Nonlinear optical Ti:PPLN wavelength conversion modules for free-space communication at 3.8 µm

K.-D. Büchter[1,*], C. Langrock[2], H. Herrmann[1], M.M. Fejer[2], W. Sohler[1]

[1] Universität Paderborn, Angewandte Physik, Warburger Str. 100, 33098 Paderborn, Germany

[2] Edward L. Ginzton Laboratory, Stanford University, Stanford, California 94305, USA

* *Corresponding author*: Phone: +49 5251 60-5870, Fax: +49 5251 60-5886, E-Mail: sol_db@physik.upb.de

Abstract –.

All-optical transmitter and receiver modules for free-space communication at 3.8 µm have been developed, essentially consisting of Ti-indiffused, periodically poled $LiNbO_3$ waveguides. Conversion of C-band radiation to/from the mid infrared is demonstrated.

Middle infrared (MIR) radiation can be advantageous in free-space transmission links due to reduced scattering and scintillation effects compared to shorter wavelength radiation [1], and an attractive transmission window exists in the atmosphere at around 3.8 µm [2]. This is why we have developed all-optical wavelength conversion modules from 1.55 µm to 3.8 µm and back [3]. The converters are based on $\chi^{(2)}$-nonlinear difference frequency generation (DFG) in periodically poled lithium niobate (PPLN) waveguides. The all-optical conversion enables data-format independent wavelength conversion. Therefore, transmission systems can be realized using readily available C-band components at both ends of the transmission line, allowing amplitude, frequency, and phase modulation schemes.

The concept of nonlinear frequency conversion is flexible, and easily transferrable to other wavelengths. The benefits of optical waveguides are the high conversion efficiencies of the nonlinear processes and the simplified use of single mode optical fibers for easy device handling.

Module design is shown in Fig. 1. We use titanium indiffused waveguides of 18 µm width and 83 mm length, on a $LiNbO_3$ substrate with a periodically poled area of 80 mm. A 3 mm long taper region is included to improve coupling to the fundamental waveguide modes. A pump at 1100 nm wavelength is used to convert a signal at 1550 nm to the MIR band.

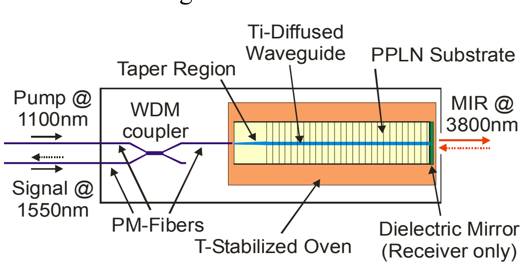

Fig. 1.: Transmitter / receiver design scheme.

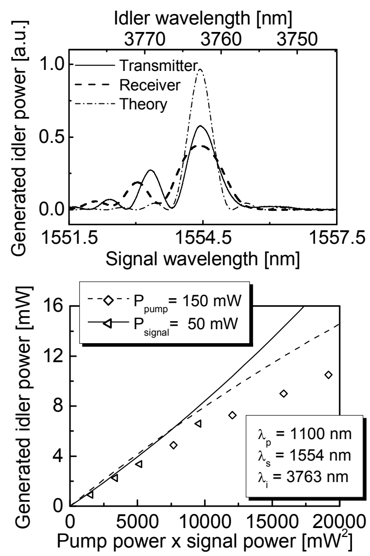

Fig. 2.: Phase-matching characteristics (top) and power characteristics (bottom) of the transmitter module.

For characterization purposes, a tunable C-band external cavity laser (ECL), followed by an erbium doped fiber amplifier (EDFA), is used as signal source. Pump and signal are joined by a WDM coupler and fiber butt-coupled to the waveguide on the 5.3° angle-polished input side of the sample, using an 8°-polished glass ferrule. Angled endfaces are used to suppress back-reflections, and thus Fabry-Perot interference effects, within the devices. A poling periodicity of 26.65 µm is used to provide quasi-phasematching for the DFG process. The devices are operated at about 200°C to suppress photorefractive effects.

The phasematching characteristics of transmitter and receiver modules, along with a calculated curve, are given in Fig. 2, top. Phase-matching occurs at a signal wavelength of 1554.5 nm, at a temperature of 197°C. The measured curves show an asymmetry which is due to a parabolic inhomogeneity gradient along the waveguide.

