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Integrated Optical PPLN Transmitter and Receiver Modules for Wavelength Conversion of C-Band Signals to / from the Mid Infrared

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Abstract

We developed transmitter and receiver modules with Ti:PPLN waveguide operated as difference frequency generator to convert a signal (λ_s ~ 1550 nm) to the mid infrared (λ_i ~ 3800 nm) and back again.

Introduction

Free-space optical transmission links are desirable to ensure highly flexible data connections of high bit rates. Wavelengths in the C-band, however, while best suitable for fiber optic communication links, are not always ideal for free-space transmission due to residual atmospheric absorption and light scattering [1].

Some wavelength bands in the mid infrared (MIR) offer lower losses and can be more attractive for this reason. Difference frequency generation (DFG) in waveguides is an efficient and convenient way to convert near infrared signals to the MIR and back again while preserving both phase and amplitude information [2].

We developed transmitter and receiver modules with integrated optical difference frequency converters. They consist of low-loss Ti-indiffused waveguides in periodically poled Lithium Niobate (PPLN). The modules were used to set up and to investigate an all-optical C-band → MIR → C-band link.

Transmitter Module

The transmitter module consists of a fibre optical WDM-coupler to combine pump (λ_p = 1100 nm) and signal (λ_s ~ 1550 nm) radiations and of the 80 mm long Ti:PPLN waveguide to generate the MIR-output (λ_i ~ 3800 nm) by DFG (fig. 1). The waveguide is glued to a copper base plate, which can be heated up to temperatures of 200°C. Elevated operation temperatures are necessary to reduce photorefractive effects thus enabling a stable MIR output. The polarization maintaining (PM) input fibre is mounted in a glass ferrule on a miniaturized 3-dim. micro-manipulator enabling optimised fibre butt coupling also at higher operation temperatures. The waveguides were fabricated by an indiffusion of 22 µm wide and 160 nm thick Ti strips for 31 h at 1060°C; they are single-mode in the MIR, but multi-mode in the near infrared. Therefore, a waveguide taper was used to achieve a mode selective excitation of pump and signal modes. After waveguide fabrication the sample was periodically poled with a domain periodicity of 26.65 µm.

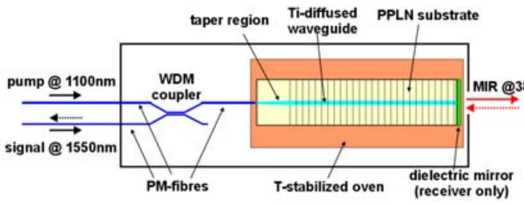

Figure 1: Schematic drawing of the transmitter / receiver modules. Only the receiver module has a dichroic mirror (AR for the MIR, but HR for the pump) to enable signal regeneration by backwards co-directional propagation of both pump and idler waves.

The transmitter was operated with an Yb-doped fibre laser as pump and a tuneable external cavity laser (ECL), followed by an erbium doped fibre amplifier (EDFA), as signal source. By tuning the signal wavelength, (temperature dependent) quasi phase matching (QPM) for DFG could be adjusted. The left-hand side of fig. 2 shows the normalized tuning characteristics of transmitter and receiver as MIR (idler) output power versus signal wavelength at constant pump power and 200 °C operation temperature.

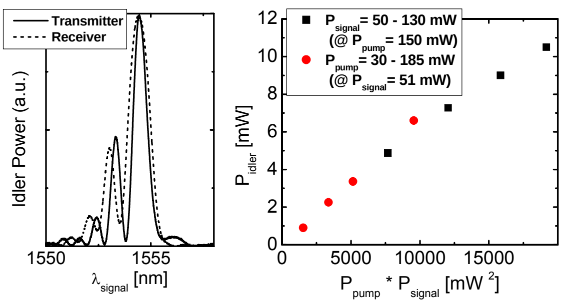

Figure 2: Generated idler power versus signal wavelength (left) and versus the product of signal and pump power (right).

The maximum output power is achieved at λ_s = 1554.4 nm, corresponding to a MIR wavelength λ_i = 3764 nm. The strong side lobe at the short wavelength side is due to slight inhomogeneities of the waveguide and/or the temperature profile. On the right of fig. 2 the MIR power is plotted versus the product of coupled pump and signal power at the input of the waveguide. The maximum MIR-power of

10.5 mW was obtained with 145 mW of pump and 131 mW of signal power. These experimental results agree well with modelling results.

