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A high-gain optical parametric amplifier tunable between 3.27 and 3.65 μm

M.J.T. Milton, T.J. McIlveen, D.C. Hanna [1] and P.T. Woods
National Physical Laboratory, Division of Quantum Metrology, Teddington, Middlesex, TW11 0LW, UK

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Pulsed optical parametric amplification has been demonstrated in lithium niobate pumped at a wavelength of 1.064 μm. A small-signal gain of 18 has been achieved at a signal wavelength of 3.59 μm. The saturated output energy at this wavelength is 17.5 mJ per pulse. The gain is continuously tunable over the range 3.27 to 3.65 μm. An idler is generated that covers the wavelength range 1.50 to 1.58 μm.

1. Introduction

The phenomenon of optical parametric amplification has been studied in several previous works [1–3] but never with a widely-tunable signal at wavelengths significantly longer than the pump. We have demonstrated tunable parametric amplification of a signal in the wavelength range 3.27 to 3.65 μm with a pump at 1.064 μm. The signal was generated by difference-frequency mixing between a tunable dye laser operating in the wavelength range from 803 to 824 nm and a Nd:YAG laser (at 1.064 μm). The results demonstrate that a high gain and large saturated output energy can be achieved using a signal with relatively poor beam quality generated from a mixing interaction. This parametric amplifier, together with a difference-frequency mixing stage required to generate the signal, forms a source suitable for performing differential absorption LIDAR measurements [4,5] of gaseous hydrocarbons in the 3 μm spectral region.

A novel feature of this work is that the input waves in both the optical parametric amplifier and the difference-frequency mixing signal source were aligned in a non-collinear geometry. This enabled them both to use the principle of tangential phase matching which provides a method for increasing the acceptance angle of a nonlinear process by the use of a geometry that enables the wavevector surfaces of the interacting waves to be tangential in the phase-matched direction [6].

2. Theory

The theory of second-order nonlinear processes has been discussed widely [7,8]. If two beams at frequencies ω_p and ω_s are incident on a second-order nonlinear medium then a third beam can be generated at the difference frequency ω_i such that

$$\omega_i = \omega_p - \omega_s , \quad \text{where } \omega_p > \omega_s . \tag{1}$$

In addition to the generation of a photon at the difference frequency ω_i, the destruction of each photon at ω_p is accompanied by the generation of an additional photon at ω_s. This is the phenomenon referred to as parametric amplification. Using the terminology commonly applied to the optical parametric amplifier: ω_p is the pump, ω_s is the signal and ω_i is the idler.

One of the parameters that determines the efficiency of such a process is the mismatch between the wavevectors of the interacting waves $\Delta \boldsymbol{k}$ defined by

$$\Delta \boldsymbol{k} = \boldsymbol{k}_p - \boldsymbol{k}_s - \boldsymbol{k}_i . \tag{2}$$

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[1] Optoelectronics Research Centre, Southampton University, Southampton, SO9 5NH, UK.

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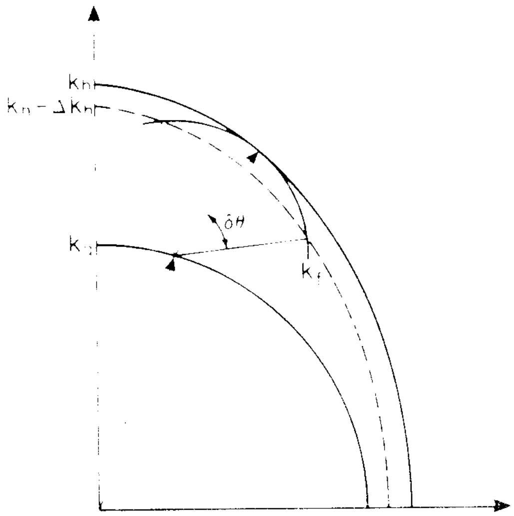

Fig. 1. The tangential phase-matching condition is met when the angle between the input beams is equal to the walkoff angle of the extraordinary beam.

For the process to be phase matched it is necessary that $\Delta k=0$. In the experiment performed here, Type I phase matching was used, hence $\boldsymbol{k}_{\mathrm{p}}$ was polarised as an extraordinary wave in the nonlinear medium and the other two beams were ordinary waves.

The gain at the signal wavelength is defined by [9]

$$\Gamma=I_{\mathrm{s}}(l)/I_{\mathrm{s}}(0)\ , \tag{3}$$

where $I_{\mathrm{s}}(0)$ and $I_{\mathrm{s}}(l)$ are the signal intensities at the input to the crystal and after propagating through a crystal of length l respectively. In the limit of the pump being very much more intense than the signal, the gain is given by

$$\Gamma=1+\sinh^2[Cl I_{\mathrm{p}}(0)^{1/2}]\ . \tag{4}$$

The properties of the nonlinear medium are described by the constant

$$C=\frac{4\pi d_{\mathrm{eff}}}{(2n_{\mathrm{p}}n_{\mathrm{s}}n_{\mathrm{i}}\lambda_{\mathrm{s}}\lambda_{\mathrm{i}}\epsilon_0 c)^{1/2}}\ ,$$

where d_{eff} is the effective nonlinear coefficient and n is the refractive index.