In Fig. 2, bottom, the power characteristics of the transmitter module is given. Here, measured power levels of the generated 3.76 µm idler radiation (which are corrected for residual losses beyond the waveguide) are shown (symbols). Alongside the measured powers, theoretical curves are given. Two different cases are shown here: In the first case, pump power is fixed at 150 mW (coupled to the waveguide), which means that the gain of the EDFA signal amplifier changes along the abscissa. At high signal levels, a roll-off of the curve is evident due to pump depletion. In the second case, signal power is kept fixed at 50 mW, while pump power is varied. Here, a superlinear behavior becomes evident at high pump power levels, which is due to parametric gain in the nonlinear process. At low power levels, an internal conversion efficiency of 69 %/W is determined, normalized to the pump power level. Measurements and theoretical curves match surprisingly well, although the impact of the observed inhomogeneities was not considered in the calculation. So actually, measured power levels are slightly above the theoretical expectation. This is due to some uncertainty concerning the mode-distributions in the deep MIR-waveguide. Also, the loss figures at near-infrared wavelengths are not precisely known and difficult to measure due to the multimode characteristics of the waveguide.

After characterization of the individual modules, a transmission experiment has been performed, using both, transmitter and receiver modules. The setup is shown in Fig. 3. Here, the 1100 nm pump radiation is split using a ratio of 50:50, to act as pump for both modules. Via DFG the MIR idler wave is generated in the transmitter module, which is coupled out of the waveguide using a CaF_2 lens of 8.3 mm focal length. Two gold mirrors are used in the 1.5 m free-space path to steer the beam to the receiver. Residual pump radiation is removed from the transmission path using an anti-reflection coated Ge filter. Using a second CaF_2 lens, the 3.8 µm radiation is coupled to the receiver waveguide, where it is again converted to 1550 nm by DFG.

At a MIR power level of 4.85 mW in the FSO link, generated by pump and signal powers of 150 and 80 mW, respectively, coupled to the transmitter waveguide, about 100 µW of signal power is regenerated in the receiver waveguide. The transmission therefore equals -29 dB from waveguide to waveguide. Of this, around -14 dB are caused by coupling losses and residual losses in the Ge filter. Another -6 dB arise on each end due to waveguide / fiber coupling.

In conclusion, a C-band–MIR–C-band transmission line was set up with an overall transmission of -41 dB, with -15 dB due to the parametric process; -26 dB are caused mainly by coupling losses in-between waveguides and fibers. Parametric losses can be reduced by pumping with higher power levels, potentially leading even to parametric gain. Free-space coupling losses from waveguide to waveguide can be reduced by the use of optimized bulk optics.

Data transmission experiments via the link were performed successfully; transmitting an analogue QPSK modulated signal at 2.488 Gbit/s, low bit error rates could be demonstrated [4]. The noise impact of the system is negligible, and the signal to noise ratio of the parametric process exceeds 10^6 [5].

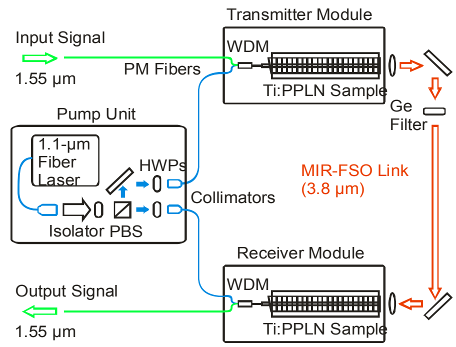

Fig. 3.: Transmission link experiment: both modules are combined to form a free-space transmission line with twofold wavelength conversion.

Acknowledgement - This work was supported by a subcontract of CeLight, Inc.

References

[1] R. Martini et al., “High-speed modulation and free-space optical audio/video transmission using quantum cascade lasers,” IEEE Elect. Lett., vol. 37, pp. 191-193 (2001).

[2] W. A. Traub, M. T. Stier, “Theoretical atmospheric transmission in the mid- and far-infrared at four altitudes,” Appl. Opt., vol. 15, No. 2, pp. 364-377, (1976)

[3] D. Büchter, C. Langrock, H. Herrmann, M. Fejer, W. Sohler, “All-optical Ti:PPLN wavelength conversion modules for free-space optical transmission links in the mid-infrared“, Opt. Lett., vol. 34, No. 4, pp. 470-472 (2009)

[4] E. Ip, D. Büchter, C. Langrock, J. M. Kahn, H. Herrmann, W. Sohler and M. M. Fejer, “QPSK Transmission over Free-Space Link at 3.8 µm using Coherent Detection with Wavelength Conversion,” ECOC2008

[5] S. Orlov, W. Grundkötter, D. Hofmann, V. Quiring, R. Ricken, H. Suche, and W. Sohler: "Mid infrared integrated optical parametric generators and oscillators with periodically poled Ti:$LiNbO_3$ waveguides" in "Mid-Infrared Coherent Sources and Applications", M. Ebrahimzadeh and I.T. Sorokina (Eds.), NATO Science Series - B: Physics and Biophysics, Springer, Dordrecht (2008).