Optical Maser Characteristics of Nd^{3+} in $SrMoO_4$

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In the same manner as described in the previous letter for CaF_2Nd^{3+}, $SrMoO_4$:Nd^{3+} was examined for optical maser characteristics. Again the same three groups of lines appear in the infrared fluorescence spectrum, characteristic of Nd^{3+}, but the precise position of individual lines is altered somewhat by the different $SrMoO_4$ crystal field environment. At 77°K, the strongest infrared fluorescence line lies at 1.064 μ (9398 cm^{-1}), and exhibits stimulated emission both at room temperature (1.0643 μ, 9396 cm^{-1}) and at 77°K. The half-width of this line is about 15 cm^{-1} at room temperature and 3 cm^{-1} at 77°K. An oscilloscope trace of stimulated emission at room temperature is shown in Fig. 1(a).

The input energy to the lamp is 16% above the threshold energy for stimulated emission. The time scale is 100 μsec/division and the lower trace displays the fluorescence, stimulated emission, and stray light passed with the grating spectrometer fixed at 1.0643 μ. A trace taken just at the threshold for stimulated emission at 77°K revealed that the sample integrates the light flux for 200 μsec before stimulated emission is observed. Closer examination of the stimulated emission spikes is shown in Fig. 1(b) where the upper trace is displayed in delay on a time scale of 10 μsec/division. Again, as for CaF_2:Nd^{3+}, there is a certain regularity in the frequency of the spikes but no smoothly decaying characteristic in the spike amplitudes, even when operating close to threshold. In this, the first sample studied, the threshold for stimulated emission was found to be 125 joules of energy into the FT 524 xenon lamp at room temperature and 42 joules at 77°K.

A more detailed account of the energy levels and optical properties of Nd^{3+} in CaF_2 and $SrMoO_4$ will be presented in a future publication.

We wish to express our gratitude to Dr. L. G. Van Uitert whose early work pointed out some of the desirable properties of molybdate host crystals and whose advice has been most helpful. We also wish to thank R. A. Thomas for preparing the maser rod.

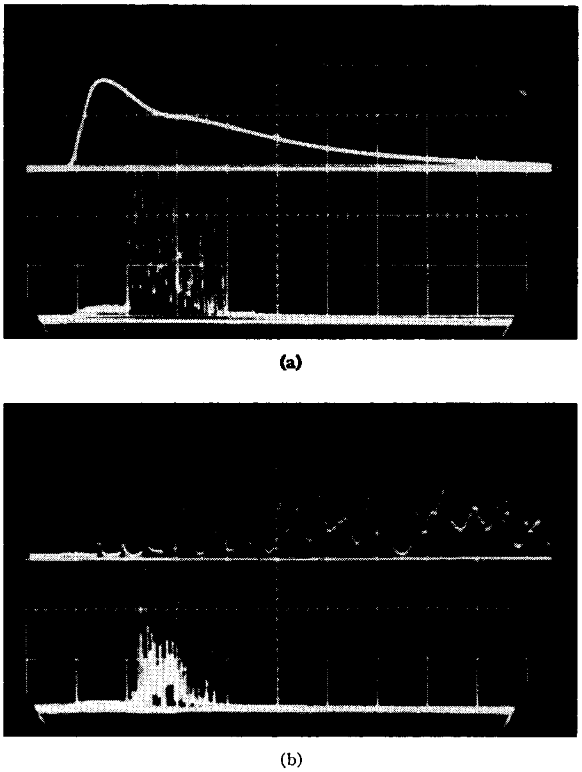

Fig. 1. Stimulated emission at room temperature in $SrMoO_4$:Nd^{3+}. (a) Upper trace: variation of lamp intensity with time; lower trace: fluorescence and stimulated emission (and scattered light) at 1.0643 μ; time scale for both traces: 100 μsec/division; pump intensity 16% above threshold. (b) Fluorescence and stimulated emission at 1.0643 μ, 9% above threshold; time scale—upper trace: 10 μsec/division; lower trace: 100 μsec/division.

Quasi-Cascaded Parametric Amplifier*

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Since Suhl's[1] original paper proposing ferromagnetic microwave parametric amplifiers, many modifications of these devices have been proposed and a few operational models have been built. In all of these, the frequency of the time varying reactive coupling between the resonant systems must be the sum of the two resonant frequencies for gain greater than unity. It is possible to build an amplifying system with a signal frequency greater than the pump frequency but the actual power gain occurs in a device in which the frequency of the reactive coupling is higher than the amplified signal. The remainder of the system will consist of some sort of frequency shifting or mixing device. A system proposed by Hogan, Jepsen, and Vartanian[2] would amplify the idler and then mix with the pump frequency for an amplified signal frequency. Gottlieb[3] proposed an amplifier with the signal frequency higher than the pump frequency. Degenerate modes at the pump frequency generate the second harmonic of the pump frequency and this is used as the reactive coupling.

