flecting at 1.06 μm and a 2.8-mm-thick antireflection-coated $Ba_2NaNb_5O_{15}$ crystal inside of the laser cavity, 350 mW of 0.53 μm radiation was generated by second harmonic conversion. The $Ba_2NaNb_5O_{15}$ crystal was maintained at a temperature of 83°C so that phase-matched second harmonic generation was achieved without double refraction. The generated green power is in good agreement with what was theoretically expected for the experimental conditions employed. The present results indicate that, with a crystal of $Ba_2NaNb_5O_{15}$ 6 mm long used in the laser employed, ~1 watt of green can be generated. Such experiments with longer $Ba_2NaNb_5O_{15}$ crystals and with higher power YAlG:Nd lasers will be reported. It is expected that with this new source, power levels at 0.53 μm can be generated, which approach the power levels that can be obtained from the basic YAlG:Nd laser.

Second harmonic conversion when the laser is operated in either the repetitively *Q*-switched or mode-locked pulse modes will also be discussed.

11K-4 Theory of Parametric Gain Near a Lattice Resonance, C. H. Henry and C. G. B. Garrett, *Bell Telephone Laboratories, Inc., Murray Hill, N. J. 07974*

Parametric oscillation has been used to generate visible and near infrared light. In principle, parametric oscillation could also be used to generate far-infrared radiation. In this case, one of the generated signals, which we will call the idler, will be close in energy to the infrared lattice absorption resonance of the crystal. As the idler approaches the lattice resonance, the absorption coefficient at the idler frequency becomes resonantly large, but so does the nonlinear susceptibility describing the parametric amplification process. It is not clear what happens to the parametric gain in this situation. The parametric gain as the idler frequency is swept through the lattice resonance is computed.

This problem has been previously treated by Loudon,[1] Shen,[2] and Butcher, Loudon, and McLean.[3] Each of these papers reports a *different* expression for the parametric gain, the expressions of Shen and Butcher, Loudon, and McLean being quite complicated. The discrepancies between these previous treatments have been resolved and a *simple* analytical expression for the parametric gain derived, both by Shen's method of solving the coupled wave equations and by Loudon's method of calculating the transition rate for the creation of idler and signal quanta.

The analysis is restricted to the simplest case, a cubic crystal with a single lattice resonance such as gallium phosphide. The expression for the parametric gain has a number of simple features.

1) The maximum gain occurs for the case of wave vector matching, if the wave vector of the linear idler wave is calculated in the absence of damping. (This was previously pointed out by Shen.)
2) The *peak gain is slowly varying* with idler frequency and is essentially unchanged as the idler frequency is swept from several line widths below resonance onto the lattice resonance.
3) The variation of parametric gain with the idler frequency results mainly from the interference of the two terms contributing to the nonlinear susceptibility. For gallium phosphide, this interference causes the parametric gain to go to almost zero at an idler energy of 250 cm^{-1}.
4) The ratio of the idler intensity to the signal intensity is inversely proportional to the infrared absorption coefficient at the idler frequency. Because of this, the amount of infrared light that can be generated becomes negligible as the idler frequency approaches the lattice resonance and absorption becomes large.

The results for gallium phosphide are evaluated numerically.

[1] R. Loudon, *Proc. Roy. Soc.* (London), vol. 82, p. 393, 1963.
[2] Y. R. Shen, *Phys. Rev.*, vol. 138, p. A1741, 1965.
[3] P. N. Butcher, R. Loudon, and T. P. McLean, *Proc. Roy. Soc.* (London), vol. 85, p. 565, 1965.

11K-5 Parametric Interactions in Optics and Tunable Light Oscillators (*Invited*), R. V. Khokhlov, *Moscow State University, Moscow, U.S.S.R.*

11K-6 Power and Bandwidth of Spontaneous Parametric Emission (*Invited*), R. L. Byer and S. E. Harris, *Stanford University, Stanford, Calif.*

Theoretical and experimental results concerned with the spectral and angular distribution of spontaneous parametric emission are reported. Application to the measurement of nonlinear coefficients in $LiNbO_3$ and perhaps in $Ba_2NaNb_5O_{15}$ are presented.

11K-7 Parametric Interaction of Focused Gaussian Light Beams, G. D. Boyd and D. A. Kleinman, *Bell Telephone Laboratories, Inc., Holmdel and Murray Hill, N. J.*

A theoretical study is presented on second harmonic generation (SHG) and parametric generation (PG) by a laser beam in a uniaxial nonlinear crystal. Pump depletion is neglected. Numerically computed curves show the dependence of the SHG power, and the reciprocal of the PG threshold power, on the parameter l/b, where l is the optical path length in the crystal and b is the confocal parameter (determined by the focal length of the focusing lens and the minimum radius of the laser beam, assumed to be in the TEM_{00} mode of an optical resonator). The calculations take full account of diffraction and double refraction. In the absence of double refraction, the optimum focusing condition is found to be $l/b = 2.84$. For PG the optimization of the crystal length l is also discussed and curves are given showing the dependence of the threshold on l for the case in which signal and idler have the same losses. It is shown that the computed functions are also relevant to the mixing of two Gaussian beams and to low-gain parametric amplification.

By means of the functions computed, the optimum focusing conditions can be determined for SHG, PG, mixing, SHG and mixing in resonators, regenerative and nonregenerative parametric amplification.

The theory of the PG threshold is applied to telurium and $LiNbO_3$. On the basis of reasonable assumptions about the losses, a PG threshold of 1.0 watt is obtained for a pump at 10.6 μm in Te. The optimum length is found to be $l = 0.14$ cm. For $LiNbO_3$ of length $l = 1$ cm, the threshold is 22×10^{-3} watts for a pump at 0.5147 μm. This calculation assumes a near degenerate parametric oscillator, phase-matched such that there is no double refraction. As another example in $LiNbO_3$, consider the pump to be the 1.0648-μm Nd:YAG laser. Phase matching in room temperature $LiNbO_3$ for degenerate PG operation would be at an angle of 43° to the optic axis. Double refraction effects would be significant and a PG threshold of 13 watts is calculated.

From both these examples it is apparent that double refraction when present can be expected to be a large effect, which must be treated quantitatively.

11K-8 Noncollinear Interactions in Parametric Luminescence, J. P. Budin, J. Ducuing, and B. Godard, *Centre de Recherches de la Compagnie Générale d'Electricité, 91 Marcoussis, France.*

Based on the available index data on lithium metaniobate and especially the temperature-dependent Sellmeier equations given in Hobden and Warner,[1] a computer program has been devised and experiments performed to inspect the possible three-wave phase-matched interactions relevant to parametric luminescence or the so-called "coherent photon decay." The following parameters have been considered:

1) number of available continous pump sources, wavelengths (argon ion laser);
2) temperature;
3) directions of signal and idler K vectors ω_r to pump beam direction.

The results are presented as curves giving 1) signal and idler wavelengths versus temperature for three collinear waves and various pump sources and 2) signal and idler wavelength versus observation angle as measured from the pump beam direction for various temperatures and pump sources. In all cases the pump is an extraordinary wave propagating normal to the crystal optic axis. It has been pre-

[1] M. V. Hobden and J. Warner, *Phys. Letters*, vol. 22, p. 243, 1966.