the spectrum shown as a broken line. The krypton bombardment reduced the first neon peak amplitude by about a factor four; the second and third by factors two, but had no significant effect on the last two. A sputtering mechanism, such as that suggested by Corkhill and Carter[8] cannot explain these results. Using published sputtering yields for polycrystalline tungsten[9] the 100-eV krypton bombardment should have sputtered only 1×10^{13} tungsten atoms/cm^2, or less than 1% of an atomic layer. As an even more extreme example, the experiment was repeated on the (110) crystal using 150-eV argon ions followed by 60-eV xenon ions. The first argon desorption peak was reduced by more than 80% although the xenon ions were estimated to have sputtered only 3×10^{11} atoms/cm^2. These results suggest that each heavy ion impact gives to a number of lattice atoms at or near the surface a transient vibrational energy sufficient to desorb gas trapped in this affected region. If the vibrational energy required is the same as the activation energy of desorption, the region must contain about ten atoms to explain the above results. A qualitatively similar mechanism has been proposed to explain the release of trapped atoms from glass.[10]

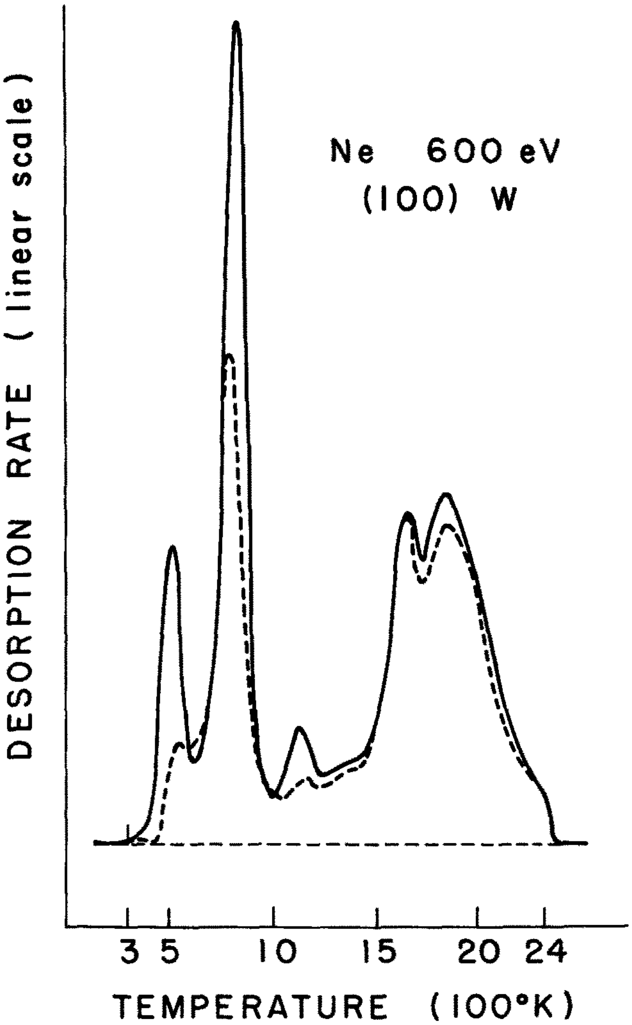

Fig. 2. The effect of subsequent bombardment with low-energy krypton ions on the 600-eV neon spectrum from a (100) crystal: ——— 600-eV neon bombardment alone, --------- 600-eV neon followed by 100-eV krypton (1.5×10^{14} ions/cm^2). The krypton bombardment alone produces no spectrum.

More detailed results will be presented in a forthcoming paper.

