strain induced by the poling process, and the impurity diffused during the field annealing. In a certain optimum condition an extinction as high as 25 dB was obtained throughout crystal of typically $5 \times 5 \times 10$ (mm)^3 with $r_0 = 140\ \mu$. The details of these results will be dealt with in separate communications.

The authors thank Drs. Y. Sasaki and S. Asanabe for their helpful suggestions and encouragement and also Dr. T. Uchida for several interesting conversations concerning this problem.

[1] G. E. Peterson, A. A. Ballman, P. V. Lenzo, and P. M. Bridenbaugh, *Appl. Phys. Letters* **5,** 62 (1964).
[2] P. V. Lenzo, E. H. Turner, E. G. Spencer, and A. A. Ballman, *Appl. Phys. Letters* **8,** 81 (1966).
[3] R. T. Denton, F. S. Chen, and A. A. Ballman, *J. Appl. Phys.* **38,** 1611 (1967).
[4] P. V. Lenzo, E. G. Spencer, and K. Nassau, *J. Opt. Soc. Am.* **56,** 633 (1966).
[5] J. E. Midwinter [*Appl. Phys. Letters* **11,** 128 (1967)] recently adopted the same method in the assessment of crystal quality for SHG, neglecting changes in dispersion.
[6] A. A. Ballman, *J. Am. Ceram. Soc.* **48,** 112 (1965).
[7] W. L. Bond, *J. Appl. Phys.* **36,** 1674 (1965).

VISIBLE CW PARAMETRIC OSCILLATOR*

R. L. Byer, M. K. Oshman,† J. F. Young, and S. E. Harris
Department of Electrical Engineering, Stanford University
Stanford, California 94305
(Received 17 June 1968)

A tunable optical parametric oscillator using a 5145-Å argon laser as a pump and lithium niobate as the nonlinear material is reported. The oscillator is constructed in a manner such that the total multimode power of the pumping laser is useful for pumping the oscillator. Operation far from degenerate, combined with a relatively long crystal, leads to measured bandwidths of oscillation about ten times less than those previously reported.

We report the operation of a parametric oscillator using lithium niobate as the nonlinear crystal and the CW output of an argon laser (5145 Å) as the pump. The signal wavelength is tunable from 6800 Å to 7050 Å with the idler in the corresponding range 2.11 μ to 1.90 μ. Central to the operation of the oscillator is the fact that the full multimode power of the laser is useful in pumping the oscillator. In addition, being far from degenerate, combined with a relatively long crystal, leads to measured bandwidths of oscillation about ten times less than those previously reported.

Pulsed parametric oscillators have been reported by a number of workers,[1-4] and a CW-pumped parametric oscillator has recently been reported by Smith, et al.[5] In contrast to all previous oscillators which used short optical cavities, this oscillator is constructed with a long cavity to allow for the full use of the multifrequency pump. The separation of the oscillator mirrors is arranged so that the $c/2L$ frequency spacing of the idler modes is equal to the $c/2L$ frequency spacing of the pumping laser. As shown by Harris, [6] this condition allows the comb of pump modes to cumulatively drive a *single* signal mode by interacting with the comb of equally spaced idler modes. Although the pump modes may be randomly phased and erratic in amplitude due to competition effects in the laser, corresponding behavior of the idler modes compensates to allow continuous pumping of a single signal mode.

The $LiNbO_3$ crystal is 1.65 cm long. Second harmonic generation experiments established that the crystal did not exhibit significant refractive index inhomogeneities. The particular wavelengths of the signal and idler allow phase-matching at elevated temperatures (nominally 240°C for our particular crystal) and thus avoid optically induced refractive index inhomogeneities.[7] These wavelengths also simplify the fabrication of dual-wavelength mirrors and antireflection coatings in that a quarter-wave coating at the idler wavelength is a three-quarter wave coating at the signal wavelength.

The measured single-pass power losses of 5.4% and 2.0% at the signal and idler wavelengths, re-

*The work reported in this Letter was sponsored jointly by the National Aeronautics and Space Administration under NASA Grant NGR-05-020-103; and by the Air Force Cambridge Research Laboratories, Office of Aerospace Research, under Contract No. F19628-67-C-0038.

†Present address: Sylvania Electronic Systems, Mountain View, California 94040.

spectively, are due primarily to scatter and reflection losses at the surfaces of the lens, mirrors, and crystal. The narrow-band nature of the antireflection coatings limits the tuning range of the signal to approximately 300 Å.

