photomultiplier. The infrared source was modulated at 10 cps and the output of the phototube, after amplification, was passed through a low-pass filter and presented on an oscilloscope. The sample was a polycrystalline ingot of 1% $PrCl_3$ in $LaCl_3$ which was refined by vacuum distillation. It was mounted in the tip of a liquid helium Dewar and cooled by conduction.

Figure 2(a) shows the output of the phototube with the 558-mμ excitation alone. The 120-cps signal is the "leak" of the AH6 lamp into the phototube. This is present when the sample is warmed up and is also present in a slightly diminished intensity when the sample in the Dewar tip is replaced by a glass tube similar to the Dewar tip. Figure 2(b) shows the output of the phototube when the infrared source alone is on the sample. Figure 2(c) is the output when both sources are on and clearly shows the 10-cps modulation of the 120-cps signal. This demonstrates that both excitation sources must be on the sample to observe the fluorescence. With a higher degree of isolation between the 558-mμ source and the 619-mμ detector it may be possible to use this solid-state system in the manner proposed by Bloembergen for an infrared quantum counter. This also provides an additional method for studying the lifetimes of the excited states.

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COHERENT LIGHT AMPLIFICATION IN OPTICALLY PUMPED Cs VAPOR*

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An excess population density in the upper of two states connected by an optical transition makes possible light amplification by stimulated emission of radiation (LASER). This has recently been demonstrated in a gaseous system employing collisions of the second kind.[1] We have measured spatially coherent amplification in cesium vapor excited by selective optical pumping.[2]

An optical pump suitable for obtaining a population inversion in cesium is the intense He 3888A line, which overlaps the third cesium resonance line (see Fig. 1). In 1930 Boeckner reported fluorescence in cesium excited by the He 3888A line.[3] We have extended Boeckner's optical-pumping experiment by measuring the absolute intensities of Cs fluorescent lines[4] and from these measurements have computed the populations of the associated states using transition probabilities calculated by the Bates-Damgaard method.[5]

Table I shows the populations of certain energy levels obtained under optimized conditions. The population of the $8P_{1/2}$ energy level was substantially greater than that of the lower levels, $8S_{1/2}$ and $6D_{3/2}$. LASER action was therefore possible at the corresponding wavelengths, $\lambda = 7.2\ \mu$ and $3.2\ \mu$.

The amplification coefficient is related to the populations by the equation,

$$k(\nu) = (h\nu/c)(B_{21}N_2 - B_{12}N_1)S(\nu), \qquad (1)$$

where $S(\nu)$ is the normalized line-shape function $[\int S(\nu)d\nu = 1]$; B is the coefficient of induced emission (Einstein B); N_1 and N_2 are the population densities.

Assuming a Doppler profile, the amplification coefficient at line center reduces to

$$k(\nu_0) = \frac{1}{I}\frac{\partial I}{\partial z} = \left(\frac{\ln 2}{16\,c^2\pi^3}\right)^{1/2} A_{21}\frac{\lambda_0^4}{\Delta\lambda_d}\left(N_2 - \frac{g_2}{g_1}N_1\right), \qquad (2)$$

where A is the spontaneous emission coefficient (Einstein A), g_1 and g_2 are statistical weights, and

Table I. Populations of Cs energy levels under optimized conditions.

Cs energy levels	Population density (10^6 atoms/cm^3)
$8P_{1/2}$	100
$8P_{3/2}$	30
$8S_{1/2}$	10
$6D_{3/2}$	3
$5D_{3/2}$	200

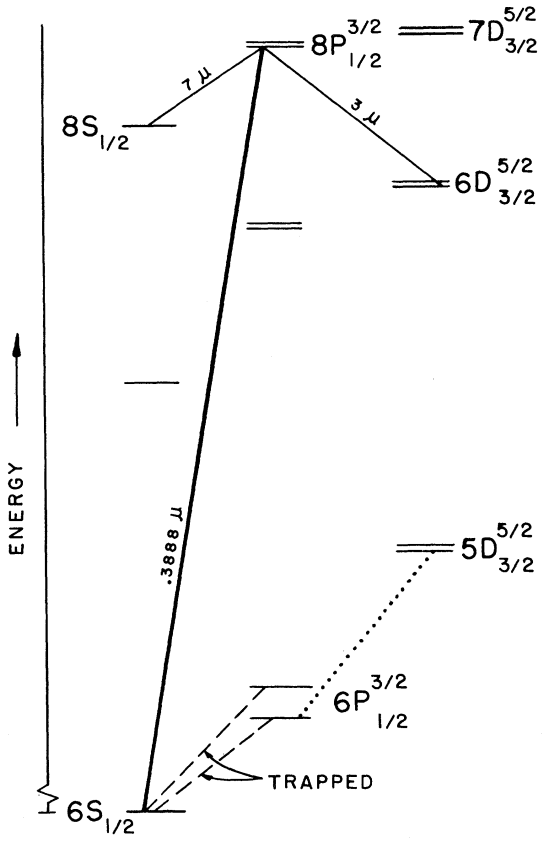

FIG. 1. Cesium doublet diagram showing optical pumping of $8P_{1/2}$ by He 3888A radiation.

$\Delta\lambda_d$ is the Doppler width.

