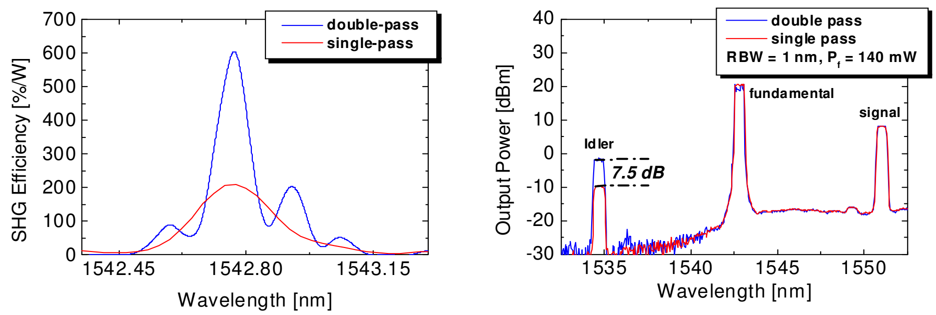

Fig. 6. Left: Measured single- and double-pass SHG efficiency versus fundamental wavelength. Right: Measured spectra for single- and double-pass wavelength conversion by cSHG/DFG. Device temperature was 190 °C in both experiments.

3.2 Exploiting the dispersion of $LiNbO_3$ within an unpoled waveguide section

In this case the waveguide is not completely periodically poled but has an unpoled section L just in front of the broadband dielectric mirror; it reflects both, fundamental and SH wavelength ranges (Fig. 7, right).

3.2.1 Higher order approach, allowing wavelength tuning

If the unpoled waveguide section has a length of several mm (Fig. 7, left), the phase relation between the interacting waves can be easily changed within 2π by slightly tuning the fundamental wavelength within the acceptance bandwidth of the QPM-condition (0.3 nm in our device for the single-pass).

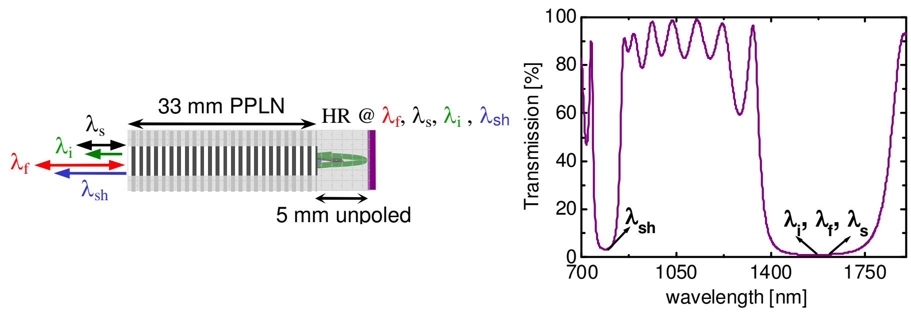

Fig. 7. Left: Operating scheme for higher order approach. Right: Measured transmission of the broadband dielectric mirror deposited on the polished waveguide end face.

In the 5 mm long unpoled waveguide section used in our experiments, a total relative phase change due to dispersion $\Delta\varphi_{dispersion} = \Delta\varphi_{dispersion,\ sh} - 2\Delta\varphi_{dispersion,\ f} = 2(2\pi/\lambda_f)(2L)(n_{sh}\text{-}n_f)$ of about 1000(2π) is induced. It strongly depends on the fundamental wavelength yielding a slope of $d(\Delta\varphi_{dispersion})/d(\lambda_f) \approx 10\pi$/nm. Therefore, a very small tuning of the fundamental wave is sufficient to adjust phase compensation. In our experiment a wavelength change of only 29 pm resulted in a 5 dB improvement of the double-pass SHG efficiency compared to the single-pass result (Fig. 8, left). This was the basis to get nearly 9 dB improvement of signal to idler conversion efficiency for cSHG/DFG-based wavelength conversion (Fig. 8, right).

#127948 - $15.00 USD Received 3 May 2010; revised 11 Jun 2010; accepted 14 Jun 2010; published 17 Jun 2010

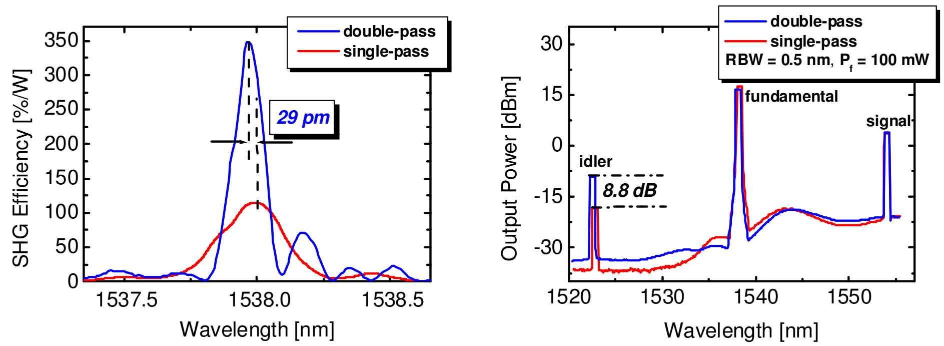

Fig. 8. Left: Measured single- and double-pass SHG efficiencies versus the fundamental wavelength. Right: Measured spectra for single- and double-pass wavelength conversion by cSHG/DFG. Device temperature was 190 °C in both experiments.

