At room temperature a 1.3% Nd:YAG crystal had a pulsed threshold of 1.0 J and cw thresholds of 730 W with the tungsten lamp and 1300 W with the Hg lamp. For double-doped crystals with 1% Cr^{3+} and 1.3% Nd^{3+} the 300°K thresholds were 2.1 J pulsed and more than 800 W for tungsten excitation, but only 750 W for Hg excitation. The 77°K cw thresholds for the doubly doped crystal were 440 W using tungsten and 180 W using Hg.[6]

The effectiveness of the cross-pumping is indicated by the ratio of Hg-excited cw threshold to tungsten-excited cw threshold for the two systems. This ratio increases by more than a factor of four in going from the Nd^{3+}:YAG where the strongest absorption is in the ir (Fig. 2*a*) to the Nd^{3+}:Cr^{3+}:YAG where the Hg lamp pumps strongly in the Cr^{3+} bands (Fig. 2*b*). In absolute terms the cross-pumping resulted in a reduction from 1300 to 750 W in the Hg-excited cw threshold despite increases in the pulsed and tungsten-excited cw thresholds, neither of which should be strongly influenced by the double doping. These higher thresholds are thought to be caused by less than ideal crystal quality of these early doubly doped crystals. Thus corrected for the factor of two pulsed threshold difference, the Hg-excited threshold decreased by a factor of 3.6, in good agreement with the predicted factor of four.

In conclusion, a cross-pumped laser in a doubly doped system, Nd^{3+}:Cr^{3+}:YAG, has been demonstrated. With the attainment of equal crystal qualities for the singly and doubly doped Nd^{3+}:YAG systems the cross-pumping should increase the overall efficiency by at least a factor of two. Since the improvement should be even greater for broad-band high-temperature exciting sources, this laser system is an extremely attractive one for sun-pumping.

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FM OSCILLATION OF THE He-Ne LASER[1]

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(internal phase perturbation; interferometry; KDP crystal; E)

We report the operation of a He-Ne laser in a manner such that all of the laser modes oscillate with FM phases and nearly Bessel function amplitudes, thereby comprising the sidebands of a frequency-modulated signal. The resulting laser oscillation frequency is, in effect, swept over the entire Doppler line-width at a sweep frequency which is approximately that of the axial mode spacing. This type of FM oscillation is induced by an intra-cavity phase perturbation which is driven at a frequency which is approximately but not exactly the axial mode spacing. Experimental evidence supporting the hypothesis of an essentially pure FM oscillation is as follows:

1. The suppression of all observable laser "beat notes" by at least 25 dB, as compared to their value in the absence of the phase perturbation. A 5%

increase in laser power was observed coincident with this suppression.

2. The observation of a scanning interferometer showing the laser modes to possess approximately Bessel function amplitudes, appropriate to the spectral components of a pure FM signal.

3. Direct demodulation of the resultant FM signal using both a Michelson interferometer and a birefringent discriminator.[2]

The laser was a Spectra-Physics Model 116 operated at 6328 Å, with an external mirror spacing corresponding to an axial mode interval ($c/2L$) of 100.5 Mc/sec. The phase perturbation was obtained via the electro-optic effect in a 1-cm long KH_2PO_4 (KDP) crystal which was anti-reflection coated and situated in a 100-Mc/sec tuned circuit inside the laser cavity. The KDP crystal was oriented with its optic axis parallel to the axis of the laser tube, and with one of its electrically-induced principal axes parallel to the direction of the laser polarization. A KDP crystal in this orientation introduces a pure phase perturbation and ideally should introduce no time-varying loss into the laser cavity. An rf input power of 2 W produced a single-pass phase retardation δ of about 0.06 rad at the optical frequency.

Of particular interest was that FM laser oscillation was not obtained when the KDP modulator was tuned exactly to the frequency of the axial mode spacing. In this case, the laser beat notes as observed on an rf spectrum analyzer were stabilized and enhanced, and appeared similar to those described by Hargrove and others,[3] and DiDomenico[4] in their papers on AM phase locking.

When the modulation frequency is detuned from the $c/2L$ frequency, then at a δ of 0.05, a frequency change of 250 kc/sec to either side produces an abrupt quenching of all of the original laser beat notes, with a coincident increase of 5% in the total laser oscillation power. This removes the possibility that the quenching of the axial mode beats is caused by some form of increased optical loss. After quenching of the original axial beat notes, a small amount of rf beat power may be observed at harmonics of the modulation frequency. At the second and third harmonics, this power level was 25 dB below that of the original beat amplitude. At the fundamental and fourth harmonics, this level was at least 15 dB below that of the original signal. Measurements at the latter two frequencies were limited by a residual AM light signal and poor photomultiplier sensitivity, respectively.