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PROPOSED BACKWARD WAVE OSCILLATION IN THE INFRARED*

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(parametric oscillation; birefringence; internal feedback; nonlinear optics; T)

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Recent experiments by Giordmaine and Miller[1] have demonstrated the feasibility of parametric oscillation at optical frequencies. Though in principle achievable at low pump thresholds, such ex-

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periments require the construction and critical adjustment of multiple optical cavities. In addition, the frequency of the output is in part dependent on the coincidental alignment of the signal and idler modes, thus requiring considerable stabilization of the optical cavities.[2] These difficulties may be avoided by means of backward wave oscillation, wherein the feedback is provided internally to the nonlinear crystal, and where therefore optical cavities are not required. The purpose of this Letter is to note that the birefringence of certain crystals is sufficiently large to allow the collinear backward wave interaction of three electromagnetic waves with a signal frequency which is tunable over a large portion of the infrared spectrum. The calculated threshold for this process is shown to be considerably lower than that for the backward wave interaction of two electromagnetic waves and an acoustic wave (stimulated Brillouin scattering) which has recently been studied by a number of authors.[3–5] We note that the possibility of a backward wave interaction involving three electromagnetic waves has been discussed by Kroll[6] and by Hsu and Tittle.[7] In Kroll's technique the **k** vectors are in general non-collinear and are selected by the position of optical cavities. However since a collinear interaction provides the largest interaction volume, it should naturally be selected in those cases where **k**-vector conditions are such that it may occur.

The three frequencies involved are termed as the signal, idler, and pump, and satisfy $\nu_s < \nu_i < \nu_p$ and $\nu_s + \nu_i = \nu_p$. We take the signal to be the backward wave, and utilize the crystal birefringence to attain the condition $|\mathbf{k}_i| > |\mathbf{k}_p|$ and thus to allow satisfaction of the **k**-vector requirement $\mathbf{k}_s + \mathbf{k}_i = \mathbf{k}_p$. If n_s, n_i, and n_p are the refractive indices of the signal, idler, and pump respectively, then the collinear **k**-vector requirement yields the condition

$$\frac{\nu_s}{\nu_p} = \frac{n_i - n_p}{n_i + n_s} \quad . \tag{1}$$

For a crystal such that $n_e > n_0$, we take the idler as an extraordinary wave, and the signal and pump as ordinary. Tuning could perhaps be accomplished by varying the angle of propagation with respect to the optic axis, and thus varying n_i. Since the maximum value of n_i is n_e, the maximum signal frequency which may be attained at a given pump frequency is limited by the available birefringence, and will generally be in the infrared.

The condition for threshold of a backward wave oscillation involving two optical waves and an acoustic wave has been given by Bobroff,[5] Kroll,[4] and others. A similar condition applies for the interaction of three electromagnetic waves, and is as follows:

$$\beta L - \tan^{-1}\left(\frac{\alpha_s + \alpha_i}{2\beta}\right) = \frac{\pi}{2} \tag{2}$$

where

$$\beta = -\frac{1}{2}\,[\eta_s\eta_i\nu_s\nu_i\delta^2 E_p^2 - (\alpha_s + \alpha_i)^2]^{1/2}.$$

In the above, the quantities ν_s and ν_i are in units of circular frequency; α_s and α_i are the losses of the signal and idler in units of Np/m; η_s and η_i are the wave impedances (377/refractive indices); L is the length of the nonlinear crystal; δ is the pertinent crystal nonlinearity such that the polarization created at one frequency is equal to δ multiplied by the product of the electric fields at the other two frequencies; and E_p is the minimum value of pump electric field strength for which backward wave oscillation will occur. For favorable cases of interaction between three electromagnetic waves the optical losses will be such that $(\alpha_s + \alpha_i)\,L \ll \pi$. In such cases the necessary pump field is approximately given by

$$E_p^2 > \frac{1}{\eta_i\eta_s\nu_i\nu_s\delta^2}\,\frac{\pi^2}{L^2}\,, \tag{3}$$

and is independent of optical loss. If L is sufficiently increased, losses become important and Eq. (2) should be used.

