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MID-INFRARED DIFFERENCE-FREQUENCY GENERATION IN PERIODICALLY POLED Ti:LiNbO$_3$ CHANNEL WAVEGUIDES

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Mid-infrared radiation around 2.8 μm was generated by difference-frequency generation in a 50 mm long periodically poled Ti:LiNbO$_3$ waveguide using a pump (signal) of about 1.5 μm (3.391 μm) wavelength. We obtained a normalized conversion efficiency of 71 %W^{-1}, the highest value ever reported.

Introduction

Many atmospheric trace gases have their fundamental absorption bands in the mid-infrared (MIR) spectral range [1]. Therefore, sensitive environmental sensing is possible using corresponding MIR (coherent) radiation. Existing lasers have different drawbacks such as limited tunability, low spectral resolution, high power consumption, large size, fragility, and some require (cryogenic) cooling. As a consequence new compact mid-infrared sources for room temperature operation are required.

Tunable coherent emission in the MIR can be generated by difference-frequency generation (DFG) in nonlinear bulk crystals or nonlinear waveguides. In comparison with bulk configurations there is no trade-off in waveguides between mode size and interaction length. Hence, in long structures the guided wave conversion efficiency considerably exceeds the efficiency of a bulk optics approach [2].

MIR-DFG in Ti:LiNbO$_3$ optical waveguides has been demonstrated using birefringence phase matching. However, the conversion efficiency was rather low ($\eta \approx 0.2$ %W^{-1}) [3]. The main disadvantages of birefringence phase matching can be avoided by using quasi-phase matching (QPM) in periodically poled waveguides. This has been demonstrated with proton exchanged channel guides in LiNbO$_3$ resulting in a conversion efficiency of 1.3 %W^{-1} [4].

In this contribution, we report quasi-phase matched mid-infrared difference-frequency generation (around 2800 nm wavelength) in long Ti:LiNbO$_3$ waveguides with the highest efficiency ever communicated.

Device Fabrication

Channel waveguides of 15, 20, 25, and 30 μm width were fabricated on the (-Z)-face parallel to the X-axis of a 50 mm long, 12 mm wide and 0.5 mm thick Z-cut lithium niobate substrate by indiffusion of 160 nm thick titanium stripes (31 h at 1060 °C in argon with a short post-diffusion in oxygen). They are single-mode waveguides in the 3 μm wavelength range [3]. Due to outdiffusion of Li$_2$O and pyroelectrically induced electric fields during the diffusion process an up to 50 μm thick homogeneous domain inversion layer was formed on the (+Z)-face. Therefore, waveguide fabrication by Ti-indiffusion is usually done on the (-Z)-face.

Unfortunately, this domain inversion layer prohibits a subsequent electric field poling of the double-domain sample at room temperature. It was necessary to remove the inverted layer by mechanical grinding to obtain a single-domain substrate again, which could be poled via electrodes on the (+Z)- and (-Z)-face of the sample with the higher potential on the (+Z)-face.

Domain inversion always starts on the (+Z)-face if the applied electric field exceeds the coercive field of $LiNbO_3$ (i.e. about 21 kV/mm). It is therefore preferable to have the periodic electrode on the (+Z)-face (and the homogeneous counter-electrode on the (-Z)-face) to fabricate a periodically inverted substrate. In this way better defined domain boundaries with a more homogeneous periodicity are obtained in particular near the (+Z)-surface below the periodic electrode. As a consequence the optical waveguides should be on the (+Z)-face. Taking these considerations into account we performed before the periodic poling a charge controlled homogeneous polarisation reversal of the whole sample using liquid electrodes on both surfaces. Thereafter, the waveguide was on the prefered (+Z)-face.

In a second poling step the periodic domain structure was made by applying a voltage of about 10 kV controlling current and charge. The periods of the electrode mask ranged from 31.2 to 32.2 μm with a duty cycle of 39 % (width of the electrode to gap). The whole (-Z)-face was electrically contacted by a LiCl solution.

