filter. In a ring laser, the mode locked pulses must be timed symmetrically in respect to the active media so that the gain which is depleted by the passage of the pulses is built up to the same value for the clockwise and counter-clockwise circulating pulses.[2] The symmetrically timed pulses cross over at the "natural crossings" which are one fourth ring perimeter from the active media.

In the laser array in Fig. 1 (a), the mode locked pulses cross over at the plane mirrors. A single loss modulator at one of the plane mirrors can phase lock the longitudinal modes of all the laser oscillators in the array. The buildup of the mode locked pulses coincides with the time of the smallest loss in the optical cavity.[3] Using an acoustooptic modulator the buildup time coincides with the minimum in the envelope of the acoustic wave. But the phase changes of the acoustic wave are slow in comparison to the time duration of the mode locked pulses.

The spatial filter can perform the precise synchronization of the counter circulating mode locked pulses. In the frequency domain where the pulses are represented by the sum of harmonic frequencies $(q + m)\nu$, $m = 0, 1, \ldots n$, whose phase angles $\theta q + m$ are in arithmetic progression, the term $(\theta q + m)/(2\pi(q + m)\nu)$ corresponds to the time shift of the pulses. To synchronize the mode locked pulses of the laser oscillator array, the phase angles of their longitudinal modes must be made the same. The spatial filter which exerts a control on the phase angles of the longitudinal modes to be the same at the spatial filter, can synchronize the mode locked pulses from the four laser oscillators to be in time coincidence at the spatial filter.

In summary, the study shows that the method of spatially coherent beam formation can be extended to an array of four Nd:glass lasers. Since most of the radiation can be concentrated in a diffraction limited beam, an increase in radiance close to 16 times the radiance from a single laser should be obtainable. A single modulator can phase lock the longitudinal modes of the laser oscillator array, and the mode locked pulses can be precisely synchronized by the spatial filter.

[2] N. Buholz and M. Chodorow, *J. Quantum Electron.*, vol. QE-3, p. 454, 1967.

[3] J. B. Gunn, *J. Quantum Electron.*, vol. QE-5, p. 513, 1969.

Fig. 1. (b) Spatial filter reproducing interference function.

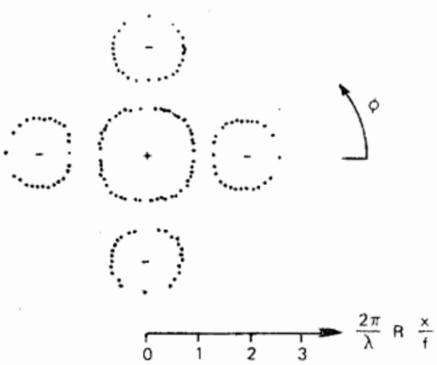
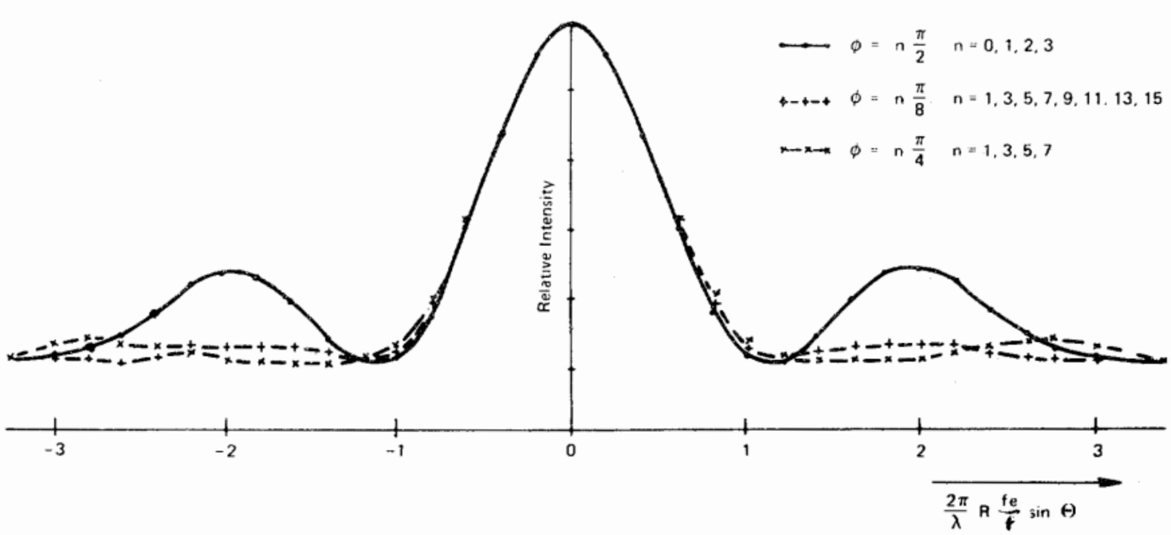


Fig. 1. (c) Far-field distribution when restored by external lens (f_e).