A promising candidate for this technique is trigonal (sometimes termed hexagonal) selenium. Patel[8] has recently shown this material to have a reasonably high nonlinear coefficient. In addition, its fractional birefringence is very large ($n_0 = 2.78$, $n_2 = 3.58$),[9] and if sufficiently pure it should have low loss from about 0.8 μ to at least 20 μ.[9] Techniques for growth of this material in crystals 1 cm in diam and up to 10 cm in length have recently been perfected.[10] The principal difficulty is apt to be free-carrier and impurity absorption about which little data are available.

If we assume a pump frequency of 1.06 μ (e.g., the Q-switched $CaWO_4 : Nd^{3+}$ laser), then neglecting dispersion, Eq. (1) yields a maximum signal frequency of 7 μ, with potential tunability to all longer wavelengths. To achieve operation in selenium (point group 32), the idler (extraordinary) sould lie in the x-z plane, while the signal (ordinary) and pump (ordinary) should be polarized along the

y axis. For this orientation the nonlinear coefficient δ of Eq. (3) is equal to $2d_{11}\cos\theta$, where θ is the angle between the wave normals and the optic axis.

With the pump at 1.06 μ, we take the signal frequency to be 18 μ, and the idler thus at 1.1 μ. Neglecting dispersion, Eq. (1) is satisfied at an angle $\theta \cong 45°$. Using the value of d_{11} given by Patel ($d_{11} = 1.9 \times 10^{-7}$ esu),[8] and assuming a crystal length of 1 cm, then Eq. (3) yields a required pump power density of about 12.5 MW/cm^2. Alternately, with the same pump, a signal at 9 μ, and idler at 1.2 μ, we find $\theta \cong 77°$ and a required pump power density of about 80 MW/cm^2. Due to the large walk-off angle between the Poynting vector and wave normal (about 11° in the worst case), tight focusing of the pump beam will in general not be possible. If we choose the area of the spot size A such that the length of the nonlinear crystal L is just equal to the aperture length,[11,12] then for the case considered $A \cong 0.04\, L^2 \sin^2 2\theta$. In the first of the above cases this yields a required power of about 0.50 MW, while in the second it yields 0.62 MW. For comparison with the above numbers we note that the calculated threshold power density for stimulated Brillouin scattering in quartz is about 10^4 MW/cm^2 (ref. 3).

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EFFICIENT ULTRAVIOLET LASER EMISSION IN ELECTRON-BEAM-EXCITED ZnS*

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(3425 to 3291 Å; 4.2 and 77°K; 6.5% efficiency; undoped single crystals; E)

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Using pulsed electron beam excitation on crystals of ZnS, we have obtained at both liquid helium and nitrogen temperatures efficient semiconductor lasers in the ultraviolet portion of the spectrum. Peak output power of up to 1.7 W with a power efficiency of 6.5% has been measured in the spectral range from 3245 to 3300 Å. Similarly efficient electron-beam-pumped laser emission[1,2] in the visible region from crystals of CdS, CdSe, and CdS_xSe_{1-x} and ultraviolet laser emission[3] with substantially lower efficiency from ZnO have recently been reported.

Laser samples were made from undoped, single-crystal, vapor-grown platelets of hexagonal ZnS. The sample preparation and experimental technique have been described previously.[1] Sample dimensions were approximately 150 $\mu \times$ 2–3 $\mu \times$ 1 mm, the first dimension being that of the optical cavity. In addition to the strong ultraviolet fluorescence, the samples exhibited some very faint yellow emission. However, none of the well-known red, green, or blue fluorescence found in ZnS phosphors was detected, indicating that these crystals were essentially free of the deep impurities responsible for this visible emission. The electron beam of approximately 0.5-mm diam was pulsed with 200-nsec pulses at a repetition rate of 60/sec.

Typical spectra at liquid helium temperature slightly below and above the laser threshold are shown in Fig. 1. The abrupt appearance of the strong laser line at 3291 Å is clearly evident. Actu-

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