a fairly constant rate of energy loss then the net effect would be to deposit most of the energy to the center of the fiber and so increase the index at the core. The index profile should also be within control.

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Tunable quantum counter for far-infrared radiation

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(Received 2 August 1976)

We report on a quantum counter which converts far-infrared radiation to visible light. The 891-GHz radiation of an HCN laser, absorbed in optically pumped ruby by the transition $\bar{E}(^2E)\rightarrow 2\bar{A}(^2E)$, was detected by an increased R_2 fluorescence. By Zeeman splitting of the ^2E levels the narrow-band detector was tuned to the laser line.

PACS numbers: 85.60.Gz

Quantum counting with up-conversion of infrared radiation to visible light has been proposed by Bloembergen[1] and was realized for the near infrared utilizing the energy levels of rare-earth ions in various crystals.[2] Radiation of an H_2O laser at a wavelength of 28 μm was detected using exciton levels in CdS for quantum-counter action.[3]

We report on the development of a narrow-band tunable quantum counter for far-infrared radiation (FIR) utilizing the energy level system of Cr^{3+} in Al_2O_3. The principle of this quantum counter is shown in Fig. 1(a). With the radiation of a suitable lamp the pump bands of ruby are excited, and hence the metastable $\bar{E}(^2E)$ and $2A(^2E)$ levels are populated by radiationless transitions. For crystal temperatures less than 2 K the $2\bar{A}$ level which is 29 cm^{-1} above the $\bar{E}$ level is essentially unpopulated and nearly no R_2 light is observed. FIR quanta at 29 cm^{-1} are absorbed by the transition $\bar{E}\rightarrow 2\bar{A}$ and R_2 quanta with a wavelength at 6922 Å are emitted.

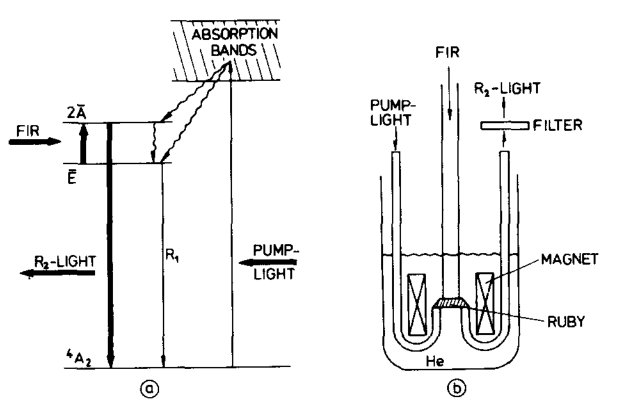

FIG. 1. Ruby far-infrared quantum counter. (a) Principle: FIR photons are absorbed by the transition $\bar{E}\rightarrow 2\bar{A}$ and lead to additional R_2 fluorescence radiation. The $\bar{E}$ level is populated by radiationless transitions (curly lines) from the ruby absorption bands. (b) Experimental arrangement.

Tuning of the detector is obtained by applying a magnetic field parallel to the crystal c axis. The $\bar{E}$ and $2\bar{A}$ levels are split with g factors $g_{\parallel}(\bar{E})=2.445$ [4] and $g_{\parallel}(2\bar{A})=1.46$.[5] The splitting of the levels is indicated in the insert of Fig. 2.

In Fig. 1(b), the experimental arrangement is shown. The crystal is aligned with its c axis parallel to the field of a superconducting magnet and is surrounded by liquid helium at 2 K. The 0.05% ruby crystal with a surface of 5×5 mm and a thickness of 1.5 mm has two 45° side faces for optical coupling of the crystal to fiber optics. As a pump source, a 700-W Hg-Xe lamp is used. The R_2 fluorescence radiation separated from the strong R_1 radiation by narrow-band interference filters is detected by a cooled RCA C-31034 photomultiplier. The chopped FIR of an HCN laser at a wavelength of 337 μ is guided to the crystal by a metal tube. The FIR-induced R_2 fluorescence radiation is