14.7 Unidirectional Travelling Wave Operation of a Mode-Locked Nd:Glass Ring Laser, R. Fedosejevs, I. V. Tomov and M. C. Richardson, *National Research Council of Canada, Division of Physics, Ottawa, Canada* (*15* min)

Although mode-locked Nd:glass lasers have been in existence for many years, they still display the undesirable features of pulse irreproducibility and lack of synchronizability. Recently, we have reported a system for highly stable, synchronizable picosecond pulse generation in a mode-locked Nd:glass ring laser.[1] We have recently extended our investigations to methods for the production of unidirectional travelling waves in these lasers in order to improve stability and coherence. To facilitate these studies a general computer model simulating the pulse development in the laser was used to determine the necessary conditions to obtain unidirectional travelling wave operation.

[1] I. V. Tomov, R. Fedosejevs, M. C. Richardson and W. J. Orr, *Appl. Phys. Lett.*, vol. 29, p. 193, 1976.

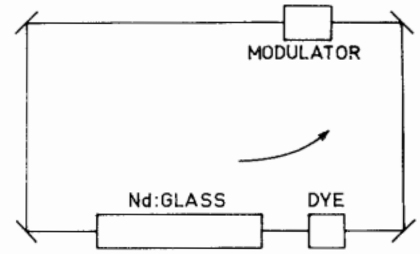


Fig. 1. Mode-locked ring laser.

Normally, in a mode-locked ring laser, two counter-propagating pulses exist in the resonator, coinciding at the mode-locking element. Due to various loss elements the amplitudes of these pulses change as they traverse the cavity, being maximum at the exit and minimum at the entrance of the laser rod. By positioning a saturable filter at one end of the laser rod, as shown in Fig. 1, where one pulse is at its maximum and the other at its minimum, different losses are experienced by the two pulses and over a number of round trips one pulse outgrows the other.

The first scheme investigated uses an electro-optic modulator and saturable dye cell as shown in Fig. 1. When the cavity is Q-switched, the modulator produces a train of pulses each of 200 ps duration which, under suitable operating conditions are shortened to 15 ps by the saturable dye cell. The dye cell, positioned where the counterclockwise pulse is at a maximum, saturates earlier for the counterclockwise (CCW) pulse than for the clockwise (CW) pulse. Thus the CCW pulse, experiencing less loss per round trip, grows more quickly, depleting the gain in the rod and suppressing the CW pulse. Experimental measurements using a dye with a small signal transmission of 75% show that a discrimination ratio of better than two orders of magnitude can be achieved between the counter-propagating pulses.

A similar system uses a strong saturable dye cell as the mode-locking element and a weaker dye cell postioned as above to obtain unidirectional travelling wave operation. Experimental observations confirm that if the difference in small signal transmission of the two dye cells is $\geqslant 10\%$, a stable mode-locking regime exists with unidirectional travelling wave operation.

A third scheme includes two active modulators in the cavity at different positions and phased correctly to prefer one direction of propagation. To obtain travelling wave operation the depth of modulation in the second modulator need only be a fraction of that in the main modulator.

Numerical simulations and experimental investigations of these methods of mode-locking will be presented, detailing the dependence of the unidirectional picosecond pulse buildup on the primary resonator parameters.

14.8 Increasing the Beam Quality and the Efficiency of a Glass Laser by Using Circular Polarization, Phosphate Glass and Double-Pass Amplifiers,[1] D. Auric, C. Charles and C. Dalmayrac, *Laboratoires de Marcoussis, Centre de Recherches de la C.G.E., Marcoussis France*

(*15* min)

The output power density of a high power glass laser is proportional to $B\alpha/n_2$, where α is the gain coefficient of the amplifier, n_2 the nonlinear index of the laser glass and B the beam break-up integral. It has been shown[2] that B should be limited to a fixed value ($B \simeq 3$ or 4).

To increase the output power we can increase α/n_2 by using phosphate glass and circularly polarized light.[3] To increase the extraction efficiency we can double pass the rod amplifiers of the laser system. We have proven experimentally that the equivalent n_2 value for a circular polarized laser beam is related to the usual n_2 for linear polarization by the relation n_2 (circular) $= n_2/1.3$. Using phosphate glass allows a further reduction of n_2 by a factor of 1.25 and a potential increase of α by a factor of 1.5 with respect to silicate glass. As a result, an increase in the maximum output power by a factor of 2.4 should be attainable. An experimental set-up was designed to test this possibility.

