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The conversion of infra-red radiation into visible in a proustite crystal when the pump beam and the infra-red signal beam are perpendicular to each other

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The conversion is considered of infra-red radiation into visible in a proustite crystal with the pump and signal waves perpendicular to each other. The angular and spectral parameters as well as the efficiency of such interactions are determined. The advantages of this interaction are discussed.

1. Introduction

The methods of non-linear optics yield, from the interaction of two waves in a non-linear crystal, radiation at a third frequency [1-4]. In previously published work in the field of image conversion from the infra-red to the visible, only the cases of collinear or quasi-collinear interaction between the pump and the signal infra-red waves have been considered. For conversion from 10 μm to the visible in a proustite crystal (Ag_3AsS_3), the phase matching conditions allow such an interaction even when the pump and signal waves are propagating in mutually perpendicular directions [5].

The principal advantages of such an interaction will be described.

2. Theoretical

Let us consider the interaction in which the pump (wave vector $\mathbf{K}_1$) is an ordinary wave but the signal ($\mathbf{K}_2$) and the visible radiation ($\mathbf{K}_3$) are both extraordinary; that is, the O-E-E interaction is being used. Let us suppose that the non-linear crystal is of infinite size, that $\mathbf{K}_1$ and $\mathbf{K}_2$ lie along the X and Y axes and that the crystal's optic axis lies in the XY-plane. Choose the pump and signal beams so that the slowly changing amplitudes of the pump and infra-red field have the forms:

$$A_1 = A_{10} \exp\left(-\frac{z^2}{a_1^2} - \frac{y^2}{b_1^2}\right),$$

$$A_2 = A_{20} \exp\left(-\frac{z^2}{a_2^2} - \frac{(x - y \tan \gamma_2)^2}{b_2^2}\right).$$

Here a_1, a_2, b_1 and b_2 are the radii of the pump and signal infra-red beams along the z, y and x directions respectively.

Let us also suppose that there is no absorption and that the phase matching condition is fulfilled with great accuracy.

Solving these simplified equations, one obtained this expression for the radiation power in the visible:

$$P_3 = \frac{256\,\pi^5\,d_{\text{eff}}^2}{cn_1\,n_2\,n_3\,\lambda_3^2\cos^2\gamma_3}\,\frac{1}{(a_1^2 + a_2^2)^{\frac{1}{2}}}\,\frac{b_2}{(g_1\zeta + g_2)^{\frac{1}{2}}}\,P_1\,P_2\;. \tag{1}$$

Here

$$g_1 = \sin^2(\psi + \gamma_3)\;,$$
$$g_2 = [\cos(\psi + \gamma_3) - \sin(\psi + \gamma_3)\tan\gamma_2]^2\;,$$
$$\zeta = (b_2/b_1)^2\;,$$

where γ_2, γ_3 are the double refraction angles, and ψ is the angle between $\mathbf{K}_2$ and $\mathbf{K}_3$.

Let us rewrite Equation 1 in this form:

$$P_3 \simeq \frac{1}{(a_1^2 + a_2^2)^{\frac{1}{2}}}\,\frac{b_1/\sin(\psi + \gamma_3)}{\lambda_3\cos\gamma_3}\,\frac{1}{(1 + (S_1/S_0)^2)^{\frac{1}{2}}}\,P_1\,P_2\;. \tag{2}$$

Here

$$S_0 = b_1\,b_2\;,$$
$$S_1 = b_1^2\,(\cot(\psi + \gamma_3) - \tan\gamma_2)\;.$$

Now we can assign physical meanings to the coefficients in Equation 2. The term $(1 + (S_1/S_0)^2)^{-\frac{1}{2}}$ describes the 'overlap' effect, that is the decrease of the radiation power in the visible because of the non-collinearity of the $\mathbf{S}_1$ and $\mathbf{S}_3$ Poynting vectors. The factor $(b_1/\sin(\psi + \gamma_3))/\cos\gamma_3$ is the effective length of the interaction when the interacting waves are propagating in mutually perpendicular directions and the factor $(a_1^2 + a_2^2)^{-\frac{1}{2}}$ describes the focusing effect. It should be noted that $P_3 \to \infty$ when $(a_1^2 + a_2^2) \to 0$ because diffraction effects have been neglected.

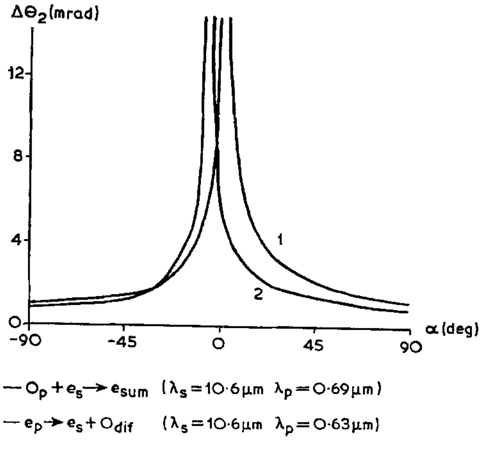

Figure 1 The dependence of the phase-matching angular width on the angle α between the pump and signal wave directions.

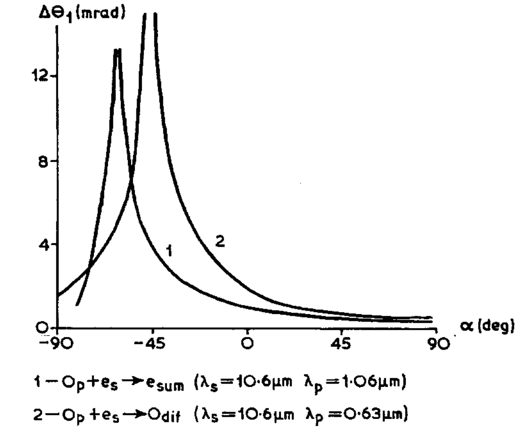

Figure 2 The dependence of the phase-matching angular width for the pump on the angle α between the pump and signal wave directions.

