Reprinted from

PHYSICS LETTERS

Volume 15, number 1, 1 March 1965

THE PHONON MASER

R. ORBACH

pp. 43 - 45

NORTH-HOLLAND PUBLISHING COMPANY
AMSTERDAM

THE PHONON MASER *

R. ORBACH **
Department of Physics, University of California, Los Angeles, California 90024

Received 15 February 1965

This letter is a proposal for a c.w., continuously tunable, phonon maser. The mechanism is quite analogous to optical pumping schemes, utilizing a double pump to preferentially populate an excited state of a paramagnetic ion.

Consider the four level system of fig. 1. The level configuration is similar to that of ruby, for example, where $|1\rangle = |^4A_2\rangle$, $|2\rangle = |^2E(E)\rangle$, $|3\rangle = |^2E(2A)\rangle$, and $|4\rangle = |^4T_2 \text{ band}\rangle$. Another system with a somewhat analogous level scheme is $Tm^{2+}:CaF_2$ [1], where $|1\rangle = |J = \frac{7}{2}, \Gamma_7\rangle$, $|2\rangle = |J = \frac{5}{2}, \Gamma_7 - \frac{1}{2}\rangle$, $|3\rangle = |J = \frac{5}{2}, \Gamma_7 + \frac{1}{2}\rangle$, and $|4\rangle = |4f^{12}5d \text{ band}\rangle$. In the former scheme, the splitting $\Delta_{32} = 29\ cm^{-1}$ is caused by the action of the electric crystalline field in consort with the spin-orbit coupling [2]. In the latter, the splitting is caused by an external magnetic field which Zeeman splits the Kramers doublet states $|2\rangle$ and $|3\rangle$.

It has recently been demonstrated by Geschwind et al. [3] that a local heating of the phonon spectrum at the energy Δ_{32} obtains when ruby is illuminated by a high intensity source of

* Supported in part by the National Science Foundation and the Office of Naval Research NONR-233(88).

** Alfred P. Sloan Foundation Fellow.

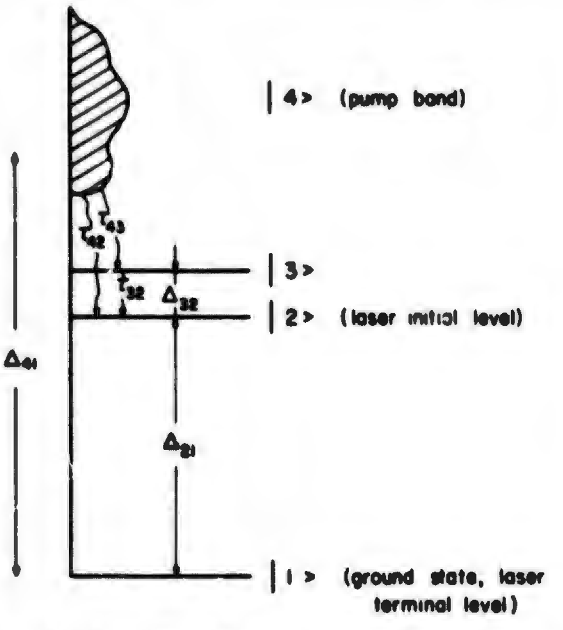

Fig. 1. A schematic of the energy levels for the proposed maser. The laser pump is applied at the energy Δ_{21}, along with the pump at the energy Δ_{41}. The resulting population inversion between levels $|3\rangle$ and $|2\rangle$ gives rise to phonon maser action at energy Δ_{32}.

light. This heating is a result of the equality of transitions to the levels $|3\rangle$ and $|2\rangle$ from the "storage" level $|4\rangle$. Spins in the state $|3\rangle$ in ruby decay [3] in a time $\tau_{32} = 4 \times 10^{-10}$ sec to the state $|2\rangle$, accompanied by the emission of a single phonon with energy Δ_{32}. If this phonon belongs to the lowest (transverse) branch; Orbach and Vredevoe [4] have shown that, at temperatures $T \ll \Delta_{32}/k$, it will possess a long lifetime, of the order of 10^{-2} sec at 1°K. It is this transition which is to be regarded as the source of the phonons which participate in maser action.

The population inversion necessary for maser action is brought about as follows. Let there be incident upon the system intense optical pump light at the energy Δ_{41}. The intensity must be great enough to excite substantially more than half of the spins out of the ground level $|1\rangle$. Let the associated time of transition be denoted by τ_{14}. The pump level $|4\rangle$ is assumed to decay rapidly, with equal probability, to the metastable levels $|3\rangle$ and $|2\rangle$ in the characteristic time τ_{43}. Next, a laser beam is applied at the energy Δ_{21}, preferentially depopulating the metastable level $|2\rangle$ with a characteristic pumping time τ_{12}. (This requirement is easy to satisfy for ruby and $Tm^{2+}:CaF_2$ because both systems are capable of optical maser action at the energy Δ_{21}.) If the pump times, τ_{14} and τ_{12} are sufficiently short, a population inversion between the levels $|3\rangle$ and $|2\rangle$ then obtains.

