alternate λ/2 layers of CdS and SiO were deposited onto one end of several Al_2O_3 single-crystal rods. After the deposition of each layer the conversion efficiencies of the transducers were measured at room temperature and compared to that of a single layer.[3] A gain of 6 dB was achieved by using two λ/2 CdS layers separated by a λ/2 passive layer of SiO. When three active CdS λ/2 layers separated by alternate passive SiO λ/2 layers were deposited, a gain of 9.5 dB over a single CdS layer was achieved. Thus indeed the conversion efficiency is proportional to the square of the number of active layers, though this variation cannot continue to hold for a larger number of layers.

It is interesting to note that X-cut quartz of the same dimensions as the Al_2O_3 rod in the same cavity using identical transmitter power exhibited a conversion loss 19.5 dB greater per transduction than that of the 3 active layer CdS transducer, after correcting for acoustic losses in the quartz and Al_2O_3 delay lines.

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[1] Sponsored in part by the Air Force Cambridge Research Laboratories, Office of Aerospace Research, under Contract No. AF 19(628)-4372.

[2] J. de Klerk and E. F. Kelly, *Rev. Sci. Instruments* **36**, 506 (1965).

[3] J. de Klerk and E. F. Kelly, *Appl. Phys. Letters* **5**, 2 (1964).

FREQUENCY SELECTIVE COUPLING TO THE FM LASER[1]

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(single frequency power output; T/E)

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The purpose of this Letter is to note that if one of the end mirrors of an FM laser[2,3] is replaced with a frequency selective transmission etalon, then the *total power* which is obtainable from the FM laser may alternately be obtained as a single optical frequency. The method described herein provides an alternative to the supermode technique of Massey et al.,[4] and may make it possible to obtain high single-frequency optical power levels from wide inhomogeneously broadened atomic lines.

Theoretical[5] and experimental[6] investigation of the FM laser has shown that if the intracavity phase perturbation δ is made sufficiently large as compared to the atomic gains and cavity losses of the various laser modes, then these modes will have relative amplitudes given by $J_n(\Gamma)$, with the modulation depth Γ dependent on δ and on the difference between the axial-mode interval and the drive frequency of the phase perturbation. It has also been shown[5,6] that for such large δ conditions, the FM oscillation saturates as an entity. If the gain or loss of any of the modes are changed, Bessel function relative amplitudes will still be very nearly maintained, and the oscillation level will adjust such that the net average power absorbed or dissipated by all modes remains zero. The method described herein is based on the fact that there is an optimum output coupling (mirror transmission) which allows the maximum power to be taken from the FM laser—and that whether this coupling is provided as a sum of equal increments to all modes, or instead is provided entirely to one mode, is not of significance.

Following the notation of Harris and McDuff,[5] we take the single-pass power loss of the nth mode α_n to be the sum of a dissipative loss α_{nd} and an output coupling loss α_{nc}; i.e., $\alpha_n = \alpha_{nd} + \alpha_{nc}$. The average power coupled out from the nth mode is then $P_n = (c/2L)\ \alpha_{nc} E_n^2$, where E_n is the mode amplitude and L is the length of the laser cavity. We assume completely inhomogeneous saturation such that the single-pass power gain of the nth mode is given by $g_n(1 - \beta E_n^2)$ where g_n is its unsaturated gain and β is a saturation parameter which is the same for all modes. Using Eq. (49) of Harris and McDuff,[5] the power coupled out of the n^{th} mode is given by

$$P_n = \frac{c}{2L}\frac{\alpha_{nc}}{\beta} J_n^{\,2}(\Gamma)\,\frac{\sum_m (g_m - \alpha_{md} - \alpha_{mc})\, J_m^{\,2}(\Gamma)}{\sum_m g_m J_m^{\,4}(\Gamma)}\,, \qquad (1)$$

where δ is assumed sufficiently large that Bessel function relative amplitudes are maintained.

