for $1s_4$ it is $2p^5(^2P_{1/2}°)3s\,(J=1)$. For notation, see C. E. Moore, Atomic Energy Levels, National Bureau of Standards Circular No. 467 (U.S. Government Printing Office, Washington, D. C., 1949), Vol. 1.

[4]See Eq. (19) in A. Szöke and A. Javan, Phys. Rev. 145, 1137 (1966).

[5]The line shape resulting from the change in population due to the laser field is a linear superposition of two Lorentzians both centered at $\omega_0'$, the center frequency of the 0.6-$\mu$ transition. Their corresponding half-widths at half maximum intensity (in angular-frequency units) are given by $\gamma_\pm = \gamma' \pm \alpha\gamma$, where $\alpha = \omega_0'/\omega_0$ and $\gamma'$ is similar to $\gamma$, except referred to the two levels of the 0.6-$\mu$ transition. The intensities of the two Lorentzians are proportional to their respective half-widths at half maximum intensity. This result applies only when the usual Doppler width is considerably larger than $\gamma_\pm$.

[6]A. Szöke and A. Javan, Phys. Rev. Letters 10, 521 (1963).

# OBSERVATION OF TUNABLE OPTICAL PARAMETRIC FLUORESCENCE*

S. E. Harris, M. K. Oshman, and R. L. Byer
Department of Electrical Engineering, Stanford University, Stanford, California
(Received 24 March 1967)

We report the observation of an optical fluorescence which is thermally tunable over a significant portion of the visible and near-infrared spectrum. Using a crystal of $LiNbO_3$ and a 4880-Å argon laser as a pump, we have observed tuning from 5400 to 6600 Å. Fluorescent powers were estimated to be about $10^{-12}$ W and to have linewidths which were measured to be less than 75 Å, and are probably less than 1 Å.

We believe that the observed effect is that of spontaneous emission or fluorescence from a phase-matched parametric system. This effect has been predicted by a number of authors[1-3] and is a result of the quantum-mechanical possibility that a driving pump photon may spontaneously split into a signal and an idler photon such that $\nu_s + \nu_i = \nu_p$. Alternatively the effect can be considered to arise from zero-point fluctuations of the signal and idler modes. From another point of view the observed fluorescence can be considered as a direct observation of the quantum noise that is associated with any linear amplifier.[4]

A schematic of the experimental arrangement is shown in Fig. 1. A cw argon laser with an output power of about 300 mW at 4880 Å was used as the pumping source. The $LiNbO_3$ crystal was 1 cm long and was oriented with its optic axis in its face and parallel to the polarization of the incoming laser beam. The crystal was mounted in an oven capable of varying its temperature from room temperature to about 375°C. By changing the crystal temperature and thereby varying the refractive indices, the momentum-matching condition $\vec{k}_s + \vec{k}_i = \vec{k}_p$ for an extraordinary pump wave and ordinary signal and idler waves could be satisfied and tuned over a wide range of wavelengths.[5,6] The output analyzer was oriented at 90° to the input polarizer and together with two blue stop filters provided about 120 dB of discrimination against the laser pumping light. A Leiss prism monochromator with a resolution which we estimated at about 75 Å followed the filter.

With the crystal temperature at about 125°C, a dull fluorescent emission in the red was observed visually. As the crystal temperature was increased, this emission moved progressively toward the green. Results obtained using the Leiss monochromator are shown in Fig. 2. For temperatures below 100°C the emission moved continuously into the far red, and at about 75°C it was no longer detectable. As a result of loss of visual sensitivity, wavelengths in this region were not measured. The short-wavelength end of the data was limited by the inability of our oven to reach hotter temperatures. If the crystal was rotated 90° around its longitudinal axis, so as to make the pump an ordinary wave, fluorescence was no longer observed. We expect that associated with the visual-range fluorescence described above, there was also a near-infrared idler fluores-

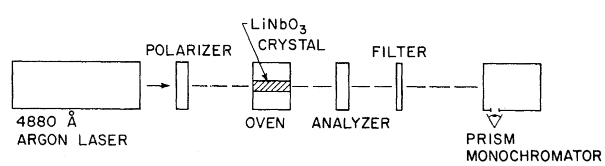


FIG. 1. Schematic of experimental arrangement.

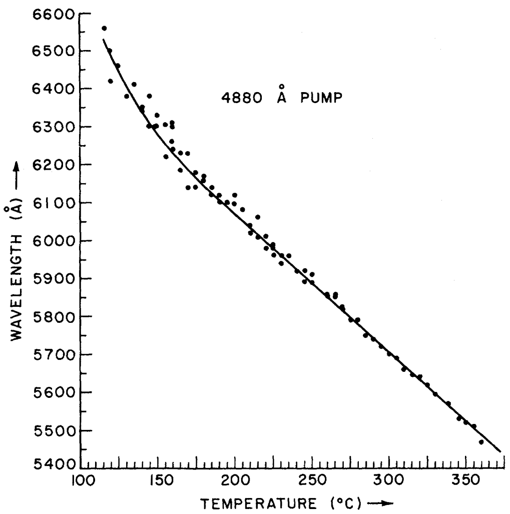


FIG. 2. Experimental results showing fluorescent wavelength as a function of crystal temperature.

cence which tuned between approximately 1.9 and 4.6 $\mu$; however, observations in this region were not attempted.