Certain features of both of these amplifiers may be combined to build a quasi-cascaded parametric amplifier which uses resonant modes of a single sample. If a sample is parallel pumped above the corresponding thresholds at both W_p and $2W_p$, and if modes exist in the sample whose frequencies add properly and which satisfy the orthogonality relations of Denton,[4] it is possible to increase the amplification over the straight Suhl amplifier. In addition to the usual signal and idler mode which in the present case use the second harmonic of W_p as a reactive coupling, there must be a subsidiary idler mode which will be used to amplify the idler. For this latter pair of modes, W_p will be the pump. The frequency relations are as follows:

$$W_s+W_i=2W_p$$
$$W_i+W_i'=W_p,$$

where W_s=signal frequency, W_i=idler frequency, W_i'=subsidiary idler frequency, and W_p=fundamental of pump frequency.

In addition to these frequency restrictions, it must be necessary that the orthogonality relations be satisfied.

(1) $m_s=-m_i=m_i'$.
(2) n_s, n_i, n_i' must all be either even or odd.

The m's and n's are the numbers which characterize the modes as used by Walker.[5]

A pair of resonant magnetostatic modes M_1 and M_2 will be coupled together through the equation of motion, $dM_1/dt=-\gamma(M_2\times H)$ when the pump field H exceeds a certain critical value (called threshold for coupling). Thus the three modes corresponding to frequencies W_s, W_i, W_i' may be represented by an equivalent circuit as shown in Fig. 1.

This equivalent circuit degenerates to a single-stage parametric amplifier if the threshold for either pair of modes is not exceeded. If the threshold for coupling between the signal and idler is exceeded (at frequency $2W_p$) then the equivalent circuit for this pair of modes would be the two tank circuits W_s and W_i coupled by a nonlinear capacitor $C_a=C_{a_0}+C_{c_1}e^{i2W_pt}$. But once there is present an rf magnetic field at the signal frequency the idler mode will begin to oscillate. The idler mode will be coupled to the subsidiary idler through $C_b=C_{0_b}+C_{c_2}e^{iW_pt}$ and will be amplified,

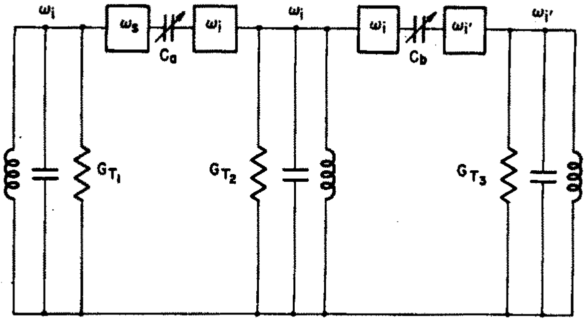

FIG. 1. Equivalent circuit of quasi-cascaded amplifier. Boxes represent narrow band ideal band pass filters. W_s, W_i, W_i' are resonant frequencies of corresponding tank circuits. G_T represents equivalent shunt conductance of associated tuned circuit. G_{T_1} includes a finite load conductance.

provided the threshold for coupling at frequency W_p is exceeded. The amplified idler will in turn amplify the signal mode by a greater amount than if the idler were unamplified. This represents a gain greater than the straight Suhl amplifier. For such amplification to have occurred, the orthogonality relations must have been satisfied and therefore there can be no nonlinear coupling between the signal and subsidiary idler at any pump frequency for less than infinite pump power. Thus the subsidiary idler and the signal frequency are a pair of modes with no interaction.

The analysis of Heffner and Wade[6] has shown that the load on the signal tank of the idler tank through the nonlinear coupling device is a negative conductance at resonance of both tanks. The magnitude of this conductance is given by:

$$G_1 = C_{c_1}{}^2 W_s W_i / G_{T_2},$$

where G_{T_2} is the equivalent shunt conductance of the idler tank. By a similar analysis, the effect of the subsidiary idler would be a negative conductance load across the idler tank. This conductance would make G_1 larger and thus increase the power gain of the signal circuit. This increased G_1 would be:

$$G_1' = \frac{C_{c_1}{}^2 W_s W_i}{G_{T_2} - (C_{c_2}{}^2 W_i W_i' / G_{T_3})},$$

where G_{T_3} is the equivalent conductance across the subsidiary idler circuit.

