TUNABLE DOWN-CONVERSION FROM AN OPTICAL PARAMETRIC OSCILLATOR

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A new method for the production of high power, tunable laser-like infrared radiation is described. An optical parametric oscillator (OPO) and a down-converter are combined so that radiation is generated at the frequency difference between signal and idler frequencies. In an experiment using proustite for the down-converter crystal and a 1.065 μm pumped OPO, tunable radiation has been produced over the range 8–12 μm. Using CdSe in the down-converter the region 10–25 μm could be spanned with peak powers approaching 100 W.

Among the variety of tunable sources of coherent radiation being developed for the infrared, both optical parametric oscillators (OPO) [1] and down-converters (difference-mixers) [2] are distinguished by their large tuning ranges and high peak powers. (They also avoid the need for cryogenics.) Acentric phase-matchable crystals are common to both and the technology of these materials, as well as of the pump lasers, determines what progress can be made. The OPO, being a resonant device, demands the highest crystal quality. By contrast, one can tolerate a poorer crystal for the down-converter but now two pump lasers are required, one at least of which is tunable. In this letter we discuss a *union* of the two devices, where the parametric oscillator provides two tunable inputs for a down-converter. In addition to outlining the essential philosophy of this new approach, an experiment is described which demonstrates the technique.

The basic idea is simple. A parametric oscillator, pumped at ω_p by a suitable laser, provides two output waves, the signal (ω_s) and the idler (ω_i), where

$$\omega_p = \omega_s + \omega_i .$$

The signal and idler frequencies can be tuned by variation of phase-matching in the OPO. Oscillation is maintained fairly close to degenerate so that

$$\omega_s \gtrsim \omega_p/2 \gtrsim \omega_i .$$

The OPO output is then focussed into another nonlinear crystal set so that phase-matching is obtained for difference mixing between the signal and idler:

$$\omega_{ir} = \omega_s - \omega_i .$$

The small, variable frequency difference between signal and idler is thus "down-converted" to a tunable wavelength well into the infrared.

Proustite (Ag_3AsS_3) [3] was chosen as the down-conversion crystal in the experiment as its large birefringence permits all three-wave mixing processes to be phase-matched for transmitted wavelengths. Its transmission range, 0.6–13 μm, includes the OPO wavelengths of interest and extends well into the infrared. Another positive consideration was the ready availability of good quality crystals, we had also previously demonstrated down-conversion in proustite using a ruby and tunable dye laser [4].

The phase-matching schemes for proustite (negative uniaxial, point group 3m) are

$$k_s^e = k_i^o + k_{ir}^o , \tag{1}$$

$$k_s^e = k_i^o + k_{ir}^e , \tag{2a}$$

$$k_s^e = k_i^e + k_{ir}^o . \tag{2b}$$

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(We have extended the conventional definition [5] of type 2 matching to indicate whether it is the middle frequency wave (2a) or the lowest frequency wave (2b) which is orthogonally polarised to the other two.) Of particular interest here is type 2b matching as the signal and idler waves have the same polarisation. No device is then required for changing polarisation between the OPO and down-converter. (We assume that the signal and idler waves have the same polarisation in the OPO.) Type 2b matching was used in the experiment reported below with phase-matching angles θ_m, calculated (see fig. 2 below) from published expressions for the proustite indices [6]. The other two phase-matching schemes require the signal and idler to be orthogonally polarised. A simple way to achieve this is to place a quarter-wave plate between the OPO and down-converter although it obviously reduces the down-converted power by a factor of four. It is worth noting that for a 1.065 μm laser pumped OPO/down-converter utilising type 1 matching θ_m remains between 16.5–17.5° for down-converted wavelengths extending over 6–13 μm.