We note that the crystal orientation described here is the same as that recently used by Giordmaine and Miller to obtain tunable optical parametric oscillation.[7,8] In comparing these experiments, we note that the single-pass parametric gain in the present experiment was about $10^{-6}$ Np/cm. Since the single-pass absorptive loss of the crystal was about $10^{-2}$ Np/cm, net parametric amplification or oscillation was not possible. The effect described here is a spontaneous emission and is therefore not dependent on parametric gain exceeding loss. We note also that optical parametric amplification and oscillation has been considered by a number of authors.[9-11]

Based on the work of Louisell, Yariv, and Siegman[1] and others,[2,3] the spontaneously emitted power per mode per unit length of crystal is given by $h\nu_s \alpha d\nu$, where $h$ is Planck's constant, $\nu_s$ is the optical frequency, $\alpha$ is the incremental power gain of the parametric system, and $d\nu$ is the incremental frequency bandwidth. If the pumping laser is focused to an area of $A=\frac{1}{2}\lambda_i L$, where $L$ is the length of the nonlinear crystal, and $\lambda_i$ is the idler wavelength, then the spontaneous emission from only a single idler mode need be considered.[12] The spontaneously emitted power $P_{\rm sp}$ in an incremental frequency range $d\nu$ per signal mode is then given by

$$P_{\rm sp}=\frac{4\pi^2 d_{15}^2 hL}{n_s n_i n_p \epsilon_0^3 \lambda_s^2 \lambda_i^2} P_p d\nu, \qquad (1)$$

where $d_{15}$ is the magnitude of the pertinent crystal nonlinearity; $\epsilon_0$ is the dielectric constant of free space; $n_s$, $n_i$, and $n_p$ are the refractive indices of the signal, idler, and pump, respectively; $P_p$ is the total power of the pumping laser. Since the number of idler modes which spontaneously emit into the signal mode is proportional to the area of the pumping beam, it is expected that Eq. (1) should also be correct, independent of the area of the pumping beam.

At this time we are uncertain as to the bandwidth of the spontaneous emission. For the data points of Fig. 2, our pump beam was unfocused and had an area of about 3 mm$^2$. By visual comparison with an attenuated He-Ne laser, the spontaneous power was estimated to be about $10^{-12}$ W. Based on Eq. (1), this would require a bandwidth of about 1 cm$^{-1}$.

We note that since $P_{\rm sp}$ is proportional to $d_{15}^2$, the technique described here provides a means to measure optical nonlinearities over a wide range of frequencies conveniently. This should be of particular interest in regions of the spectrum which are close to, or within, an absorptive region. The technique also provides a convenient method for determining the dispersion and phase-matching conditions of nonlinear crystals to be used in optical parametric oscillators. Knowledge of the spontaneously emitted power as a function of frequency determines the magnitude of the pump field which will be necessary to achieve oscillation, and also determines the tuning curve of the oscillator.

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# ULTRAHIGH-FREQUENCY INTENSITY-MODULATED LIGHT FROM A PLASMA

Glen J. Morris
Boeing Scientific Research Laboratories, Seattle, Washington
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Intensity-modulated light emanating from a region of a plasma, wherein strong oscillations were excited by means of the familiar two-stream instability, has been detected at frequencies of several hundreds of Mc/sec.[1] The observations were made using a photomultiplier radiometer.[2] In essence, this device coupled a short time resolution photomultiplier to a radio receiver. Intensity-modulated components present in the light were detected by scanning the receiver in frequency and recording the receiver output as a function of frequency.

The photomultiplier used was an RCA 7746 with <2-nsec rise time and an $S$-11 photocathode response. A synchronous-detection technique was used to aid in recovering periodic signals from the white-noise output of the photomultiplier. This, in combination with careful shielding of the photomultiplier and receiver, eliminated any possibility of spurious responses due to direct pickup of radio signals. The details of the instrument will be published elsewhere.

The principal source studied with the radiometer was an experimental tube in which the two-stream instability was used to excite coherent, longitudinal plasma oscillations. In the tube used in this experiment, two contrastreaming coaxial electron beams 2 mm in diameter were used to generate a plasma and to excite longitudinal plasma electron oscillations in it. The spacing between the two gun anodes was 5 cm, and a weak axial magnetic field was used to confine the beams. Krypton or xenon at pressures in the range from 1 to $10\times10^{-3}$ Torr were the gases commonly used. Such devices as the tube described above and the two-stream mechanism have been discussed by several authors.[3,4]

Longitudinal electron oscillations occur in such a tube at a frequency slightly lower than the plasma frequency. For the experiment discussed here, the degree of ionization was $\sim10^{-4}$. Electron number densities in the range from $10^9$ to $10^{10}$ $cm^{-3}$ were typical. Corresponding oscillation frequencies ranged from about 300 to 600 Mc/sec. In the absence of oscillations, electron temperatures of 2-3 eV were measured. This type of plasma oscillator is known to radiate electromagnetic waves at the second harmonic of the oscillation frequency.[4] As discussed earlier, there was no possibility of direct pickup of a signal by this means.

A noteworthy characteristic of this type of oscillator is its ability to sustain simultaneously oscillations in two different modes at different frequencies. This was particularly true of the oscillator used here because each electron stream was reflected upon itself at the anode of the opposing gun. As a consequence, each stream interacted with itself. The superposition of the two oscillating fields resulted in the familiar phenomenon of a high-frequency field modulated in amplitude at a low frequency.

A low dispersion spectrophotometer was used to determine the spectral characteristics of the light emitted by the plasma oscillator. Within the range from 3400 to 6000 Å ($S$-11 photocathode response), five to ten lines were detected. The lines were superimposed on a weak continuum, but the relative intensities indicat-