

cavity. The four mirrors are arranged to form a Z-shaped internal beam. The parallel sides of the Z are collimated beams, the upper one a few millimeters in diameter and the lower one several centimeters. The sloping side of the Z contains a focus near the narrow beam. A two-meter He-Ne laser tube with polarizing Brewster angle windows is located in the thin upper beam, and the optical delay line is located in the wide lower beam. An aluminized mirror having an aperture is placed at the focus in the sloping side so that the laser beam passes through the aperture. A pulse applied to the piezoelectric transducer bonded to the delay line causes a thin shear pulse to propagate down the line. The shear pulse produces a localized birefringence which causes part of the plane-polarized light passing through it to emerge polarized in the orthogonal direction. Since this component is narrow, it expands by diffraction and cannot pass through the aperture in the aluminized mirror. Instead, it is reflected out of the cavity and can be projected through a lens system, which images the moving pulse on a screen. Thus, a single scan line is produced on the screen as one shear pulse moves across the laser beam. A repetitive linear scan can be produced by a sequence of these pulses.

Because the delay line is inside the cavity, intense light passes through it in both directions. It is therefore desirable for the projection system to form a focused image on the screen of both the delay line and its virtual image in the mirror which terminates the enlarged collimated beam. For this to be possible, the delay line must be close to that mirror, and this is most easily accomplished by having a multiple layer dielectric coating deposited directly on the delay line.

Since quartz has a shear wave propagation velocity of approximately 3840 m/s, a 30 Mc/s delay line can propagate pulses 0.13 mm wide. A beam 100 mm in diameter would have 770 resolvable spot locations.

This system has been operated using a 10 Mc/s Corning delay line in a one-inch collimated beam.

Oscillograms of the scanning beam sweeping past a photomultiplier slit show the scanning beam to be a doublet. This occurs because shear waves are produced by the rising and falling edges of the applied pulse. The number of resolvable spot positions was about 15. The peak power in the scanning beam was 4 mW. The circulating energy observed through one of the laser mirrors with a photodetector was observed to dip as the shear pulse went through the internal beam extracting energy.

The speed and linearity of the swept beam obtained from this system make it very attractive for use as the horizontal scanner in a TV display. In this application, cylindrical optics would be used to collapse the moving line of light to form a scanning spot, which could be scanned in the vertical direction by some external scanning device, such as an electrooptic¹ or vibrating mirror² deflector.

¹ V. J. Fowler, C. Buhner, and L. Bloom, "Electro-optic light beam deflector," *Proc. IEEE (Correspondence)*, vol. 52, pp. 193-194, February 1964.

² J. Schlafer, and V. Fowler, "A precision high speed optical beam steerer," presented at the 1965 Electron Devices Meeting, Washington, D. C.

5C-6 Nonlinear Theory of the Internally Loss Modulated Laser,¹ O. P. McDuff and S. E. Harris, *Microwave Laboratory, Stanford University, Stanford, Calif.*

Various authors have considered internal modulation of a laser by means of linearized approximate equations.²⁻⁶ This paper presents the results of a nonlinear analysis of internal loss modulation and points out the departure of the actual solution from the linearized ones.

Summary of Results: Contributions of this paper include: 1) the determination of the obtainable peak spike amplitudes and minimum spike width for a given atomic line as a function of the drive strength of the internal perturbing element; 2) the calculation of the minimum drive strength (threshold) necessary to the obtaining of locking for a given atomic line; 3) a comparison of spike amplitudes and threshold conditions of AM vs. FM-type phase locking; 4) consideration of the case where the modulation frequency is not exactly equal to the mode spacing frequency. In particular, it is found that the hyperbolic Bessel function solution obtained earlier by Yariv² is not a correct solution for the true nonlinear problem.

Discussion: Previous authors^{3,5} assume equal mode amplitudes and equal relative phases for the on-frequency case, i. e., modulator frequency equal to cavity mode spacing. Hyperbolic Bessel functions were obtained for the off-frequency case.² We find that at low modulation levels, the mode amplitudes are approximately the free-running values and that there is extreme departure of the phase angles from the ideal values. The resulting time variation of laser intensity is not a simple spiking but instead each spike has sidelobes of the same order of magnitude. At high modulation, the angles are approximately equal and the relative mode amplitudes become Gaussian, giving a spike which is also Gaussian-shaped. In disagreement with the linear approximation,⁵ the average power level is dependent upon modulator drive. As the drive is increased, the spike width can be reduced by about half before extinguishing the laser and the peak value can be increased about 50 percent. The off-frequency solution is correctly described as a perturbation of the on-frequency solution. The hyperbolic Bessel functions produce a spike which would pass through the modulator at an unfavorable instant of time.