3.2.2 Zero order approach, selecting the right section length

The same adjustment can be achieved by a very short waveguide section of appropriate length, corresponding to a fraction of half a domain period ($\Lambda/2 = L_c$). Waveguide sections of slightly different lengths before the end face mirror were fabricated by tilting a homogeneous domain grating over a set of waveguides. Then the specific channel leading to optimum phase compensation with $\Delta\varphi_{comp} = 2\pi L/L_c$ can be selected.

The operating scheme to investigate double-pass cSHG/DFG-based wavelength conversion in the zero order approach is shown in Fig. 9, left. A slightly tilted (< 1°), homogeneous domain grating across the waveguides leads to different fractions of the final domain period in front of the mirror. The dependence of the SHG-efficiency on the length of this last domain fraction has been investigated (Fig. 9, right). The results confirm the strong phase dependence of the double-pass efficiency and allow selecting the optimum waveguide.

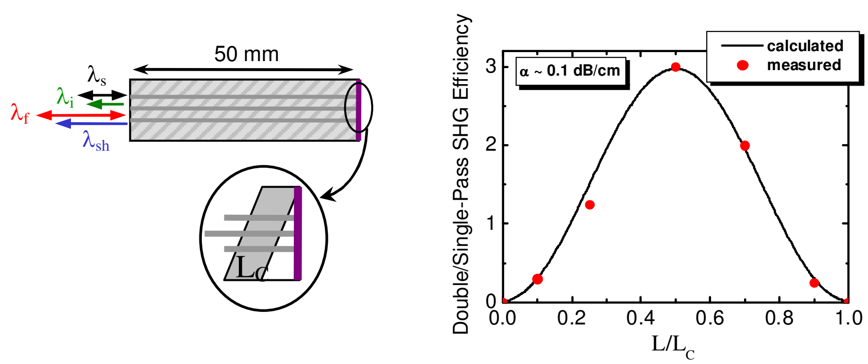

Fig. 9. Left: Schematic drawing of the Ti:PPLN-waveguide sample with a tilted domain grating (L indicates the wedged domain fraction, L_C is the width of a complete domain). Right: Measured and calculated double-pass SHG efficiency with respect to the single-pass efficiency for waveguides with different fractions L/L_C of the last domain, propagation loss α ~0.1 dB/cm.

Using this specific waveguide, SHG-efficiency and cSHG/DFG-based wavelength conversion have been investigated for both, single- and double-pass configuration, respectively. The results are shown in Fig. 10. On the left, the SHG characteristics are plotted; besides a spectral narrowing, an improvement of the efficiency of about 5 dB was achieved in comparison with the single-pass result, similar to the higher order approach. On the right, cSHG/DFG-based wavelength conversion spectra are shown; the conversion efficiency could

#127948 - $15.00 USD Received 3 May 2010; revised 11 Jun 2010; accepted 14 Jun 2010; published 17 Jun 2010

be improved by 8.5 dB. As this compensation scheme is of zero order ($\Delta\varphi_{comp} < 2\pi$), a large bandwidth can be expected suitable for multi-wavelength conversion in WDM-systems.

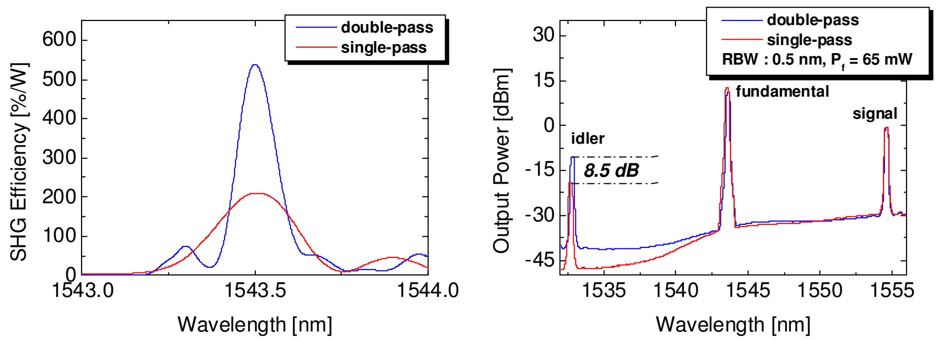

Fig. 10. Left: Measured single- and double-pass SHG-efficiencies versus the fundamental wavelength. Right: Measured spectra for single- and double-pass wavelength conversion by cSHG/DFG. Device temperature was 190 °C in both experiments.

The difference of the noise levels for single- and double-pass conversion in the vicinity of the idler wavelength is due to the different conversion efficiencies for the amplified spontaneous emission (ASE) of the EDFA in front of the waveguide (see Fig. 4). This difference becomes visible if the power level of the converted ASE is larger than the power level of the unconverted ASE in the same wavelength range. The optical signal to noise ratio (OSNR) could be improved by suppressing the ASE in front of the waveguide by appropriate filtering.

4. Conclusions

SHG and cSHG/DFG-based wavelength conversion in the C-band of optical communications have been investigated using Ti:PPLN waveguides in single- and double-pass configuration, respectively. To optimize the wavelength conversion efficiency in the double-pass device three different schemes for compensating wavelength dependent phase shifts by reflection have been investigated. The most promising one is compensation by dispersion in a short ($< \Lambda/2$) waveguide section, enabling even broadband operation. Using this scheme, the SHG-efficiency could be improved by 5 dB compared to the single-pass approach. The efficiency for wavelength conversion in the C-band by cSHG/DFG was improved by even 8.5 dB close to the theoretical limit of 10 dB (assuming an effective interaction length of 35 mm).

Acknowledgment

This work has been funded by the Deutsche Forschungsgemeinschaft (DFG) within the project “Contention Resolution in Optical Burst Switching (OBS) using Wavelength Conversion.”