For the spacings shown in Fig. 1, the signal and idler beam waists are located at the center of the crystal with calculated radii of 34 μ and 67 μ, respectively. The internal collimating lens is necessary to allow a long optical cavity while maintaining small signal and idler spot sizes at the output mirror. The pump was focused to a beam waist of 29 μ. For these beam sizes and losses, the results of Boyd and Ashkin[8] predict a single-mode threshold power of approximately 530 mW.

Realization of theoretical threshold depends critically on cavity alignment. Initial alignment was aided greatly by placing a He-Xe plasma tube into the parametric oscillator cavity. The difference frequency (6896 Å) signal generated between the 2.02-μ He-Xe oscillation and the 5145-Å pump was then maximized by adjusting the oscillator components. Removing the plasma tube and performing a final adjustment yielded a threshold power of 410 mW. Observation of the beat spectrum of the laser output verified the erratic, multimode nature of the pump which, together with the threshold results, confirms the fact that the full multimode power of the laser was useful in pumping the oscillator.

The results of measurements of the output power of the oscillator are shown in Fig. 2. A maximum output power of 1.5 mW as measured with a thermopile was observed when the pumping power was 2.8 times the threshold value. The output mirror of the oscillator has a transmission of only 0.04% and it is expected that larger powers will be obtained with optimum output coupling. The parametric output consists of pulses with lengths typically 0.1 msec long but occasionally lasting 1 msec. The oscillator wavelength can be continuously tuned by changing the temperature of the crystal, and the oscillator maintains nearly constant output power during the tuning process.

Measurements of the spectrum of the oscillator were made with a scanning Fabry-Perot etalon. With an etalon spacing of 1.0 mm corresponding to a free spectral range of 5.0 cm^{-1}, it was found that the total oscillation width (i.e., the bandwidth over which individual cavity modes can oscillate) approaches 3 cm^{-1} if the oscillator is driven reasonably far above threshold. For weaker pump drives this bandwidth is reduced, as shown in Fig. 2. The maximum oscillation width of 3 cm^{-1} is in good agreement with the minimum spontaneous emission bandwidth of $0.886/bL = 4.0$ cm^{-1} where

$$b = \frac{\partial k_s}{\partial \nu_s} - \frac{\partial k_i}{\partial \nu_i}$$

and L is the length of the nonlinear crystal.[9]

A Spectra-Physics confocal etalon with a free spectral range of about 3 GHz was used to examine the output spectrum in finer detail. The signal tended to oscillate in a single axial mode at a time, although occasionally two or more modes were observed simultaneously. Erratic signal beat notes at $c/2L$, $2c/2L$, and $3c/2L$ were observed on a rf spectrum analyzer.

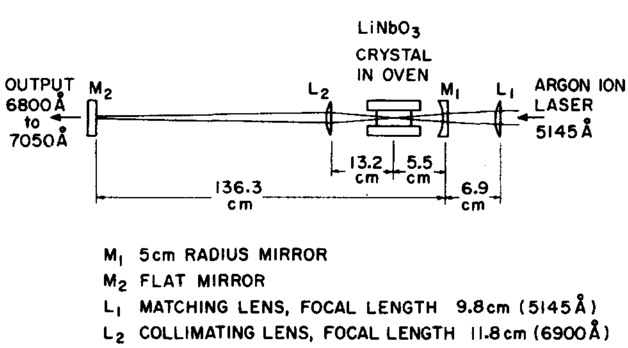

Fig. 1. Schematic of parametric oscillator.