The angular acceptance of the process can be defined as the change in direction of the incident waves required to introduce a specified amount of phase mismatch to the interaction. As a consequence of the pump beam being an extraordinary wave its wavefront is not spherical and the acceptance angle of the interaction is limited. This problem can be overcome by the use of tangential phase matching which uses a non-collinear geometry to enable the wavefronts of the interacting beams to be tangential for the direction of propagation of the idler wave. The geometry required is shown in fig. 1. The principle of tangential phase matching has been discussed elsewhere [6,10,11]. It has been demonstrated that the angular acceptance is a maximum when the angle between the input beams is equal to the walkoff angle of the extraordinary beam. The directions of the beams required to achieve this condition in the optical parametric amplifier are shown in fig. 2.

3. Experimental details

The primary laser source used for this work was a Q-switched Nd:YAG laser (Quantel International YG682) operating at a fundamental wavelength of 1.064 μm. It had a repetition rate of 10 Hz, a pulse length of 6–8 ns and an injection-seeded linewidth of 0.002 cm^{-1}. A fraction of the output from this laser was frequency-doubled (in potassium di-hydrogen phosphate) to 532 nm and used to pump a tunable dye laser (Quantel International TDL60). The tunable dye laser used the dye LDS 821 (Exciton) in methanol and was tunable over the wavelength range 785–851 nm with a linewidth of 0.1 cm^{-1}.

Figure 3 shows how the experiment was arranged. The tunable source used as the signal input to the optical parametric amplifier was generated by difference-frequency mixing between the tunable dye laser and the fundamental output of the Nd:YAG laser. This was performed in a lithium niobate crystal (50×10×10 mm) cut with the normal to the input face at a nominal angle of 47 degrees to the optic axis and orientated with its principal plane horizontal. The incident beams from the tunable dye and Nd:YAG lasers were polarised horizontally and vertically respectively and the generated beam was polarised vertically. A broadband polarisation rotator (Newport Research Corp) was used to rotate the polarisation of the dye laser beam into the horizontal plane. Rotating the polarisation of this beam away from the optimum plane allowed the energy generated by the difference-frequency mixing to be varied

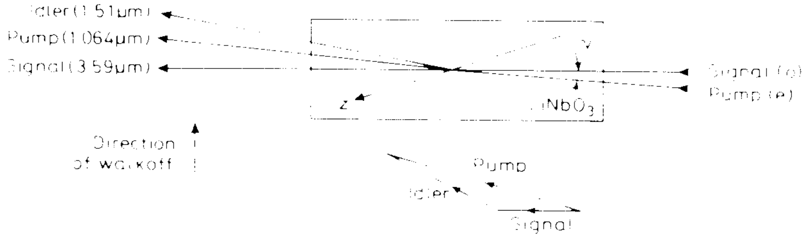

Fig. 2. The direction of the beams in the parametric amplifier. With the beams in these directions the tangential phase matching condition is met.

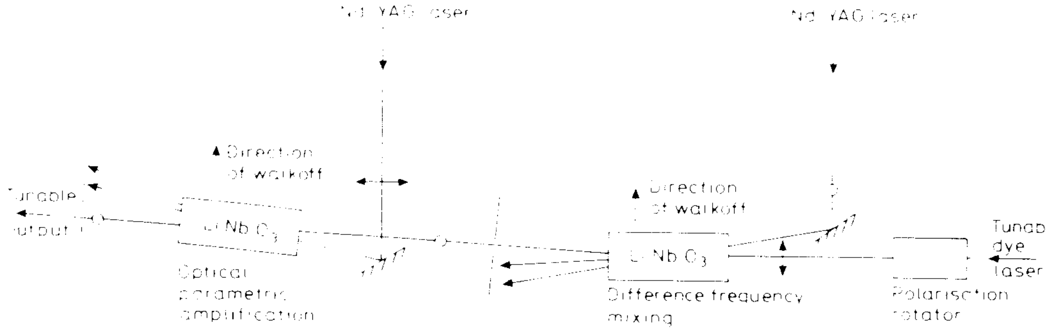

Fig. 3. Schematic diagram of the difference-frequency mixing and parametric amplification stages. Both the signal generated by the difference-frequency mixing stage and the idler generated by the parametric amplifier are polarised vertically. The tunable input to the difference-frequency mixing stage and the 1.064 µm pump for the optical parametric amplifier are both extraordinary waves and are polarised horizontally.

without altering the alignment or spatial quality of the generated beam.