The experimental apparatus for the amplification measurement consisted of an optically pumped Cs fluorescent source, an optically pumped amplification cell, a narrow-band interference filter, and a radiation detector (see Fig. 2). The measurement was carried out at 3.2 μ, rather than at 7.2 μ, because of the superior detectivity of a PbS liquid-nitrogen-cooled detector compared with the best 7μ detectors.

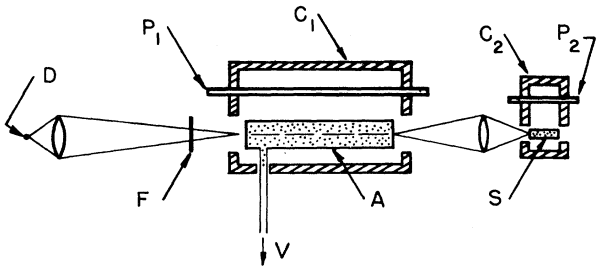

FIG. 2. Experimental arrangement for amplification measurement. P_1, P_2 = helium lamps; C_1, C_2 = reflective cavities; S = Cs source cell, A = Cs amplifier cell, F = narrow bandpass filter, D = radiation detector, and V = entrance to vacuum pump.

The source and amplifier were heated Cs cells, 9 cm and 90 cm long, respectively, positioned within reflective cavities and illuminated by helium discharge lamps. The source lamp, P_2, was operated at 30 Mc/sec and modulated at 105 cps in order to avoid chopping the thermal radiation emitted by the heated Cs cell. The amplifier lamp, P_1, was operated at 400 cps, since rf power, which provides more efficient excitation, was not available to run a tube of its dimensions. The temperature of the Cs was adjusted for maximum fluorescence. The absorption coefficient at the center of the third Cs resonance line was then $k_0 \approx 1/r$, where r is the cell radius. The Cs source and amplifier diameters were 4 and 10 mm, respectively, corresponding to an optimum Cs temperature of 175°C in the source and 165°C in the amplifier. In order to reduce the effects of impurity gases upon the population inversion, a continuously pumped vacuum system was used in the amplifier cell. The conductance was designed to establish a vacuum system gradient of no more than 3% along the amplifier tube in order to insure uniform absorption of pumping light. It was found that fluorescence lines originating from levels ordinarily populated by collisions were reduced greatly in intensity when the vacuum system was utilized.

Phase-sensitive detection was used with a time constant, $\tau \approx \frac{1}{3}$ sec, which made possible detection of 2×10^{-13} watt. The power reaching the $\frac{1}{4}\times\frac{1}{4}$ mm detector from the source was about 10^{-9} watt, and provided a signal-to-noise ratio of 100:1. The discrepancy between system detectivity and observed signal-to-noise was due to mechanical vibration of the very small image with respect to the minute detector.

The direct amplification measurement was made by turning on and off the 400-cps helium lamp illuminating the amplifier cell. The detection system, locked in on 105 cps, showed an increase of (4 $\pm$ 1)% each time the amplifier helium lamp was turned on. The following checks were made, each time repeating the above procedure:

1. Cs vapor pressure was reduced; gain disappeared.
2. Source power was turned off; signal went to zero and remained there.
3. Source power was on, but source light was blocked. Signal remained at zero.

4. Wavelength filter was changed to $\lambda = 3.01\ \mu$ ($6P_{1/2} - 5D_{3/2}$ transition); absorption was observed.

5. Linearity of the detection system was checked by introducing $3.2\ \mu$ radiation after, instead of through, the amplifier cell. This was done by means of a beam splitter. The source and amplifier intensities were adjusted so that the power levels reaching the detector were comparable to their original respective values. The detection system was again locked to the source; no enhancement effect was observed.

We feel that the above checks rule out the possibility of artifact. The measured amplification is in reasonable agreement with the value computed from Eq. (2) using populations given in Table I.

$$k(\nu_0) = 0.002\ \text{cm}^{-1} \text{ for } \lambda = 3.2\ \mu.$$

This coefficient may be reduced by a factor as large as 2 due to incipient hyperfine splitting in $8P_{1/2}$. Assuming a Doppler shape for both source and amplifier, the measured amplification coefficient, averaged over the line shape, is smaller by a factor of $\sqrt{2}$ than the value at line center. From these considerations one predicts a measured gain of approximately 6% for a 90-cm cell.

Butaeva and Fabrikant recently investigated the possibility of obtaining a population inversion in Cs by a combination of optical pumping and collisions of the second kind.[6] They measured variations in the relative intensities of the $7D$-$6P$ fluorescence transitions which they suggest may be due to stimulated emission of radiation. The interpretation of Butaeva and Fabrikant rests on the assumption that the lifetimes of $6P_{1/2,3/2}$ are not appreciably lengthened by radiation trapping. According to the theory of light imprisonment due to Holstein,[7] the lifetime of these states should be increased from the natural lifetime of[8] 3×10^{-8} sec to about 10^{-4} sec, under the conditions of their experiment. Since the trapped lifetime is longer than that of any other excited Cs level, we do not believe the populations of $6P_{1/2,3/2}$ could be less than that of any other Cs level, except the ground level. This conclusion we substantiated by measurement of strong absorption in the $6P_{1/2} - 5D_{3/2}$ transition.

An improved apparatus is being built which we believe will increase the amplification coefficient by a factor of 5. An oscillator incorporating Cs vapor is also under construction.

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