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CdSe down-converter tuned from 9.5 to 24 μm

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The signal and idler outputs from a proustite parametric oscillator have been difference mixed in a CdSe crystal to produce infrared radiation tuned continuously from 9.4 to 24.3 μm. Difference-frequency powers, monitored by a pyroelectric detector, range from 10 W at 10 μm to 100 mW at 22 μm.

A number of tunable laser devices have been developed for the medium infrared region (2.5–25 μm). These include semiconductor lasers, spin-flip lasers, parametric oscillators, and down-converters. The last two have the important advantage of a very wide tuning range and the experimental convenience of not requiring cryogenics. To date, the region between 14 and 25 μm has been virtually untouched[1] by nonlinear optical devices based on crystals. For example, the threshold pump intensity of parametric oscillators increases with wavelength; the longest wavelength so far produced being[2] 13.7 μm from a CdSe oscillator. By contrast, the long-wavelength limit of a crystal down-converter is determined solely by the onset of lattice absorption. However, a crystal which shows transmission well into the infrared will generally have its band edge in the near infrared. This precludes the use of dye lasers which have provided a convenient source of tunable radiation for down-conversion (see, e.g., Ref. 3). Even if the visible transmission is good, the birefringence may be insufficient to phase match for down-conversion with dye lasers, and it will then be necessary to use near-infrared mixing sources. Parametric oscillators can readily provide tunable near-infrared outputs and thus offer the possibility of generating much longer infrared wavelengths by mixing the signal and idler in a second nonlinear crystal. We first demonstrated this scheme[4] by mixing the outputs of a proustite optical parametric oscillator[5,6] in a second proustite crystal, thereby generating radiation from 8 to 12 μm. In the same letter, we proposed the application of this technique to down-conversion in other materials such as the ternary chalcopyrites, or CdSe. The latter is of particular interest as infrared can be generated out to ~25 μm. Since then, Byer *et al.* using essentially the same technique with crystals of both $AgGaSe_2$ and CdSe,[8]

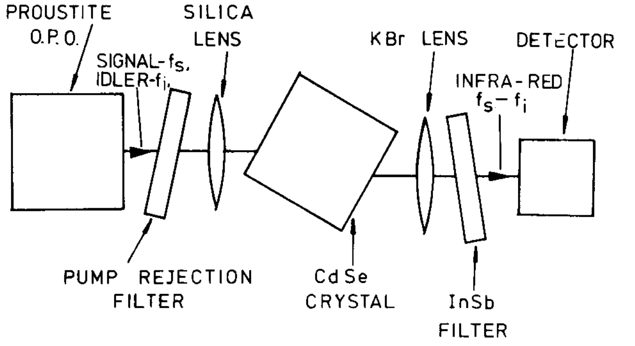

FIG. 1. Schematic arrangement for OPO/down-converter using CdSe.

have extended the tuning range to ~13.5 μm. In this letter we report the achievement of our original proposal for CdSe which has allowed us to generate infrared between 9.4 and 24.3 μm. The generated powers ranged from 10 W at 10 μm to 100 mW at 22 μm, thus permitting the use of pyroelectric detectors. It is also worth noting that the generated power in the region of 25 μm is some three orders of magnitude greater than the corresponding power reported to date for alkali-vapor down-converters.[9]

The proustite parametric oscillator used in this experiment was a doubly resonant oscillator[5]; this configuration offers the convenience of accurately collinear signal and idler outputs. The oscillator used a crystal 8 mm long pumped by a single longitudinal mode Q-switched Nd:YAG laser[10] operating at 1.064 μm. The TEM_{00} output of the laser was focused to a field spot radius (W_0) of 0.6 mm at the crystal with a resulting power density of 5 MW/cm^2. The oscillator outputs were also in the TEM_{00} mode. The total output power (signal + idler) was typically 3 kW (15-ns pulse) over the signal wavelength range 1.8–2.1 μm.