In order to directly verify the presence of an FM signal, the output of the FM laser was passed through an optical discriminator (Michelson interferometer) with a path length difference of 30 cm. The interferometer was followed by a photomultiplier and rf detector. With both arms of the interferometer open, a strong signal at the modulation frequency was observed with a 15-dB signal-to-noise ratio. If either arm of the interferometer was blocked, this signal completely disappeared.

The most interesting and perhaps startling results of our experiments were obtained by direct observation of the laser mode amplitudes with a Spectra-Physics scanning interferometer. In the absence of modulation, the laser modes appear as in Fig. 1*a*. As the modulation depth is increased, the central mode amplitude begins to fall, and the first pair of sidebands increase. At still larger δ's, the second and third pair of sidebands achieve significant amplitudes, and there is a diffusion of power toward the wings of the Doppler line. Examination shows the modes to have approximately Bessel function amplitudes, which are not determined by independent saturation of the Doppler line, as might have been expected. Figures 1*a* through 1*f* are captioned in terms of both the depth of the single-pass modulation δ, and also in terms of the depth of the frequency modulation on the output signal of the FM oscillator. This latter modulation depth is denoted by Γ, and from the "varying frequency" viewpoint of frequency modulation, it is the ratio of the peak frequency deviation to the modulation frequency. The ratio of Γ/δ, that is, the ratio by which the modulation process is enhanced by the presence of the cavity and active media, is ~ 40. Alternate measurements of Γ were made using the Michelson interferometer, and similar results were obtained. Our highest measured Γ was ~ 6, which at a modulation frequency of 100 Mc/sec corresponds to a peak-to-peak frequency swing of 1200 Mc/sec.

The process appears to be a regenerative parametric oscillation, with a resultant quenching of the original laser modes; as opposed to a phase locking process which has been considered by Hargrove and others,[3] and DiDomenico.[4] FM lasers may make possible many spectroscopic and communication applications which otherwise would have required single-mode lasers, with their correspondingly lower power.

To our knowledge, this type of FM laser was first

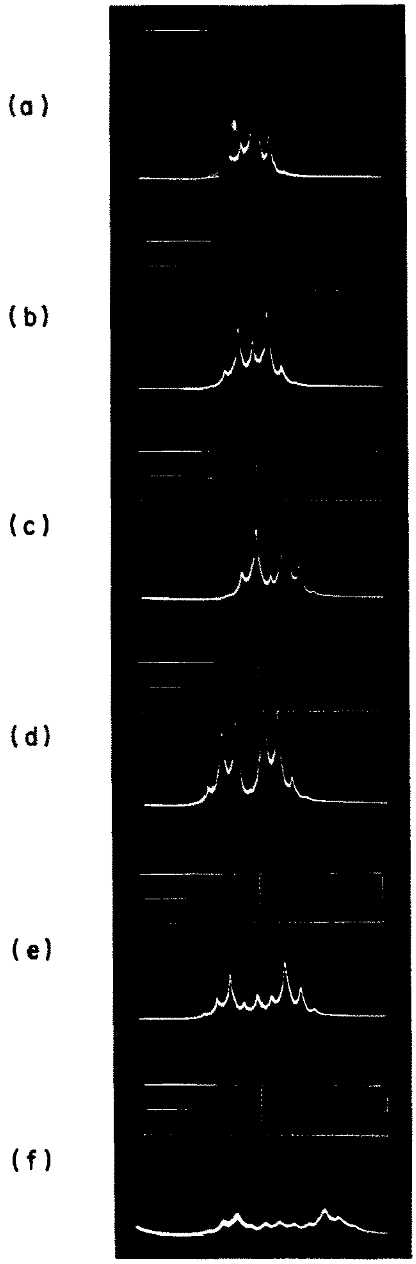

Fig. 1 Laser mode amplitudes versus optical frequency for variable modulation depth.

(*a*) $\delta = 0$ $\Gamma = 0$
(*b*) $\delta = .045$ $\Gamma \sim 2$
(*c*) $\delta = .063$ $\Gamma \sim 2.6$
(*d*) $\delta = .069$ $\Gamma \sim 2.8$
(*e*) $\delta = .072$ $\Gamma \sim 3$
(*f*) $\delta = .088$ $\Gamma \sim 4.5$

proposed by Harris in October 1963 at Stanford University under Contract AF 33(657)-11144. The problem of phase perturbations in a passive resonant cavity has been considered analytically by Gordon and Rigden.[5] The effect of phase perturbations in an active cavity has been studied by Yariv.[6,7] We greatly appreciate the encouragement and support provided by B. J. McMurtry of Sylvania and A. E. Siegman of Stanford. We acknowledge the expert technical assistance of L. E. Wilson, and thank Spectra-Physics for lending us the scanning Fabry-Perot interferometer used in these experiments.

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