

levels between lasing and nonlasing regions. Such a mechanism would enable the lasing wavelength to remain unchanged as observed both for homojunction devices [2] and in our own measurements on double-heterostructure devices.

Experimental results to date then are not definitive in assessing the validity of either the Gold-Weisberg or extended Longini mechanisms. Future discussions about these degradation mechanisms must however take into account the comments on the saturation of gain above threshold, discussed here.

Superficially, it would seem that stripe geometry devices would enable definitive experiments to be carried out. However, the same reservations apply as they do to multifilament lasers. That is, due to the very nature of the stripe, gradients in carrier concentrations are set up laterally, themselves necessary to produce the confinement of the optical energy. Hence the production of nonradiative defects in regions adjacent to the stripe have a direct effect on the magnitude of the lateral carrier feeding to the lasing filament and to the optical guiding induced.

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## Second-Harmonic Generation in Proustite With a CW CO<sub>2</sub> Laser

G. J. ERNST AND W. J. WITTEMAN

**Abstract**—The possibilities for nonlinear optics in proustite have been explored in a wavelength region previously indicated as having low absorption. We used a 10-W CW CO<sub>2</sub> laser oscillating on a single transition at 9.2- $\mu$  wavelength. The observed values for nonlinearity and absorption are, respectively,  $(7.9 \pm 2.0) \times 10^{-23}$  in MKS units and 0.29 cm<sup>-1</sup>.

In spite of the easy availability of high power from CW CO<sub>2</sub> lasers, one has not been very successful in carrying out nonlinear optical experiments with these laser beams. The major problem is the lack of good nonlinear materials with little absorption. Tellurium also has high absorption, and it is the only material for which phase-matched CW second-harmonic generation (SHG) has been reported [1], [2] using a low-power CO<sub>2</sub> laser beam. It is a practically useful material because of its relatively large nonlinear coefficient and its good power-handling capabilities. For other materials such as HgS, selenium, and proustite, SHG was only possible with

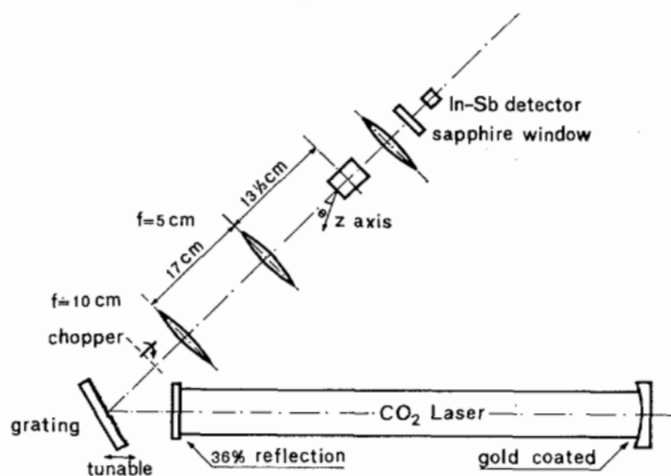


Fig. 1. Experimental setup for SHG in proustite with a CW fundamental beam of 9.2- $\mu$  wavelength.

pulsed fundamental beams in view of their high absorption [3]-[5].

This work is an experimental study of frequency doubling with a CW CO<sub>2</sub> laser using proustite as the nonlinear material in a wavelength region where its absorption should be low. According to a graph given by Hulme and coworkers [6] the absorption coefficient of proustite is about 0.5 cm<sup>-1</sup> at 10.6- $\mu$  wavelength and below 10  $\mu$  it drops fast towards smaller wavelengths. Hence it appears interesting to explore the possibilities of CW SHG in the low-absorption region.

Previously [7] we described an experimental technique for obtaining CW high-power single-oscillating transitions of the vibrational bands of CO<sub>2</sub>. Using this technique we built a single-mode 15-W CW CO<sub>2</sub> laser oscillating on the R (34) rotational transition of the 00<sup>1</sup>-02<sup>0</sup> vibrational band having a wavelength of 9.2  $\mu$ . The experimental setup is shown in Fig. 1. The wavelength and mode pattern are determined by the rotational position and tuning distance of the grating with respect to the laser cavity. The laser beam is a pure TEM<sub>00</sub> mode. By means of two lenses of, respectively, 10- and 5-cm focal distance the beam is focused on the crystal with the beam waist at its center.

The confocal parameter (in air) of our setup was 44 mm giving a beam waist diameter of about 0.54 mm inside the crystal. The power leaving the laser was set to 10 W CW, which after passing the chopper for lock-in amplification resulted within the waist to an average power density of about  $2 \cdot 10^2$  W/m<sup>2</sup>. The beam leaving the crystal is filtered by a plane parallel plate of sapphire transmitting only the second harmonic. The 4.6- $\mu$  radiation is detected by an ORP indium antimonide photoconductive infrared detector from Mullard. From a proustite crystal of 1 cm length we observed maximum SH power of about  $4 \cdot 10^{-5}$  W. Although it was reported that the absorption of proustite at 9.2  $\mu$  is very low, we were disappointed to find for our crystal about 25 percent absorption (i.e.,  $\alpha = 0.29$ ).

From the known dispersion relations [8] the phase matching conditions are easily calculated. Choosing the fundamental as ordinary and the second harmonic as the extraordinary ray, the direction of propagation was calculated to make an angle  $\Theta_m$  of 19.1° with the z axis, which is in good agreement with the experimental observed value of  $19.9^\circ \pm 1.0^\circ$ .