Finally, the electrodes were removed and the whole crystal was chemically etched in $HF:HNO_3$ for a few minutes to reveal the domain structure. By this process, mainly the (-Z)-faces are attacked. The inset in Fig. 1 shows a micrograph of the waveguide surface with the domain boundaries clearly observable and a nearly optimum duty cycle of 50:50. We also used a nondestructive second-harmonic microscope to reveal a successful domain inversion [5]; in this case, chemical etching was not necessary.

Experimental Set-Up

Fig. 1 shows the experimental set-up to perform DFG experiments. We used a single-frequency fibre coupled external cavity semiconductor laser as pump laser tunable from 1500 to 1580 nm with a maximum output power of 2 mW. The pump radiation was amplified by an erbium doped fibre amplifier up to 11 mW in the 1520 to 1580 nm spectral range. The signal laser was a monomode TEM_{00}, single longitudinal He-Ne laser with 1 mW output power at $\lambda = 3391$ nm.

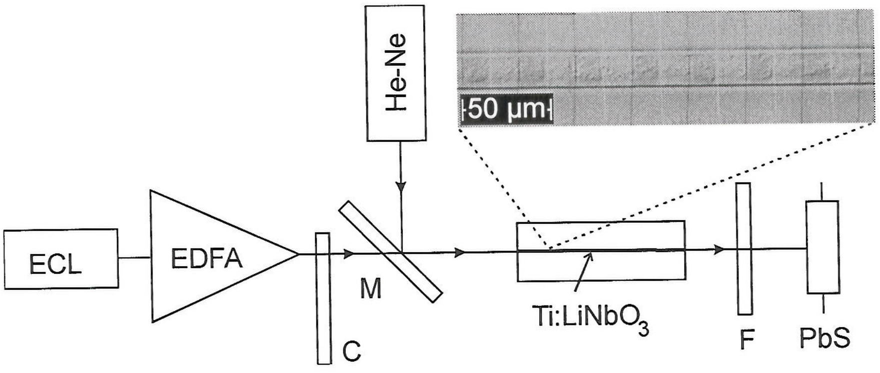

Fig. 1: Experimental set-up: ECL (external cavity laser), EDFA (erbium doped fibre amplifier), C (chopper), M (dichroic mirror), He-Ne (helium-neon laser), F (germanium filter), PbS (lead sulfide photoconductive detector), lenses not shown.
Inset: Surface of periodically poled and chemically etched $Ti:LiNbO_3$ waveguide.

Superimposing of the two laser beams was done by using a dichroic beam splitter with high reflection around 3391 nm and high transmission around 1550 nm. The combined beams in TM polaristaion were focused in the $Ti:LiNbO_3$ waveguide by a f = 8.3 mm or a f = 10 mm CaF_2 lens with an estimated coupling efficiency of 70 %. By a second lens of the same type the signal and the generated idler radiations were focused on a lead sulfide (PbS) photoconductive detector. The pump radiation was absorbed by two Ge filters at brewster angle orientation in front of the detector. As the pump was chopped the idler was periodically generated and the signal periodically amplified. Both contributions were measured together by using a lock-in technique. However, the spectral responsivity of the PbS-detector at the signal wavelength $\lambda = 3391$ nm is estimated to be only one thirtieth of the responsivity at the idler wavelength around $\lambda \approx 2800$ nm, so that the detected power corresponds almost exclusively to the idler signal.

Experimental Results and Discussion

The attenuation of the periodically poled waveguides has been investigated in TM-polarisation at $\lambda = 3391$ nm using the low-finesse resonator method [6]; we measured losses between 0.15 and 0.25 dBcm^{-1} with no significant difference between periodically and homogeneously poled waveguides. At this wavelength (signal wavelength of DFG) only the fundamental mode is guided.

The phase matching curve in Fig. 2 presents the generated idler power as function of the pump wavelength at room temperature for both experiment and theory at constant signal wavelength ($\lambda_S = 3391$ nm) and power; the investigated waveguide has a domain period of $\Lambda = 31.4$ µm.