For the experiment a proustite parametric oscillator was used whose essential features have been described previously [7]. The only significant departure from the original design is a better technique [8] for longitudinal mode selection of the Nd:CaWO$_4$ laser. This has lead to improved OPO stability. The total output power (signal plus idler) used in the experiment was $\approx$ 100 W. Tuning was from 1.87–2.47 μm. It should be noted that although we used a proustite oscillator in our experiment any OPO with its degenerate wavelength at $\approx$ 2 μm would have been equally suitable.

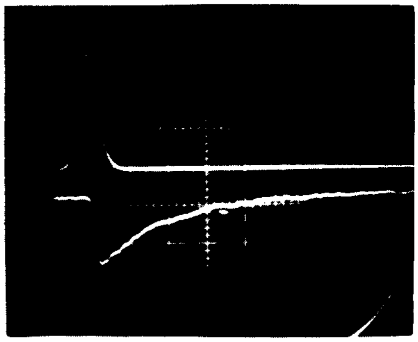

Fig. 1. Operation of the proustite OPO/down-converter. Upper trace – 1.065 μm laser pump; lower trace (inverted) – output at $\approx$ 10 μm. Time scale 100 nsec/division.

The 5 mm long proustite down-converter crystal* was cut for propagation in the x_1, x_3 plane with the optic axis at 37 ± 0.5° to the face normal. The crystal was mounted on a circle for adjustment of θ_m. The rest of the experimental set up was straightforward. Laser pump power transmitted through the OPO was eliminated by means of a Ge filter. A fused silica lens then focussed the OPO output into the proustite crystal and the resulting down-converted radiation was isolated by use of an InSb filter. A liquid nitrogen cooled $Hg_xCd_{1-x}Te$ photodetector followed by a preamplifier was used to detect the down-converted power; a KBr lens being employed to focus the beam onto the small element.

Fig. 1 shows a typical CRO trace from the $Hg_xCd_{1-x}Te$ detector together with that for the corresponding laser pump pulse (S1 vacuum photodiode). The greater length of the down-converted pulse is due to the relatively slow response of the $Hg_xCd_{1-x}Te$ device. The peak detected power was $\approx$ 200 μW. A calculation using eq. (1) of ref. [4], with 50 W each of signal and idler and TEM$_{00}$ spot diameters $2W_s = 2W_i \approx 100\ \mu$m, predicts a 10 μm down-converted power of 10 mW. This calculation assumes that the OPO operated only in the lowest order transverse mode. The discrepancy between observed and predicted powers is almost certainly due to oscil-

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* Supplied by the Electronic Materials Unit of the Royal Radar Establishment.

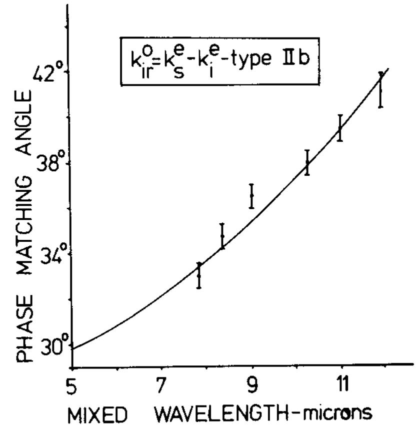

Fig. 2. Tuning curve for type 2b phase-matched proustite OPO/down-converter. Shown are both experimental points and a theoretical curve calculated using ref. [6].

lation on a number of higher order modes. The output was tuned from 7.8–11.9 μm and the measured phase-matching angles are in good agreement with those calculated (fig. 2). The down-converted wavelengths were not measured directly but calculated from the known signal and idler wavelengths. Broad-band filters were, however, used to check that infrared power in the correct region was being produced. The polarisation of the down-converted radiation was also confirmed to be that expected for the phase-matching scheme adopted.

Our aim in performing the above experiment was to demonstrate the feasability of the new technique. Considerable improvements could be made to the proustite device. In particular, a relatively small extension of the OPO tuning range to 1.6–3.15 μm would allow down-converted radiation to be generated from 3.15 μm out to the 13 μm cut-off of proustite. No other device can be continuously tuned from 1.6–13 μm.

