Letters to the Editor

Radiation Damping Effects in Two Level Maser Oscillators*

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SEVERAL experimenters[1,2] have noted recently that when an inverted two-level spin system was permitted to radiate spontaneously, the resulting oscillation was characterized by an appreciable amplitude modulation. The phenomenon was first believed to be the result of interference of different spin packets in an inhomogeneously broadened spectrum.[1] A theoretical analysis (which will be reported separately) shows that this is not the case. The spins are not independent but are coupled together by means of their radiation field. This explanation has since been dismissed by its original authors.†

A second and more recent theory[3] explains the phenomenon by means of a linearized coupling between the spin system and the cavity. We have re-examined the situation and found that the linear treatment which assumes M_z to be a constant predicts modulated oscillation only for the case $M_z=+M_0$ and not for the two-level maser case where $M_z=-M_0$.

Following a line of analysis analogous to that of Bloembergen and Pound, asuming M_z to be a constant and neglecting relaxation effects, we get for the coupled magnetization and circuit equations,

$$\frac{2j\omega}{T_R|M_0|\,|\gamma|}M_1+\frac{2}{T_R|M_0|\,|\gamma|}\,\frac{dM_1}{dt}+2jQ\Delta\omega H_1+Q\frac{dH_1}{dt}+\omega H_1=0, \tag{1}$$

$$\frac{dM_1}{dt}-j\gamma M_z H_1=0, \tag{2}$$

where, $\omega=|\gamma|H_0$, $Q=\omega L/R=$loaded Q of the cavity, and $\Delta\omega=\gamma H_0-[1/(LC)^{\frac{1}{2}}]=$ (spin resonant frequency—cavity resonant frequency). $T_R=1/2\pi\eta M_0 Q_L|\gamma|$, $\eta=$filling factor, and $M_0=$dc equilibrium magnetization.

$M_1(t)$ and $H_1(t)$ are the complex amplitudes of the transverse magnetization and magnetic field, respectively, i.e.;

$$M_x(t)=\mathrm{Re}[M_1(t)e^{j\omega t}],$$
$$H_x(t)=\mathrm{Re}[H_1(t)e^{j\omega t}].$$

We assume $\exp(\alpha t)$ variation for $M_1(t)$ and $H_1(t)$ which when substituted in Eqs. (1) and (2) yields two algebraic equations.

For nontrivial solution we have:

$$\alpha^2+\left(2j\Delta\omega+\frac{\omega}{Q}-\frac{2_j M_z}{T_R Q M_0}\right)\alpha+\frac{2\omega M_z}{T_R Q M_0}=0, \tag{3}$$

$$\alpha=-\left(\frac{-jM_z}{QT_RM_0}+j\Delta\omega+\frac{\omega}{2Q}\right)\pm\left[\left(\frac{-jM_z}{QT_RM_0}+j\Delta\omega+\frac{\omega}{2Q}\right)^2-\frac{2\omega M_z}{QT_RM_0}\right]^{\frac{1}{2}}. \tag{4}$$

Assuming, (1) cavity tuned to free precession frequency, i.e., $\Delta\omega=0$, (2) $(1/T_R)\gg\omega/Q$, and (3) $T_R\gg(1/\omega)$, Eq. (4) becomes,

$$\alpha_{1,2}=\frac{-\omega}{2Q}\pm\left(\frac{-2\omega M_z}{QT_RM_0}\right)^{\frac{1}{2}}. \tag{5}$$

If $M_z=+M_0$, α_1 and α_2 are complex conjugate and the resultant solutions for $M_1(t)$ and $H_1(t)$ are oscillatory, the oscillation taking place at an angular frequency $(2\omega/QT_R)^{\frac{1}{2}}$. This is the situation described by Bloembergen and Pound.[4]

If we assume $M_z=-M_0$, which is the case for an inverted spin system, α_1 and α_2 are both real and give rise to exponential solutions.