Because our confocal parameter is much larger than the crystal length, the beam inside the crystal is essentially parallel and we can use the plane-wave approximation. For phase matching and the condition that the fundamental beam has a Gaussian distribution (TEM<sub>00</sub>) with polarization along

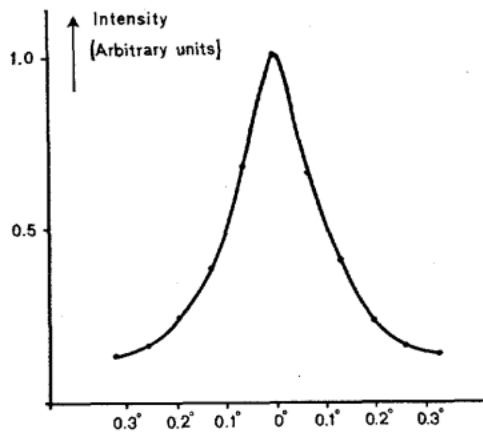


Fig. 2. Second-harmonic power as a function of the external angle of deviation from the phase-matching conditions.

the  $x$  axis, we find for the second harmonic power, using MKS units,

$$P(2\omega) = 2\left(\frac{\mu}{\epsilon}\right)^{3/2} \omega^2 L^2 d_{\text{eff}}^2 \frac{P^2(\omega)}{\pi\omega_0^2} G(t, q) \quad (1)$$

where

- $P(\omega)$  fundamental power,  
 $\omega$  fundamental frequency,  
 $d_{\text{eff}}$   $|d_{31}| \sin \Theta_m + |d_{32}| \cos \Theta_m$ ,  
 $\omega_0$  beam waist radius,  
 $L$  length of the crystal,  
 $G(t, q)$  correction due to birefringence and absorption as defined by Boyd *et al.* [9].

Substituting values for our experimental conditions gives

$$G(t, q) = G(2.84, 0.05) = 0.65. \quad (2)$$

Substituting the numerical values we find

$$P(2\omega) = 6.4 \times 10^{37} d_{\text{eff}}^2 P^2(\omega). \quad (3)$$

From the observed second-harmonic power we then deduce

$$d_{\text{eff}} = (7.9 \pm 2.0) \times 10^{-23} \quad (\text{MKS}), \quad (4)$$

which is a smaller value than that obtained from a mixing experiment in the  $1\text{-}\mu$  wavelength region [6].

In Fig. 2 we have plotted the second-harmonic power as a function of the external angle of deviation from the phase-matching condition. From this we deduced the half-width to be  $0.22^\circ$ . According to calculations using the dispersion of the refractive indices [8] it should be a factor of 2 larger.

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## Parametric Oscillator Tuning Curve from Observations of Total Parametric Fluorescence

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**Abstract**—Measurements of total emitted parametric fluorescence power are presented and used to fix one point on the predicted tuning curve of a parametric oscillator. The method is particularly useful for predicting the tuning curve of infrared pumped parametric oscillators. Experimental results, which verify the usefulness of the technique in a  $1.06\text{-}\mu$ -pumped oscillator, are presented.

#### INTRODUCTION

Optical parametric fluorescence has been studied extensively both theoretically [1]–[4] and experimentally [3], [5]–[8]. One application of parametric fluorescence observations is in obtaining the tuning curve for an optical parametric oscillator, but because of low fluorescence power and small monochromator bandwidth, measurements to date have been made only in the UV to near IR regions where at least one of the generated wavelengths falls in a range where photomultipliers can be used. We present here a technique for predicting the tuning curve of a parametric oscillator using known index of refraction data and a measurement of total emitted fluorescence power. This method is especially useful for infrared-pumped oscillators where high sensitivity detectors are not available and the fluorescence power is greatly diminished. The results reported here were obtained using a  $Q$ -switched laser, but the method is equally applicable to CW pump sources.

#### THEORY

From the plane-wave theory of Byer and Harris [3], the total signal-plus-idler parametric fluorescence power incident on a detector with acceptance angle  $\theta$  is

$$P_T = L^2 K P_3 \int_{-\infty}^{\infty} \int_0^{\theta} \frac{\sin^2(\Delta k L/2)}{(\Delta k L/2)^2} \phi \, d\phi \, d\omega \quad (1)$$

where  $L$  is the nonlinear crystal length,  $P_3$  is the pump power in watts, and  $\Delta k = |\mathbf{k}_3 - \mathbf{k}_1 - \mathbf{k}_2|$  is the wavevector mismatch. The constant  $K$  is given in [3]. For small angles  $\Delta k$  can be expanded in a Taylor series about the collinear phase-matched frequencies. The result to second order is

$$\Delta k = -b_0 \omega - b_1 \omega^2 + g \phi^2 \quad (2)$$

$$g = \frac{k_{10} k_3}{2k_2}, \quad \omega \equiv \omega_1 - \omega_{10} = \omega_2 - \omega_{20} \quad (3)$$

$$b_0 = \frac{\partial k_1}{\partial \omega_1} \Big|_{\omega_{10}} - \frac{\partial k_2}{\partial \omega_2} \Big|_{\omega_{20}} \quad (4)$$

$$b_1 = \frac{1}{2} \left[ \frac{\partial^2 k_1}{\partial \omega_1^2} \Big|_{\omega_{10}} + \frac{\partial^2 k_2}{\partial \omega_2^2} \Big|_{\omega_{20}} \right] \quad (5)$$

where  $\omega_{10}$  and  $\omega_{20}$  are the collinear signal and idler frequencies such that  $\omega_3 = \omega_{10} + \omega_{20}$ ,  $\omega$  is the deviation from the collinear frequencies, and  $\phi$  is the angle between  $\mathbf{k}_1$  and  $\mathbf{k}_3$ .

A careful examination of (1) and (2) shows that the total power  $P_T$  peaks as the fluorescence is tuned toward collinear degeneracy. The location of the peak fluorescence power when  $P_T$  is plotted as a function of the tuning parameter (the crystal temperature, for example) will vary depending on the

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