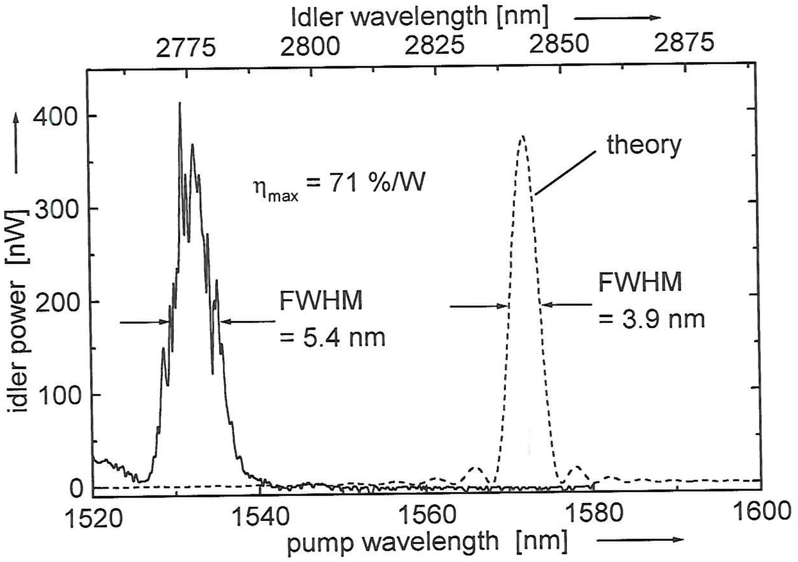

Fig. 2: Idler power versus pump wavelength in a 20 µm wide Ti:LiNbO_3 waveguide with 31.4 µm QPM period length; experiment (line), theory (dashed line); theoretical curve is calculated with 50 mm interaction length and 0.2 dBcm^{-1} attenuation

The maximum idler power measured at optimum phase matching was around 350 nW. The fine structure of the experimental response results from Fabry-Perot resonances of the waveguide, which represents a low finesse resonator. These resonances are excited with different efficiencies due to the mismatch of resonator mode spacings (0.011 nm) and wavelength tuning steps (0.05 nm) of the pump laser. With coupled power levels of about 7 mW (pump) and 70 µW (signal) a maximum conversion efficiency of 71 $\%\text{W}^{-1}$ has been achieved (of 85 $\%\text{W}^{-1}$ if the 415 nW are taken into account as the maximum idler power); this conversion efficiency is normalized to the pump power level. In comparison with literature results in both, bulk and waveguide configurations, this is the highest efficiency ever reported; it exceeds published efficiencies for DFG in bulk nonlinear crystals (e.g. [1]) by about four orders of magnitude and those for DFG in waveguides (e.g. [7], [8]) by nearly two orders of magnitude. If our result is normalised to the square of the waveguide length we get an efficiency of 2.8 $\%W^{-1}cm^{-2}$ (3.4 $\%W^{-1}cm^{-2}$, respectively), comparable with a corresponding result achieved with periodically poled proton exchanged waveguides in $LiNbO_3$ at somewhat shorter wavelengths [8]. Theoretical evaluations of the conversion efficiency using fundamental modes of pump, signal and idler radiation with a Gauß-Hermite-Gauß approximation of the mode field distributions provide the same results, if we assume a loss factor of $\alpha = 0.20$ $dBcm^{-1}$ for all three waves. The halfwidth of the experimental characteristic of 5.4 nm is best reproduced by a modelled response if an effective interaction length of 45 mm is taken into account. This result demonstrates that 90 % of the 50 mm long periodically poled waveguide contributed to the frequency conversion process; the waveguide homogeneity is excellent.

Whereas experimental and theoretical power characteristics are in good agreement, there is a relatively large deviation of the respective wavelength position. The difference is due to uncertain index data of $LiNbO_3$ in the MIR spectral range.

Conclusions

In conclusion we have generated mid-infrared radiation around 2800 nm by quasi-phase matched difference-frequency generation of He-Ne laser ($\lambda = 3391$ nm) and extended cavity semiconductor laser ($\lambda \approx 1550$ nm) radiations in Ti:$LiNbO_3$ waveguides with the highest conversion efficiencies so far reported. Conversion efficiencies up to 85 $\%W^{-1}$ in 50 mm long waveguides demonstrate the excellent homogeneity of the periodically poled Ti:$LiNbO_3$ structures. This result is a great step towards a compact, widely tuneable, low threshold, and highly efficient mid-infrared optical parametric oscillator (OPO).

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