A spiking output can be obtained from a laser having gain in a single mode. We find that a peak intensity three times the value for the single free-running mode is obtainable. The corresponding spike width is

¹ This work was supported by AF 33(657)-11144. O. P. McDuff was supported in part by a National Science Foundation Science Faculty Fellowship.

² A. Yariv, "Internal modulation in multimode laser oscillations," *J. Appl. Phys.*, vol. 36, pp. 388-391, February 1965.

³ M. DiDomenico, Jr., "Small-signal analysis of internal (coupling type) modulation of lasers," *J. Appl. Phys.*, vol. 35, pp. 2870-2876, October 1964.

⁴ S. E. Harris and O. P. McDuff, "FM laser oscillation-theory," *Appl. Phys. Lett.*, vol. 5, pp. 205-206, November 1964.

⁵ M. H. Crowell, "Characteristics of mode-coupled lasers," *IEEE Journal of Quantum Electronics*, vol. QE-1, pp. 12-20, April 1965.

⁶ S. E. Harris and O. P. McDuff, "Theory of FM Laser Oscillation," *IEEE Journal of Quantum Electronics*, vol. QE-1, pp. 245-262, September 1965.

about 20 percent of the period of the modulator drive. The spike width can be made smaller with an accompanying reduction in power.

In the multimode laser, the spike height at optimum conditions is about 20 percent lower than with FM-type phase-locking. Another important difference is that FM-type phase-locking of the single-mode laser does not produce spiking.

Assuming inhomogeneous broadening, the mode-pulling of the atomic medium sets a threshold upon phase-locking. One interpretation is that the loss perturbation has to pull the modes to the proper multiple of the modulator frequency and thereby overcome the effects of the atomic medium which vary from mode to mode. The limiting case occurs when the resulting angles depart $\pm 90^\circ$ from the ideal equal-angle situation. One is able to predict a minimum modulator loss and optimum drive frequency that will phase-lock the laser. The predicted multiple spikes at this threshold may explain the previously experimentally observed multiple spikes.⁶

The calculated threshold is lowest when the center mode is exactly at the atomic line center. There is an increase of about 2 when it moves off center and a variation of about 2 to 1 as an edge mode comes above free-running threshold. If the other parameters are held constant, the threshold varies inversely as the cavity mode interval. Similarly, if only cavity loss is varied, the required modulator drive varies approximately as the square of excess gain. A normalized curve of modulator loss at threshold has been obtained which includes loss values over a range of about 10^4 for a variety of laser parameters.

5C-7 A High-Power Single-Frequency He-Ne Laser,¹ R. Targ and B. J. McMurtry, *Electronic Defense Laboratories, Sylvania Electronic Systems—West, Mountain View, Calif.*

Harris and McMurtry² recently proposed and demonstrated a new technique for obtaining single-frequency output from a laser which normally oscillates in a number of axial modes. This technique involves the use of a Fabry-Perot etalon as the output coupler for an FM or phase-locked laser. By tuning the pass band of the coupler to one of the laser sidebands or oscillations, one can obtain at a single frequency essentially all the power that could be obtained from the same laser operated multimode. This paper reports detailed experiments on a high-power He-Ne laser using this technique. A Spectra-Physics Model 125 laser, which normally produces 50-80 mW in a number of axial modes, has been modified to permit its operation as a phase-locked or FM laser and with a frequency selective output coupler to produce a single-frequency output at high power. An automatic power level control system has been constructed to guarantee that the etalon remains tuned to the proper laser oscillation even though

¹ This work has been supported by the Research and Technology Division of the U. S. Air Force at Wright-Patterson AFB, Ohio, under Contract AF 33(615)-2884.

² S. E. Harris and B. J. McMurtry, "Frequency selective coupling to the FM laser," *Applied Physics Lett.*, vol. 7, pp. 265-267, November 15, 1965.