Quantitatively, let τ_R represent the flourescent lifetime for the levels $|2\rangle$ and $|3\rangle$ to decay to $|1\rangle$. The rate equations governing the populations of the four levels are, in the limit of $kT \ll \Delta_{ij}$, and at high pump levels,

$$\begin{aligned} \dot N_1 &= (N_3+N_2)/\tau_R - (N_1-N_2)/\tau_{12} - (N_1-N_4)/\tau_{14}; \\ \dot N_2 &= N_2/\tau_R - (N_2-N_1)/\tau_{12} + N_3/\tau_{32} + N_4/\tau_{43}; \\ \dot N_3 &= -N_3/\tau_R - N_3/\tau_{32} + N_4/\tau_{43}; \\ \dot N_4 &= -2N_4/\tau_{43} - (N_4-N_1)/\tau_{14}. \end{aligned} \qquad (1)$$

In steady state, the left hand sides vanish and the ratio of populations N_3/N_2 becomes,

$$N_3/N_2 = \tau_{32}(\tau_R+\tau_{12})\{\tau_R\tau_{12} + (2\tau_{14}+\tau_{43}) \times \times (\tau_R+\tau_{32}) + \tau_{12}(\tau_R+\tau_{32})\}^{-1} . \qquad (2)$$

In the limit of pump times τ_{12} and τ_{14} short compared to τ_{43}, τ_{32} and τ_R, (this will be difficult to achieve in ruby) the ratio (2) reduces to

$$N_3/N_2 = \tau_R\tau_{32}/\tau_{43}(\tau_R+\tau_{32}) . \qquad (3)$$

A necessary condition for phonon maser action in this system is that N_3/N_2 be greater than unity. For this to obtain, the rate of phonon production $1/\tau_{32}$ must not become too small. In the limit $\tau_{32} \ll \tau_R$, $N_3/N_2 \sim \tau_{32}/\tau_{43}$, and the requirement $N_3/N_2 > 1$ then necessitates $\tau_{32} > \tau_{43}$, a condition which is not easily satisfied in practice. In ruby, for example, Maiman [5] has argued that $\tau_{43} \sim 2 \times 10^{-7}$, though Sturge [6] infers a much shorter time, $\tau_{43} \sim 10^{-12}$, from the line width of the $^4T_2$ level. The population ratio N_3/N_2 may therefore lie anywhere between 10^{-3} and 10^2 depending on which value is chosen for τ_{43}. In any case, one can certainly overcome the difficulty of a short τ_{32} by using a salt where the levels $|2\rangle$ and $|3\rangle$ are time conjugate states of a Kramers doublet (e.g. $Tm^{2+}:CaF_2$). The relaxation time τ_{32} can then be closely controlled by varying the strength of the magnetic field [7], the direct phonon relaxation rate being proportional to H^5.

It is to be emphasized that any four level system of the type shown in fig. 1 which satisfies the requirement that $\tau_R > \tau_{32} > \tau_{43}$ will be capable of phonon maser action. The choice of a Kramers doublet for the states $|2\rangle$ and $|3\rangle$ can be a crucial step, since it insures that the rate inequalities can be satisfied at some value of the magnetic field. The variability of the splitting $\Delta_{32} = g\beta H$ (and the hence phonon energy) leads to the possibility of continuous magnetic tuning and frequency modulation.

This letter has been materially improved as a result of a conversation with Dr. M. D. Sturge. In addition, very helpful discussions with Drs. J. Ball, R. Braunstein, S. Geschwind and P. Kisliuk are gratefully acknowledged.

References

1. Z.J.Kiss and R.C.Duncan, Proc.I.R.E.50 (1962) 1531.
2. S.Sugano and Y.Tanabe, J.Phys.Soc.Japan 13 (1958) 880.
3. S.Geschwind, G.E.Devlin, R.L.Cohen and S.R.Chin, Phys.Rev., in press.
4. R.Orbach and L.A.Vredevoe, Physics 1 (1964) 91.
5. T.H.Maiman, Phys.Rev.Letters 4 (1960) 564.
6. M.D.Sturge, private communication.
7. R.de L.Kronig, Physica 6 (1939) 33 and J.H.Van Vleck, Phys.Rev.57 (1940) 426.

* * * * *