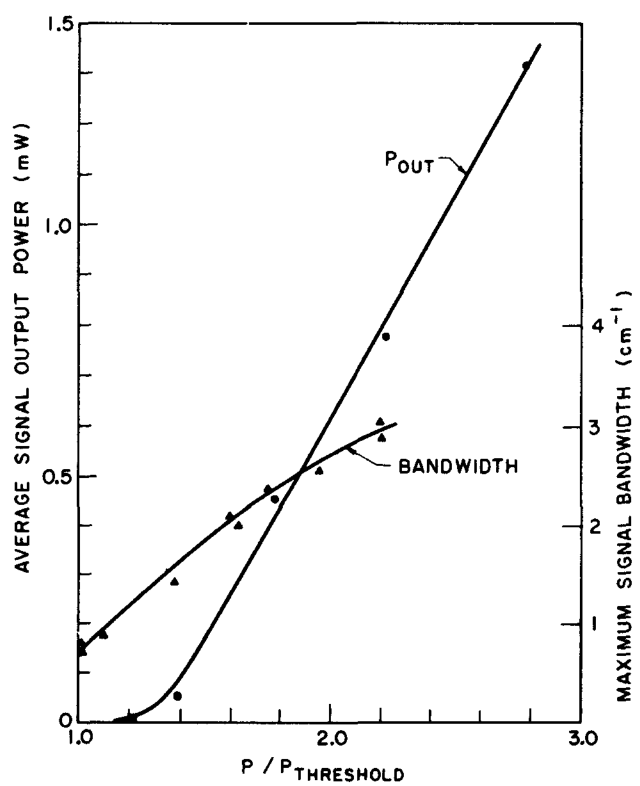

Fig. 2. Power output and bandwidth vs $P_{pump}/P_{pump\,(threshold)}$.

The authors gratefully acknowledge the efforts of R. Feigelson of the Stanford Center for Materials Research who grew the crystal used in the experiment, and of Spectra-Physics Corporation who supplied the pumping laser and fabricated the optical coatings. In particular the efforts of Tom Cottral, J. Ecstrand, D. Sinclair, and R. Stark of Spectra-Physics are very much appreciated. We also appreciate the skilled technical assistance of Ben Yoshizumi and R. Griffin during the course of this work. M. K. Oshman acknowledges the Sylvania Independent Research Program for partial support.

[1]J. A. Giordmaine and Robert C. Miller, *Phys. Rev. Letters* **14,** 973 (1965); *Appl. Phys. Letters* **9,** 298 (1966).
[2]S. A. Akhmanov, A. I. Kovrygin, A. S. Piskarskas, V. V. Fadeev, and R. V. Khoklov, *Zh. Eksp. Teor. Fiz (Sov. Phys.—JETP)* **3,** 372 (1966).
[3]Robert C. Miller and W. A. Nordland, *Appl. Phys. Letters* **10,** 53 (1967).
[4]L. B. Kreuzer, *Appl. Phys. Letters* **10,** 336 (1967).
[5]R. G. Smith, J. E. Geusic, H. J. Levinstein, J. J. Rubin, S. Singh, and L. G. Van Uitert, *Appl. Phys. Letters* **12,** 308 (1968).
[6]S. E. Harris, *IEEE J. Quantum Elect.* **QE-2,** 701 (1966).
[7]A. Ashkin, G. D. Boyd, J. M. Dziedzic, R. G. Smith, A. A. Ballman, H. J. Levinstein, and K. Nassau, *Appl. Phys. Letters* **9,** 72 (1966).
[8]G. D. Boyd and A. Ashkin, *Phys. Rev.* **146,** 187 (1966).
[9]R. L. Byer and S. E. Harris, *Phys. Rev.* **168,** 1064 (1968).

ERRATA

In "A Simple Analysis of the Propagating Acoustoelectric High Field Domain," [*Appl. Phys. Letters* **12,** 273 (1968)], E. Mosekilde, Physics Laboratory III, Technical University of Denmark, Lyngby, Denmark, the acoustic dispersion was neglected. This approximation, in general, is not valid for an acoustic domain traveling with a velocity close to the velocity of sound. Taking dispersion into account, Eqs. (1), (2), and (5) should be amended to read

$$\frac{\partial w}{\partial x} + v_{s3}^{-1}\frac{\partial w}{\partial t} = \beta w - 2\alpha_L w \tag{1}$$

$$\beta = B[(v/v_{s1}) - 1] \tag{2}$$

$$\frac{dF}{ds} = \frac{e}{\epsilon}(n - n_0)(v_D - v_{s0})/(v_D - v_{s2}) \tag{5}$$

Here v_{s0} and v_{s2} are the unstiffened and the piezoelectrically stiffened velocity of sound. v_{s1} and v_{s3} are the phase and the group velocity of the acoustic modes being amplified. Thanks are due to Dr. B. K. Ridley for pointing out these corrections to me.

In "Multijoule Pulses from CO_2 Lasers," [*Appl. Phys. Letters* **12,** 324 (1968)]. Alan E. Hill, Lear Siegler, Inc., Ann Arbor, Michigan, the captions beneath Figs. 2 and 3 should be interchanged.