

# Coherent summation of injection-locked, diode-pumped Nd:YAG ring lasers

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A binary grating has been used to achieve coherent summation of diode-laser-pumped Nd:YAG ring lasers operating at 1.06  $\mu\text{m}$ . Mutual coherence of two such devices was achieved by optical injection locking. This is believed to be the first demonstration of cw injection locking of solid-state lasers other than semiconductor diode lasers. By combining two beams, an efficiency of 75% (92% of the theoretical limit) has been demonstrated in a configuration that could be used to combine a large number of individual lasers.

Coherent summation of laser beams with phase-only transmission gratings has been demonstrated to be an effective technique for increasing the apparent brightness of a number of individual lasers.<sup>1,2</sup> This is important in applications in which the required source radiance (i.e., the power emitted per unit area per unit solid angle) exceeds that which can be achieved given the inherent physical limitations of a single source. In separate experiments, efficient beam combination using binary gratings has been demonstrated with three infrared helium-neon lasers<sup>1</sup> and with six GaAlAs diode lasers.<sup>2</sup> In both cases, the lasers were operated in an external cavity with a common output coupling mirror in order to achieve the required mutual coherence. In this work, beam summation has been demonstrated at 1.06  $\mu\text{m}$  with diode-laser-pumped Nd:YAG ring lasers. Mutual coherence of two lasers was achieved by cw optical injection locking.

The principle of beam summation with phase-only gratings has been detailed in the literature.<sup>1,3,4</sup> To combine  $N$  similar beams efficiently, one must design a grating that divides a single beam into  $N$  central diffraction orders of equal amplitude and with minimal residual energy in higher orders. Each of the beams to be combined must be propagated along one of the grating orders in such a way that the beams are well matched spatially and have the proper relative phase at the grating surface. In this case, the incident energy is efficiently combined in a single outgoing beam. If the incident beams are not mutually coherent, or if they fail to match the phase pattern determined by the grating, the incident energy is distributed in various outgoing directions.

The binary grating used here was developed and supplied by MIT Lincoln Laboratory. A fused-silica substrate was etched to produce a groove spacing of 6  $\mu\text{m}$ , with a phase depth of  $\pi$  and a 50% duty cycle, to provide a theoretical summation efficiency of 81%. Both surfaces of the grating substrate were antireflec-

tion coated in order to obtain near-theoretical performance.

The Nd:YAG lasers were designed for stable, single-frequency operation with immunity to backreflections. Each of the two identical ring cavities consisted of a 5-mm Nd:YAG rod, two high-reflectivity flat mirrors, and a 2%-transmitting output coupler with a 25-cm radius of curvature, arranged in an X configuration. The internal surface of the rod was antireflection coated for 1.06  $\mu\text{m}$ , and the reflecting surface was coated for high reflectivity at 1.06  $\mu\text{m}$  and high transmission at the 0.81- $\mu\text{m}$  pump wavelength. One of the flat mirrors was mounted on a piezoelectric transducer (PZT) to permit continuous tuning of the cavity frequency over the free spectral range (approximately 750 MHz). The cavity, diode pump laser, and pump focusing optics were supported by a four-bar structure and carefully vibration isolated. The pump lasers were Spectra Diode Laboratories SDL-2420 GaAlAs diode-laser arrays. Each pump beam was collimated, partially symmetrized with a 6:1 anamorphic prism pair, and refocused for longitudinal pumping through the dichroic rod face. The pump optics resulted in a throughput loss in excess of 50%. The Nd:YAG rods were centrally mounted in cylindrical magnets to induce some nonreciprocal polarization rotation through the Faraday effect. Without additional intracavity optics, the ring lasers operated unidirectionally with a stable, linear polarization. The specific physical nature of this result remains under investigation. The direction of oscillation was sensitive to cavity alignment, and simultaneous bidirectional oscillation could also be achieved. However, when the cavity was optimally aligned, the direction of oscillation remained stable, and single-frequency operation was maintained as the laser output power was increased from threshold to more than 25 mW.