The oscillator is a passive mode-locked YAG with 2 prisms inside the cavity to force operation on the 1.052 μm laser wavelength. After preamplification and spatial filtering, we use the double pass technique with circular polarization through 3 rods, of 32 mm, 45 mm and 64 mm clear aperture. At the output of the 64 mm rod, a 200 GW, 100 ps, laser pulse with remarkably good optical quality is obtained with only 60 kJ total pumping energy.

Gain characteristics of phosphate glass rod amplifiers are reported and their gain limitation by parasitic oscillation is discussed in regard to their geometric configuration.

The near field and far field characteristics of the beam for the phosphate glass system are discussed versus the beam break-up integral of the system and are compared to previous results obtained with silicate glass and linear polarization.

[1] This work has been supported by Commissariat a l'Energie Atomique, Division des Applications Militaires.

[2] A. Bettinger, presented at the Europhysics Study Conference, Oxford, U. K. Dec. 1975.

[3] D. Auric and A. Labadens, to be published.

14.9 One Gb/s Laser Space Communications (*Invited*), M. Ross, J. D. Wolfe, J. Abernathy, J. P. Carter and E. S. Clarke, *McDonald-Douglas Corp., St. Louis, Mo. 61366*

(*30* min)

No summary.

14.10 Conductively Cooled, Nd:YAG Laser Pumped by a Long Life RF Excited Krypton Arc Lamp,[1] L. J. Rosenkrantz, D. A. Huchital and G. N. Steinberg, *Perkin-Elmer Corp., Norwalk, Conn. 06857*

(*15* min)

Essential requirements for the Nd:YAG laser that will be used to generate mode-locked, frequency-doubled pulses in satellite-borne communications systems include long life, reliability, efficiency and compatibility with conductive cooling. The concept of pumping Nd:YAG with RF excited krypton arc lamps has been under investigation during the past few years[2-4] as a potential pumping technique having inherently high reliability and long operating life due to the absence of electrodes and troublesome glass-to-metal seals. The viability of this approach was recently demonstrated by the successful completion of an essentially degradation-free 1000 hour life test on an RF-excited, krypton pumped 25 watt laser.

The objective of the present program is to extend the concept to a smaller, conductively-cooled device that must operate on a severely restricted input power budget in a spacecraft environment.

Using the configuration shown in Fig. 1, CW multimode output power in excess of 1.5 watts, and incremental slope efficiencies of 1.4% have been observed.

The 4 mm diameter × 25 mm long Nd:YAG laser rod was bonded to the OFHC copper heat sink over 180° of its circumference, and was inserted into one end of a diffusely reflecting pump cavity containing an RF excited krypton arc lamp that could be driven up to 250 watts using a specially-designed high-Q coil. Lasing threshold was observed to be 130 watts of input power, in a resonator consisting of a 0.67% transmission and a highly-reflective coating applied to each of the ends of the rod, which had been polished to a 1 m convex radius of curvature. One watt of output power was achieved with only 200 watts of RF power into the lamp. Using a different laser rod having antireflective-coated flat ends and an external resonator structure, more than 420 mw of CW TEM_{00} mode power was observed at 250 watts input.

The laser rod was cooled to $-15°$ C by the flow of refrigerated ethanol through the copper heat sink. The coolant channel configuration simulates the interface with a passive heat pipe in a spacecraft. Heat was removed from the coil-lamp-diffuse reflector assembly by the flow of 10° C tap water through the lamp heat sink and by a jet of dry nitrogen over the coil. Thermal insulation was used to restrict the flow of heat from the pump cavity to the laser rod heat sink. A number of different heat shields are currently being investigated to reduce laser rod heating caused by pump light that falls within the 2.2–2.6 μm absorption band of the Nd:YAG.

Efforts are also underway to develop techniques for conductively cooling the lamp, which will make the entire package conductively cooled and compatible with current heat pipe technology, as required for spacecraft operation.

Life tests carried out at the 150 watt power level indicate that essentially degradation-free operation can be expected over 2200 hours of operation for an air-cooled lamp that is thermally cycled on a daily schedule. The present life test is continuing with a goal of 10,000 hours.

[1] Research supported by USAF Avionics Lab. under contract F33615-76-C-1281.

[2] D. A. Huchital and G. N. Steinberg, *Proc. IEEE*, vol. 60, p. 233, 1972.

[3] D. A. Huchital and G. N. Steinberg, 1975 IEEE/OSA Conf. Laser Engineering and Applications, paper 14.1.

[4] D. A. Huchital and G. N. Steinberg, 1976 Conf. Laser and Electrooptical Systems, paper WB9.

Fig. 1. Design of conductively cooled, long life Nd:YAG laser.