If the cavity resonant frequency and the free precession frequency $|\gamma|H_0$ do not coincide $\Delta\omega\neq 0$, and if $\Delta\omega^2>(2\omega/QT_R)$ oscillatory solutions are possible even for $M_z=-M_0$. This mechanism too must be dismissed as a possible explanation, because the observed modulation was of a constant reproducible frequency.

The authors believe that the answer lies in the nonlinear solution of the equations of motion, in which M_z is allowed to vary with time. The possibility of programing this problem for a computer is being considered.

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Influence of Selenium Microstructure on Photocell Characteristics

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A POSSIBLE dependence of the sensitivity and spectral characteristics of selenium barrier layer photocells on the grain structure of the selenium layer has been noticed on the basis of measurements made on over 1600 photocells of the Se–Cd–Au type. These cells were prepared by spreading and molding the selenium on roughened steel base plates and then applying the barrier layer and transparent electrode by the sputtering of cadmium and gold. Results appear to indicate that a high proportion of small gains on the selenium layer leads to a slightly diminished output and red sensitivity in the completed cell for this method of cell fabrication.

A considerable amount of work has been done recently on the microstructure and the electrical properties of selenium. Grain growth in pure and doped selenium was studied by Losco.[1] Halverson[2] noticed an increase in the resistivity on account of heating and attributed it to increase in grain size. Henkels[3]

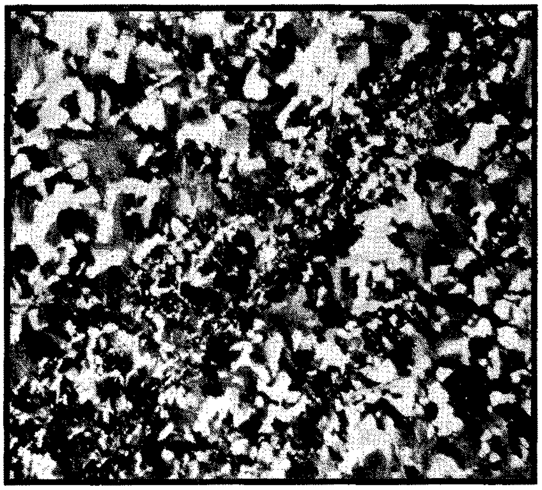

Fig. 1. Selenium microstructure on a typical photocell blank. 200×.

TABLE I. Relationship between photocell characteristics and percentage cell area covered by small grains.

	Number of batches		
	(a)	(b)	(c)
Red response	62	1	27
Current output	53	4	33

proposed a model of semiconducting selenium based on theoretical considerations. In earlier papers[4,5] he indicated that potential barriers existed in the body of the selenium and that the grain boundaries would be the natural location for such barriers. According to him, most of the impurities are rejected at grain boundaries and the formation of electrostatic barriers here is the major factor contributing to the dc resistivity. The existence of intergranular potential barriers has also been postulated by Plessner.[6] Observed values of Hall effect and thermoelectric power, as also deviations from Ohm's law, were considered, in this case, as sufficient evidence for the existence of such barriers.

In view of these findings an attempt was made to determine whether the characteristics of the selenium photocell would be related to the microstructure of the selenium layer. The grain structure was examined on 1620 cell blanks and the current outputs and spectral characteristics of the completed cells were measured. The cells being 45 mm in diameter, it was not practicable to examine the entire surface of each cell. On every cell, therefore, sixteen small areas, well distributed over the entire surface, were chosen and the grain size and structure examined under polarized light. The results were tabulated in terms of the estimated percentage area covered by small grains (less than 10^{-3} cm). Figure 1 shows the grain structure of a typical cell blank.

As it would be laborious to trace the complete spectral sensitivity curve for every cell, blue, green, and red filters of narrow pass band were used and the cell output current measured with these interposed in succession. The output ratios blue/green and red/green were then tabulated for each cell. Numerous measurements made earlier had shown that a check as described above gave a dependable indication of the relative blue and red response. The current sensitivity for white light was measured at an illumination of 40 ft-c at 2700°K color temperature.