Assume that a frequency selective transmission etalon is employed as the end mirror of an FM laser, and is adjusted such that the q^{th} mode is the only mode which has a finite (nonzero) output coupling. Setting $dP_q/d\alpha_{qc} = 0$, we find that the power output of the q^{th} mode will be maximized when the coupling loss to the q^{th} mode α_{qc} is given by

$$\underset{\text{optimum}}{\alpha_{qc}} = \frac{1}{2J_q^{\,2}(\Gamma)} \sum_m \,(g_m - \alpha_{md})\, J_m^{\,2}(\Gamma)\;. \qquad (2)$$

For this choice of output coupling, the power output of the selected mode is then

$$\underset{\text{maximum}}{P_q} = \frac{c}{8L\beta}\,\frac{[\sum_m (g_m - \alpha_{md})\, J_m^{\,2}(\Gamma)]^2}{\sum_m g_m J_m^{\,4}(\Gamma)}\,. \qquad (3)$$

Consider next the more typical case where a transmission etalon is not employed and all modes have the same coupling loss $\alpha_{nc} = \alpha_c$. The total power output is then the sum of the power out of all modes and from Eq. (1) is given by

$$P = \frac{c}{2L}\frac{\alpha_c}{\beta}\,\frac{\sum_m (g_m - \alpha_{md}) J_m^{\,2}(\Gamma) - \alpha_c}{\sum_m g_m J_m^{\,4}(\Gamma)}\,,$$

This is readily shown to be maximized when

$$\alpha_c = \frac{1}{2}\sum_m (g_m - \alpha_{md}) J_m^{\,2}(\Gamma)\ , \qquad (5)$$

and for this choice of output coupling, is exactly equal to the maximum power which can be obtained at a single frequency, as given by Eq. (3).

Comparing Eqs. (2) and (5), it is seen that if it is desired to extract the entire power output as a single frequency from the q^{th} mode, the ratio of necessary coupling to that mode, as compared to the coupling which should optimumly be seen by all modes, is $1/J_q^{\,2}(\Gamma)$.

Experimentally, FM laser oscillation was obtained by using a KDP intracavity phase perturbation in a Spectra-Physics Model 116 He–Ne laser operating at 6328 Å with an axial-mode interval of 100 Mc. One end mirror of the laser was replaced with a Fabry-Perot etalon[7] having a free spectral range of 2.1 Gc and a resolution of about 30 Mc. A piezoelectric crystal was attached to the outer mirror of the etalon and saw-toothed voltage applied such that the etalon was scanned over its free spectral range. Laser mode amplitudes were displayed on an oscilloscope whose horizontal sweep was driven synchronously with the etalon. It was assumed that as the etalon was swept past each of the laser modes, then at some point optimum output coupling would be provided to that mode, and that therefore peak amplitudes on the oscilloscope were to represent the maximum power which could be obtained from a particular mode.

With the laser gain adjusted such that nine modes were free running, it was found that peak mode intensities with power applied to the intracavity phase perturbation were about eight times as great as those obtained with power absent. Of particular interest, it was found that large enhancements in single-mode power were obtained at perturbation strengths which were considerably smaller than had been expected. To obtain a low distortion FM oscillation for a situation with nine modes free-running requires a δ of at least 0.02 rad.[5,6] It was found, however, that at δ's as small as 0.004 rad nearly full power could still be obtained in a single mode. At such small δ's, it is likely that the laser was operating in an unquenched manner, i.e., more than one axial mode was acting as a carrier,[5] and that thus what appeared to be a single frequency may instead have been a number of frequency components spaced by the difference in frequency between the driving frequency of the phase perturbation and the axial-mode interval (approximately 250 kc). Enhancements of single frequency output power were also obtained in the on-frequency or phase-locked region of operation,[5,6] but were somewhat smaller than those obtained in the FM region. Due to the presence of the KDP crystal in the laser cavity, the output power in the present experiment was only about 0.5 mW.