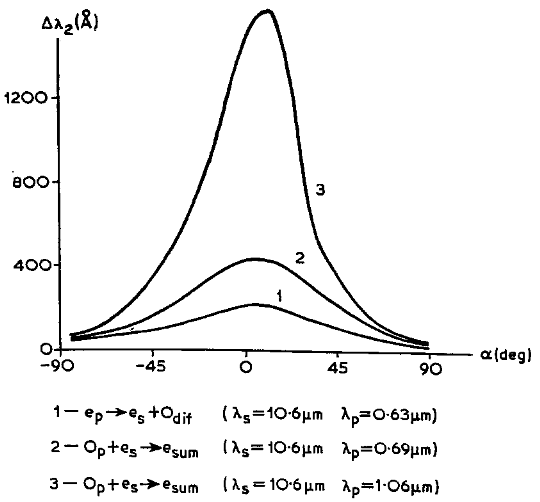

Figure 3 The dependence of the conversion spectral bandwidth on the angle α between the pump and signal wave directions.

In order to estimate the conversion efficiency one must find the value of the effective non-linearity d_{eff}. Calculations for proustite give this result:

$$d_{\mathrm{eff}}^{\mathrm{oee}} = \frac{\sin\theta\cos\epsilon}{(1+(\tan\theta\cos\epsilon)^2)^{\frac{1}{2}}}\,[d_{22}\sin(3\phi-\epsilon)+d_{31}\tan\theta\sin\epsilon]\ .$$

Here, θ is the phase-matching angle for the pump wave; ϕ is the angle subtended in the x_1x_2-plane by the pump wave polarization vector with the x_1 crystallographic axis, and ϵ is the angle between the projection of $\mathbf{K}_1$ and $\mathbf{K}_3$ on the x_1x_2 plane.

Let us now consider the angular and spectral parameters for conversion in proustite from 10.6 μm to the visible. Fig. 1 shows the dependence of the phase-matching angular width $\Delta\theta_s$ on α the angle between pump and signal wave directions. One can see that the value of $\Delta\theta_S$ decreases monotonically from a maximum value corresponding to non-critical, non-collinear phase-matching [6] down to a value ~ 1 mrad at $\alpha = 90°$.

The phase-matching angular width $\Delta\theta$ for the pump has a maximum value at $\alpha \sim 63°$ (for $\lambda = 1.06$ μm) and decreases (when α grows) to ~ 0.5 to 1 mrad (see Fig. 2).

Fig. 3 shows the dependence of the conversion spectral bandwidth on α. As can be seen, the conversion bandwidth for the geometry considered is rather narrow, less than about 10 nm.

3. Experimental

Fig. 4 shows a diagram of the experimental set-up used to investigate the angular parameters of an infra-red up-converter with perpendicular signal and pump beams.

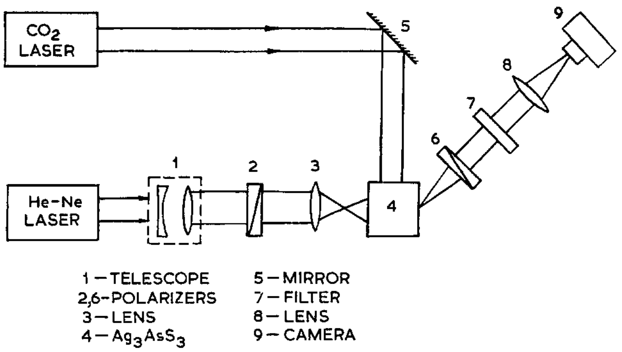

Figure 4 The experimental set up.

A He–Ne laser ($\lambda = 0.63$ μm) was used as the pump source, and a CO_2 laser as the infra-red signal source. The following interaction in the proustite was used: $0.63 - 10.6 \rightarrow 0.67$ μm. The pump wave propagated at $\theta = 64°$ to the crystal optic axis. The phase-matching scheme was: pump, O-wave; signal and difference frequency, E-wave.

The method of determining the phase-matching angular width is well known: namely, one can obtain (with the help of lens 3) a diverging pump (or signal infra-red beam) falling on the crystal. The distribution of difference frequency intensity at the focal plane of the lens 8 enables one to calculate the phase-matching angular width.

Results obtained experimentally were as follows: $\Delta\theta \simeq 0.6$ mrad for $\alpha = +90°$ and $\Delta\theta \simeq 2.7$ mrad for $\alpha = -90°$. These experimental results are twice as large as predicted theoretically. This can be explained as the effect of inhomogeneities in the crystal used.

4. Conclusions

This method, presented possibly for the first time, in which the pump and signal waves propagate in mutually perpendicular directions, provides a way of obtaining many interesting applications for research work in the infra-red, as well as in the field of highspeed, high sensitivity infra-red image convertors. Let us list the advantages of the method.

1. There is the possibility of placing the non-linear crystal inside a resonator which will give an increased pump-power density and consequently an increased image conversion efficiency.

2. For parametric oscillators, the matching problem for the resonator is simplified because all three wavelengths are separated from each other. Besides this, it is possible to significantly decrease the losses due to the possibility of providing different anti-reflection coatings on the different surfaces of the crystal for the different wavelengths. When proustite is used, anti-reflection coatings are very necessary because of the large refractive indices (~ 3).

3. The pump and the sum (or difference) frequency radiation are separated in space, so the parasitic pump background is essentially excluded. This is very important in order to reach the threshold sensitivity of an image-converter receiver.

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