The 1620 cells were made up in 90 batches of 18 each, in exactly the same manner, and using selenium from the same source. Since the cells in each batch were prepared from the same sample of selenium, and at the same time, parameters relating to past history and impurity content would be the same for all cells in the same batch. It was, therefore, considered appropriate to look for any correlation within each of the 90 batches rather than on the totality of the cells. Scatter diagrams were prepared, for each batch of cells, of red response and, separately, current sensitivity *vs* percentage cell area covered by small grains. Only qualitative trends were sought. The results are tabulated in Table I. In column (a) are given the numbers of batches showing a decrease in the red response and a decrease in the current sensitivity, respectively, for increasing percentage cell area covered by small grains. The numbers of batches with the reverse tendency are shown in column (b). Column (c) gives the inconclusive cases. It is significant that the numbers under (a) are overwhelmingly large compared with those under (b). The fairly large number of inconclusive scatter diagrams will be readily appreciated on remembering the limitations of an investigation of this nature.

However, the results do indicate that the presence of large numbers of small grains tends to diminish slightly the general photosensitivity, and the red sensitivity in particular, of selenium barrier layer cells of this type. The role played by grain boundaries has been recognized in the references cited above. If the impurities are rejected at the grain boundaries the concentration of impurities would depend, for a given sample of selenium, on the total conduction path along the boundaries and hence on the size and structure of the grains. Furthermore, according to Henkels' postulate, the electrostatic barriers at the grain boundaries would form effective *p-n* junctions if the impurities happen to be metals or tend to form a uniform *p*-type material when nonmetals form localized acceptor levels. The increased red sensitivity, when comparatively few small grains are present, may be due to direct excitation from the low-lying acceptor levels originating from excessive concentrations of impurities. The observed influence of the selenium grain structure on the photovoltaic effect appears to lend support to the intergranular barrier theory of Henkels and Plessner.

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Strength of Gold Whiskers

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THE mechanical behavior of whiskers such as copper, silver, and zinc is characterized by (1) high elastic strengths (sometimes in excess of $0.01E$, where E is the Young's modulus), (2) very sharp yield points, and (3) plastic flow with the propagation of Lüders bands at a flow stress as small as 1% of the yield stress.[1] In addition, Price and Cabrera[2,3] report the occurrence of small amounts of saturation creep in some of the zinc and copper whiskers *prior* to yielding. (This creep has as yet not been verified.[1]) An attempt has been made by Price and Cabrera[3] to attribute both the high elastic strength and the mode of plastic flow to the thin oxide layer that is unavoidably present on the whisker surfaces at atmospheric conditions. They propose that during creep, dislocation loops generated at randomly spaced dislocation sources pile up against the oxide film which ruptures when the pileup becomes sufficiently large. The motion of the Lüders band was proposed to occur by the propagation of a crack between the oxide film and the metal substrate.

In view of Price and Cabrera's hypothesis it was desirable to test gold whiskers which probably are free of surface films (disregarding adsorbed gases). For instance the free energy of forming gold oxide in air at room temperature is positive.

Fourteen gold whiskers were strained in tension in the apparatus described elsewhere.[4] The gold whiskers were grown on quartz by C. R. Morelock of this laboratory by condensing supersaturated gold vapor in air at about 1040°C. Most of the whiskers tested were less than 1 mm in length with some as short as 300 μ. X-ray diffraction from one of the whiskers showed that its axis was parallel to the [110] direction. The cross-sectional areas of the whiskers were estimated to range from 2 to 14×10^{-8} cm^2.

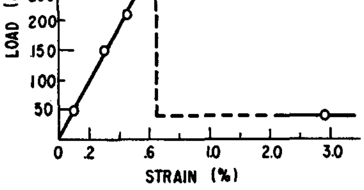

FIG. 1. Strain *vs* load of gold whisker 400 μ in length. Calculated cross-sectional area (using $E_{110}=8500$ kg/mm^2) equals 6×10^{-8} cm^2.