The optical parametric amplifier also consisted of a lithium niobate crystal (50×10×10 mm) cut with the normal to the input face at a nominal angle of 47 degrees of the optic axis and orientated with its principal plane horizontal. (The near coincidence of the phase-matching angles of the difference-frequency mixing and the optical parametric amplifier interactions at the wavelengths used here has been commented upon elsewhere [12].) The pump beam from the Nd:YAG laser was polarised horizontally and propagated as an extraordinary wave. The input signal and generated idler were both polarised vertically.

As described in the previous section, the highest conversion efficiency was achieved for both processes with the beams aligned in a horizontal plane but at a small angle with respect to each other in that plane. The relative directions of the beams are shown in fig. 3. The small angle between the beams at the input to each crystal enabled them to be combined with simple reflectors split in half along a diameter. It also resulted in the three beams being well separated spatially at the output.

4. Results

The performance of the difference-frequency mixing stage has been described extensively elsewhere [6]. In this work it was aligned in a non-collinear geometry, and was capable of giving a maximum energy of 5 mJ in the wavelength range 3.27–3.65 µm. The restriction on the wavelength range used for this work was due to the limited range over which the dye laser operated efficiently. The ultimate limits to the wavelength range over which the optical parametric amplifier works are imposed by the wavelength of the pump (1.064 µm) and the transmission limit of lithium niobate [13] (4.5 µm), respectively.

Figure 4 shows the measured performance of the

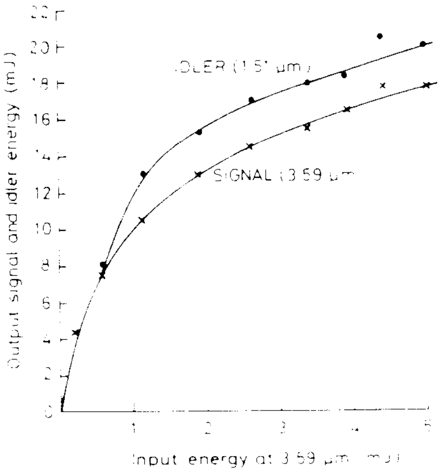

Fig. 4. Energy measured at the signal and idler wavelengths at the output from the parametric amplifier as a function of the signal input.

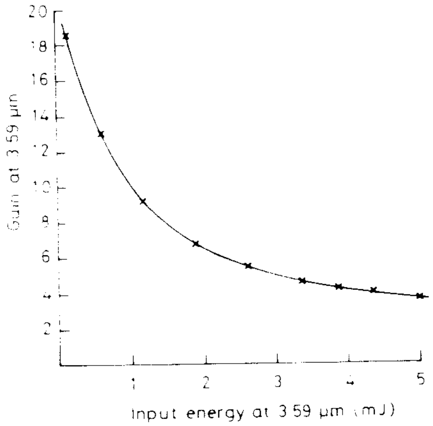

Fig. 5. Parametric gain at a signal wavelength of 3.59 μm versus the signal input.

optical parametric amplifier including both the amplified signal energy and the generated idler energy. Figure 5 shows the same measurements converted into values for the gain at the signal wavelength. These measurements were made at a signal wavelength of 3.59 μm and with a pump energy of 175 mJ which was the maximum feasible without damaging the crystal. In this experiment the energy extracted is ultimately limited by the overlap between the pump and signal beams. These results are consistent with those achieved at similar pump and signal energies in an experiment with a diffraction-limited signal [3] and show the form expected from eq. (4). The similarity between these measurements with relatively poor quality beams and the previous work with diffraction-limited beams is explained by the use of tangential phase matching in this case to enhance the acceptance angle of the interaction.

The values for the gain were calculated as the ratio of the signal measured at the input to the crystal, and the signal measured at the exit from the crystal. Consequently, they represent the gain that may be achieved practically with such a device. The actual gain within the crystals is much greater than this because the signal beam experiences reflection losses at the uncoated input and output surfaces of the crystal. Based on a refractive index of 2.15 for lithium niobate at 3.5 μm, the gains defined by eq. (3) should be increased by 33% to give the internal values.

5. Summary

Tunable pulsed parametric amplification has been observed in lithium niobate when pumped at a wavelength of 1.064 μm. The performance of this parametric amplifier is consistent with measurements made at shorter signal wavelengths [3], and is ultimately limited by the damage threshold of the crystal at the pump wavelength and the limited overlap between the pump and signal beams.

This source has been successfully used for making range-resolved differential absorption LIDAR measurements of gaseous hydrocarbon species including methane, propane and butane.

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