We believe that an even greater significance of our new technique lies in its potential use with other non-linear crystals so as to extend tuning far beyond the 13 μm limit of proustite. There are a number of reasons why the OPO/down-converter combination would be adopted:

(i) poor optical quality of the non-linear crystal preventing its use in an OPO;

(ii) crystal transmission range incompatible with available tunable lasers for conventional difference-mixing (dye lasers show poor reliability for wavelengths beyond ≈ 0.7 μm);

(iii) realisation of very broad-band tuning where OPO tuning is limited for practical reasons like non-availability of suitable mirrors. (For a given crystal, ultimate tuning ranges are very similar whether the material is used in an OPO or for the final stage of an OPO/down-converter. Careful choice of pump wavelengths are required for both devices.)

Good examples for (i) and (ii) are certain members [9] of the family of ternary chalcopyrite compounds which have been attracting increasing interest following the first measurements [10] on $AgGaS_2$. An important example of condition (iii) is CdSe for which large crystals of excellent quality are now available [11]. A singly-resonant OPO using CdSe was demonstrated very recently [12, 13] but for only a very limited tuning range 7.9, 9.8–10.4 μm.

Using the best published values for the refractive indices [11] and for birefringence [14], Sellmeier equations have been derived for CdSe:

$$n_o^2 = 4.1321 + \frac{1.8587\,\lambda^2}{\lambda^2 - 0.2187} + \frac{3.0461\,\lambda^2}{\lambda^2 - 3380}\,,$$

$$n_e^2 = 4.0829 + \frac{2.0038\lambda^2}{\lambda^2 - 0.2075} + \frac{3.5540\lambda^2}{\lambda^2 - 3629}\,,$$

where λ is in microns. To obtain good predictions for long wavelengths, the lower dispersion frequencies in these equations have been fixed at the experimentally measured CdSe reststrahls [15]. As CdSe belongs to point group 6 mm and is positive uniaxial only type 2 phase-matching is permitted [5]. Computations using these Sellmeier equations show that only type 2a matching is possible for an OPO/down-converter pumped at 1.065 μm (see fig. 3). Down-conversion is seen to produce wavelengths extending from ≈ 10 μm to the 25 μm long-wave transmission limit. With a 3 cm CdSe crystal and 5 kW pulsed powers on signal and idler, ≈ 100 W of down-converted power could be generated at wavelengths as long as 20 μm. (The peak radiation intensity would be no greater than one quarter of the threshold for laser damage.) A lithium niobate OPO [16] operating singly-resonant appears to be the best choice. Good frequency purity should then be possible for both signal and idler, provided a single longitudinal mode pump [8] is used. A Fabry–Pérot etalon inside the OPO may be an additional aid in obtaining a narrow

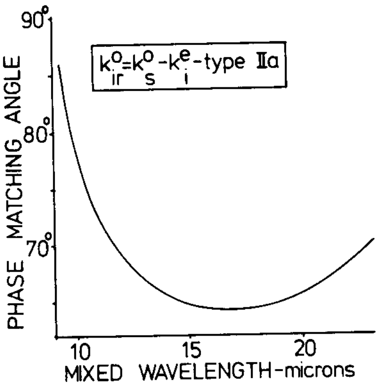

Fig. 3. Predicted tuning curve for a 1.065 μm pumped OPO/down-converter using CdSe.

band-width [17], as well as offering fine tuning with the OPO close to degeneracy. Band-widths of the down-converted output should be smaller than 0.1–0.2 cm^{-1}.

We conclude, therefore, that down-conversion from the optical parametric oscillator output is capable of providing tunable infrared radiation in wavelength ranges unapproachable by other methods. The problem of power loss in the down-converter stage may possibly be overcome by locating the down-converter crystal inside the OPO resonator.

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