Denton[4] has shown that the power gain of the pair of modes G_p is:

$$G_p = \frac{[\Omega_p{}^2 + \lambda_2(\lambda_1 - \gamma \Delta H)]^2}{|\Omega_p{}^2 - \lambda_1 \lambda_2|^2}.$$

$\Omega_p = \gamma h_p$, where h_p is the pump field strength and $\lambda_{1,2}$ are the damping coefficients of modes, 1 and 2, respectively. By the same procedure, the power gain of the idler-subsidiary idler pair would have a similar expression. By comparison to the circuit analogy, the effect of the load on the idler of the subsidiary idler mode would be to lower the effective damping and increase the gain at the signal frequency. If it were not for coupling of the idler to the load and other losses, the gain of the idler subsidiary idler pair would represent the additional gain of the device. The amount of additional gain would depend on how well the additional energy in the idler were coupled to the signal mode. Thus it is possible to increase the gain of a Suhl type amplifier by amplifying the idler, providing all the necessary conditions are satisfied.

It is desirable to keep the pump power as low as possible yet it must exceed the threshold for coupling. Therefore, mode pairs with the lowest threshold should be used. Denton[4] has shown that mode pairs will be coupled at a much lower threshold for parallel pumping than for transverse pumping. The sample should be parallel pumped at W_p and $2W_p$ in a cavity resonant at W_p which also has a high Q at $2W_p$. $2W_p$ may be generated by means of a ferrite doubler. Hefner and Wade (see reference 6) have pointed out that the phase relations of a two tank parametric amplifier have no influence on gain. The idler mode merely acts as a source for the second stage of parametric amplification so the phase of this mode relative to W_p is unimportant. Therefore the phase angle between W_p and $2W_p$ can have no influence on the gain of the amplifier.

For maximum pumping efficiency the uniform precession should be resonant at the pump frequency. Obviously this condition can only be satisfied for one of the pump frequencies. It would be most efficient to set the uniform precession resonant at the pump frequency for the pair which has the highest threshold for coupling. It is assumed that sufficient pump power will be available at either pump frequency. This sacrifice of pumping efficiency for increased power gain is a fundamental limitation of the amplifier. However if mode pairs with the lowest threshold for coupling are selected this amplifier should significantly improve the power gain of current Suhl type amplifiers.

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[1] H. Suhl, J. Appl. Phys. **28**, 1225 (1952).

[2] C. L. Hogan, R. L. Jepsen, and P. H. Vartanian, J. Appl. Phys. **29**, 422 (1958).

[3] P. Gottlieb, J. Appl. Phys. **31**, 172S (1960).

[4] R. Denton, J. Appl. Phys. **32**, 300S (1961).

[5] R. L. Walker, Phys. Rev. **105**, 390 (1957).

[6] H. Heffner and G. Wade, J. Appl. Phys. **29**, 1321 (1958).

The $1/f$ Noise on Surface-Doped Germanium Filaments

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IT is well known that the $1/f$ noise generated in a germanium filament can be varied by varying the surface potential of the filament. These surface potential variations are usually produced by varying the ambient conditions[1] or by the use of a field effect technique,[2] with the actual value of the *average* surface potential being inferred from a conductivity measurement. However, by heavily doping the surface of a germanium filament, it is possible to clamp the surface potential at a value determined by the doping level, and thus achieve an "effective" surface which is isolated from ambient conditions.[3] A series of experiments have been conducted on such surface-doped germanium filaments including measurements of the frequency spectrum, noise correlation, and sensitivity of the $1/f$ noise level to the electric field strength, temperature, and magnetic field.[4] The results of some of these experiments will be reported below.

The filaments were constructed from 10 Ω-cm n-type or 15 Ω-cm p-type germanium. The surfaces were doped by evaporating and alloying thin layers of gallium-gold (source: $2\frac{1}{2}\%$ gallium-$97\frac{1}{2}\%$ gold wire) or antimony-gold (source: 0.6% antimony-99.4% gold wire) onto the filament. (See Fig. 1.) The thickness of the evaporated layers was between 200 and 1000 A, this being thin enough to keep the electrical resistance of the filaments approximately constant. As is customary, the filaments were driven by a current source and separate side contacts were used for the noise voltage measurements.

The frequency spectrum of the noise observed on three separate n-type filaments is shown in Fig. 2. The $1/f$ noise is observed to

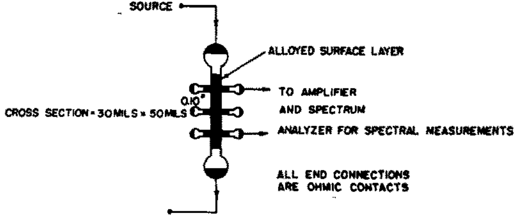

FIG. 1. Schematic representation of a typical germanium filament used in the experiments.