Receiver Module

The receiver module is very similar to the transmitter module; the only difference is the dichroic mirror (AR for the MIR, but HR for the pump) on the waveguide end face enabling signal regeneration by backwards co-directional propagation of both pump and idler waves. Its tuning characteristic is very similar to that of the transmitter if operated as MIR-generator (see fig. 2). However, additional propagation and reflection losses of the pump and stronger inhomogeneities lead to a ~3 dB lower conversion efficiency.

C-Band → MIR → C-Band Link

Both, the transmitter and the receiver modules have been used to set up a 1.5 m long free space all-optical link from the C-band to the MIR and back to the C-band (fig. 3). CaF_2 lenses of a focal length of f = 8.3 mm were used for collimating the MIR-beam and for coupling it back into the receiver module. The loss of the MIR-link (received power to emitted MIR power) was estimated to be -14 dB mainly due to imperfect coupling. Both modules were pumped at λ_p = 1100 nm using a single Yb-doped fibre laser as pump source followed by a free-space power splitter and fibre collimators. Therefore, the resulting C-band signal regenerated by the receiver has exactly the same wavelength as the C-band signal coupled to the transmitter.

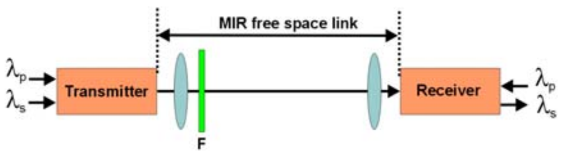

Figure 3: Scheme of the all-optical link from the C-band to the MIR and back to the C-band again. F: filter to suppress pump and signal radiation of the transmitter.

First experiments were done with 150 mW pump power coupled to the waveguides of both modules. By injecting 80 mW of signal power at λ_s = 1554.4 nm into the transmitter, 8.4 mW of MIR power was generated. About 0.3 mW was coupled to the receiver resulting in a regeneration of 100 µW of NIR power at λ_s = 1554.4 nm. Thus, the overall losses of the C-band → MIR → C-band link are ~ -29 dB. The tuning characteristic of this link is shown in fig. 4 as measured receiver output power versus signal wavelength.

Discussion

The normalized efficiency of the transmitter module, defined by $\eta_t = P_i / (P_p \times P_s)$, is 69 $\%W^{-1}$ at power levels below pump depletion (see fig. 2). The efficiency of the receiver, defined by $\eta_r = P_s / (P_p \times P_i)$, should be by a factor of $5.95 = (\omega_s / \omega_i)^2$ higher than η_t, as both efficiencies are defined for power conversion (identical internal losses assumed). Under this assumption, both modules should have the same conversion efficiency for down- and upconversion in terms of photon numbers. However, due to higher internal losses of the receiver, its efficiency is reduced to η_r = 203 $\%W^{-1}$. Therefore, assuming a lossless MIR transmission between both modules and a coupling efficiency to the receiver of 1, the regenerated signal power at the receiver output is given by $P_{s,out} = \eta_r \times \eta_t \times P_p^2 \times P_{s,in}$. As a consequence, pumping with 0.8 W would be sufficient to regenerate the input signal power.

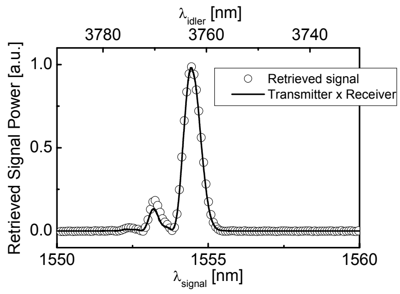

Figure 4: Measured receiver output power versus signal wavelength in the link experiment. For comparison, the product of the measured characteristics of the two modules is shown as well.

Unfortunately, the free-space link with the coupling to the receiver has considerable losses. They arise from uncoated lenses, residual MIR-losses in the filter and from a low coupling efficiency to the receiver. As all these parameters can be improved we are confident to be able to significantly reduce these losses and to set up a nearly transparent C-band → MIR → C-band all-optical link in the near future.

Moreover, the scheme investigated, is able to regenerate the signal at a different wavelength than at the input by using two separate pump sources at different wavelengths, one for each module.

Conclusions

We developed transmitter and receiver modules with Ti:PPLN wavelength converters for wavelength conversion of near infrared signals to / from the mid infrared. A C-band → MIR → C-band free-space all-optical link was demonstrated for the first time. High speed QPSK transmission using this link has just been demonstrated [3].

References

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