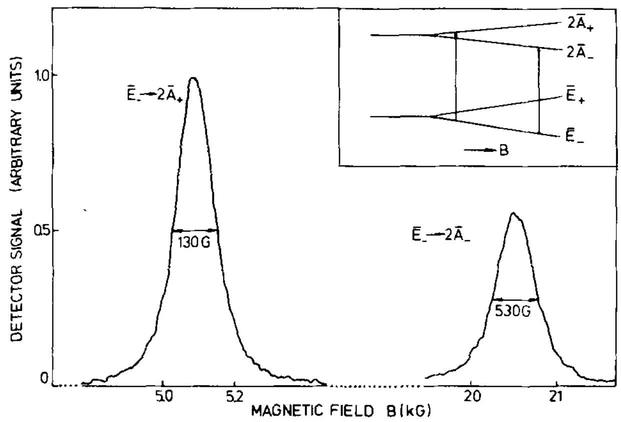

FIG. 2. Observed quantum-counter signals for the 891-GHz radiation of a HCN laser. Detector response is obtained at two magnetic fields. From the half-widths (note scale change for the B axis) a bandwidth of 0.36 GHz and a response time of less than 10^{-9} s follows for the ruby quantum counter (see text). The inset shows the Zeeman splitting of the metastable ^2E levels of Cr^{3+}. The transitions at the laser frequency are indicated by arrows.

monitored by a lock-in technique. As the energy of the FIR photons (29.7 cm^{-1}) is greater than the energy difference between the $\bar{E}$ and the $2\bar{A}$ levels (at 29.1 cm^{-1}), the transitions $\bar{E}_- \to 2\bar{A}_+$ and $\bar{E}_- \to 2\bar{A}_-$ can be tuned to the laser line (see inset of Fig. 2).

Our experimental result is shown in Fig. 2. At fixed laser frequency we find two quantum counter signals at the magnetic fields $B_1 \approx 5$ kG and $B_2 \approx 20$ kG, respectively. These signals correspond to the spin-flip transition $\bar{E}_- \to 2\bar{A}_+$ and the non-spin-flip transition $\bar{E}_- \to 2\bar{A}_-$. The two transitions are found to have similar strengths (see Fig. 2).

The experimental half-widths of the two signals at the fields B_1 and B_2 are $\Delta B_1 = 130$ G and $\Delta B_2 = 530$ G. From these values we can calculate the bandwidth of the quantum counter from the relation $\Delta\nu_{1,2} = \Delta B_{1,2}(\mu_B/2h)[g(\bar{E}) \pm g(2\bar{A})]$. We obtain from ΔB_1 and ΔB_2 the same value for the frequency bandwidth of $\Delta\nu = 360$ MHz (or 0.012 ± 0.001 cm^{-1}).

The Lorentzlike lineforms of the two signals (Fig. 2) indicate lifetime broadening of the $2\bar{A}$ level. We obtain $T_1 = (2\pi\Delta\nu)^{-1} = 4.4 \times 10^{-10}$ s. This value is in good agreement with a theoretical estimate of 3×10^{-10} s [6] for the low-temperature relaxation by the direct process between the $2\bar{A}$ and the $\bar{E}$ level due to spontaneous emission of 29-cm^{-1} phonons. Our result indicates that the ruby quantum counter has a rise time of less than 10^{-9} s.

The experimental result in Fig. 2 is obtained with a concentration of about 10^{16} excited Cr^{3+} ions/cm^3. We estimate a quantum efficiency for the quantum counter (the ratio of R_2 fluorescence output to FIR input) of the order of 10^{-7}. The signal of Fig. 2 is recorded with a laser power of about 10 mW arriving at the crystal. The minimal detectable signal is about 1 μW. This value is limited by the population of the $2\bar{A}$ level produced in the pump process [see Fig. 1(a)]. It should be possible to extend this limit considerably by direct optical excitation of the $\bar{E}$ level with a dye laser.

With a 100-kG magnet, the $\bar{E}_- \to 2\bar{A}_+$ transition can be tuned from 29 to 39 cm^{-1}, whereas for the same field interval the $\bar{E}_+ \to 2A_-$ transition decreases from 29 to 19 cm^{-1}. For the latter transition, lower sensitivity is expected for high magnetic fields due to decreased population of the $\bar{E}_+$ level.

The reported detector principle can be applied to other systems. For example, the $E_- \to 2A_+$ transitions of V^{2+} and Mn^{4+} in Al_2O_3 are tunable in a 100-kG magnet from 12 to 20 cm^{-1} and from 80 to 90 cm^{-1}, respectively.

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Background suppression in coherent Raman spectroscopy*

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(Received 28 June 1976)

Background signals which appear in Coherent anti-Stokes Raman spectroscopy and in the Raman-induced Kerr effect can be eliminated using polarization technqiues based upon four-wave mixing. Specific polarization conditions will suppress all signals with the exception of those arising from Raman modes. The interference between resonant and background contributions is eliminated, and undistorted line shapes are obtained.

PACS numbers: 42.65.Dr, 78.30.Cp

A major advantage of the various techniques of coherent Raman spectroscopy is the ability to suppress the incoherent fluorescence which often obscures the desired spectrum in a spontaneous Raman scattering experiment.[1,2] There are, however, two kinds of effects—linear and nonlinear—which lead to background