The experimental evidence and also the results of early numerical analysis[8] indicate that the derivation presented herein is too restrictive and that the method should work with a variety of conditions of detuning and perturbation strength. We also expect that similar power enhancements could be obtained by means of a sufficiently large AM-type perturbation such as that of Hargrove et al.[9]

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R. Targ for interesting discussions.

Note added in proof: We have recently learned that this technique has been proposed by C. F. Buhrer at G. T. & E. Laboratories, and also by Don G. Peterson and Amnon Yariv in a Lockheed Technical Brief, April 1965.

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[3] S. E. Harris and O. P. McDuff, *Appl. Phys. Letters* **5**, 205 (1964).

[4] G. A. Massey, M. K. Oshman, and R. Targ, *Appl. Phys. Letters* **6**, 10 (1965).

[5] S. E. Harris and O. P. McDuff, "Theory of FM Laser Oscillation," (to be published, *IEEE Journal of Quantum Electronics).*

[6] E. O. Ammann, B. J. McMurtry, and M. K. Oshman, "Detailed Experiments on Helium-Neon FM Lasers," (to be published, *IEEE Journal of Quantum Electronics).*

[7] We note that an etalon output coupler has also been used in an experiment demonstrating electro-optic frequency translation. D. G. Peterson and A. Yariv, *Appl. Phys. Letters* **5**, 184 (1964).

[8] Private communication with L. Osterink.

[9] L. E. Hargrove, R. L. Fork, and M. A. Pollack, *Appl. Phys. Letters* **5**, 4 (1964).

DIRECT MEASUREMENT OF THE DEPLETION LAYER WIDTH VARIATION VS APPLIED BIAS FOR A *P-N* JUNCTION[1]

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(scanning electron microscopy; MOS devices; Si-Al; E)

Using the scanning electron microscope, the width of the depletion region of a reverse-biased silicon N^+-P junction was measured as a function of the applied voltage. It was observed that as the reverse bias across the junction is increased, dynamical broadening of the depletion layer occurs in both the voltage-contrast and the electron-beam-induced current (EBIC) modes of operation.[2] In the voltage-contrast mode of operation, a primary electron beam approximately 0.1 μ in diam is scanned in a raster pattern over the sample, and secondary electrons produced by this beam are collected. The resulting video signal modulates the intensity of a synchronously scanned cathode-ray tube (CRT). The relative intensity of different areas on the CRT display have been shown to be a measure of the potential on the sample surface corresponding to those areas. In the EBIC mode of operation, the video signal is proportional to the currents generated in the device by the electron beam.[3] In the experiments reported here, the beam energy V_0 was 18 kV, the beam current I_0 was approximately 0.5 nA, and the maximum EBIC was approximately 2 μA.

The width of a depletion region of a one-dimensional abrupt planar N^+-P junction is related to the applied voltage by the following well-known equation,

$$w = \left[\frac{2\epsilon}{qN_a}(V_a + V_d)\right]^{1/2}, \tag{1}$$

where w is the depletion region width, ϵ is the dielectric constant of the semiconductor, N_a is the acceptor concentration on the high-resistivity side of the junction, V_a is the applied voltage, V_d is the diffusion voltage, and q is the electronic charge. If the junction position is known, and if the depletion region boundaries can be detected with an accuracy of 1 μ or better, depletion-region widening should be observable for acceptor atom concentrations in silicon of approximately 10^{15} atoms/cm^3, or less.

A lapped metal-oxide-semiconductor field-effect transistor (MOSFET), shown schematically in Fig. 1, was used in the measurements described below. A phosphorus diffusion into a high-resistivity (350 Ω-cm) P-type silicon substrate was used to form the passivated N^+-P junction. The specimen was then lapped at an angle of approximately 25° with the device surface in order to expose the junction region. A thin layer of aluminum was evaporated onto the N^+-diffused region, and a gold lead was bonded to this aluminum. The bottom of the device was gold-bonded to a transistor header, forming the electrical contact to the high-resistivity P-type material.