Figure 1 shows the experimental layout. It was arranged that the polarizations were correct for type-IIa phase matching.[4] The focused power density at the CdSe was 14 MW/cm^2, well below the reported damage threshold.[11] Two detectors have been used, a Ge:Cu detector for preliminary alignment and a TGS pyroelectric for subsequent work. The CdSe crystal, from Gould Inc., was 2.8 cm in length and oriented with the optic axis at 85° to the face normal. This crystal had originally been used in a parametric oscillator pumped by an HF laser[12] and consequently the orientation of the optic axis was not ideal for our down-conversion experiment. In fact for generation in the wavelength range between 13 and 20 μm the difference-frequency beam could only be extracted from the crystal after internal reflection from one of the side faces. Meaningful power measurements could not be made over this range, although the phase-matching angle could still be satisfactorily determined. Beyond 20 μm it again became possible to phase match with the beams passing straight through the crystal (see Fig. 2). Measurements of power at 22 μm using the Ge:Cu and pyroelectric detectors both gave a value of 100 mW. The power of 10 W measured at 10 μm is within a factor of 4 of that calculated. The larger discrepancy at longer wavelengths was most probably a result of the large diffraction spread of the generated infrared beam. The signal and idler wavelengths were measured with a grating monochromator and the down-converted wavelengths were calculated from these values.

The down-converted wavelength was continuously tuned from 9.4 to 24.3 μm. The long-wavelength limit it determined by the onset of lattice absorption[13] (1.5 cm^{-1} at 24.3 μm). There is also a narrow impurity absorption centered on 18.5 μm which varies in strength from one crystal to another.[13] The short-wavelength limit of 9.4 μm is the result of insufficient birefringence for phase matching at shorter wavelengths. The measured phase-matching angles are shown in Fig. 2 and are in satisfactory agreement with the solid curve calculated using the Sellmeier equations of Ref. 4. A useful feature of the tuning curve is the flat region around 16 μm. This, together with the relatively wide angular tuning width (which results from the small birefringence), means that a significant range of infrared wavelengths can be generated without the need to reorient the crystal for phase-matching. This will be of value in applications requiring a wide wavelength scan.

In conclusion, we have shown that by combining a near-infrared parametric oscillator with a CdSe down-converter, it is possible to generate radiation at high power levels over a very wide wavelength range. Shorter infrared wavelengths, i.e., 3–12 μm can be covered in the same way using proustite as the down-converter.[4] Thus a device based on a 1.06-μm-pumped parametric oscillator (using either proustite or $LiNbO_3$) tuned over the limited range 1.6–3.2 μm together with proustite and CdSe down-converters will span the entire range from 1.6 to 25 μm.

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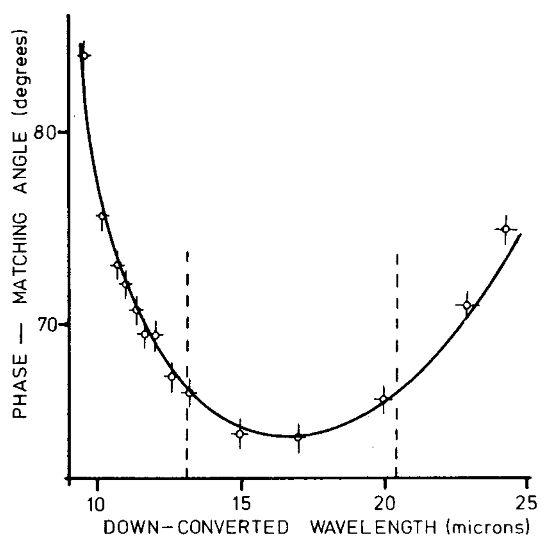

FIG. 2. Angular tuning curve for CdSe down-converter. The full curve is calculated from the Sellmeier equation of Ref. 4. For wavelengths between the dotted lines, a total internal reflection was used to extract the infrared.

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