Cw injection locking has been demonstrated with He-Ne,<sup>5</sup> CO<sub>2</sub>,<sup>6</sup> and Ar-ion (Ref. 7) gas lasers and with

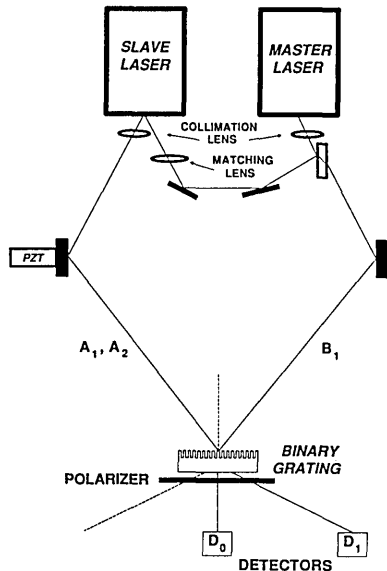


Fig. 1. Schematic of the beam-summation experiment.

GaAlAs diode lasers.<sup>8</sup> Mutual coherence of individual sources can be established by injecting light from a master laser into the oscillating mode of one or more slave lasers so that all the lasers are phase locked at a common oscillation frequency. Optical injection locking requires excellent frequency stability and careful mode matching. The phase lock is maintained as long as the absolute difference between the master and slave frequencies remains within the injection-locking bandwidth  $\Delta f_L$  given by<sup>9</sup>

$$\Delta f_L = \Delta f_c (P_M/P_S)^{1/2}, \quad (1)$$

where  $\Delta f_c$  is the cold-cavity bandwidth of the slave laser,  $P_M$  is the master power injected into the oscillating slave mode, and  $P_S$  is the power emitted by the gain medium of the slave laser into the mode.

Figure 1 shows the experimental arrangement employed here for injection locking and beam summation. A single lens was used to spatially match the injected beam to the lasing mode of the slave oscillator. Feedback from the slave coupled only to the nonlasing circulating mode of the master laser so that the master was effectively isolated from backreflections. In the same way, both lasers were insensitive to light reflected back from down-line optics. The cavity frequency of either laser could be piezoelectrically tuned in order to obtain a locked condition. On injection locking, the slave-laser frequency would generally shift to another longitudinal cavity mode that was favored given the additional injected power. This behavior was observed on a scanning Fabry-Perot interferometer (150-MHz free spectral range; 2-MHz FWHM resolution) that provided a graphic demonstration of injection locking. Figure 2(a) shows the Fabry-Perot output with the cavity frequencies of the two lasers tuned to differ by just more than  $\Delta f_L$ . Two sets of resonances are evident, corresponding to the two single-frequency lasers, although their absolute frequency spacing is many times the interferometer's free spectral range. The figure shows the output of

150 consecutive scans photographed in a 4-sec period. Changing the cavity frequency of either laser by less than 1 MHz resulted in injection locking, so only the master oscillator frequency appears in the Fabry-Perot output [Fig. 2(b)].

Mechanically and thermally induced cavity frequency fluctuations limited the stability of the injection-locking system. Under typical experimental conditions, injection locking was maintained for several seconds with the lasers free running and the power injected into the slave oscillator equal to about 10% of the circulating power there. The calculated bandwidth of the ring cavities was  $\Delta f_c = 3$  MHz, so with perfect mode matching the locking bandwidth could have been as high as  $\Delta f_L = 0.9$  MHz. Periods of injection-locked operation in excess of 10 sec were observed with larger ratios of  $P_M$  to  $P_S$ .

Coherent beam summation was demonstrated in two sets of experiments using the configuration of Fig. 1. First, two beams derived from the master laser were combined to determine the efficiency that could be achieved with perfectly phase-locked beams. Then master and slave beams were combined in unlocked and injection-locked states. In all cases, the path length of one beam was varied with a PZT-controlled tuning mirror in order to change the relative phase of the two beams at the grating. By manually scanning the PZT drive voltage, it was possible to determine the characteristics of the beam summation for comparison with theory. Two detectors ( $D_0$  and  $D_1$  in Fig. 1) were used to monitor the throughput along the primary and secondary transmission orders of the grating. One beam consisted of two mutually incoherent components,  $A_1$  and  $A_2$ . The second beam,  $B_1$ , was derived solely from the master laser and was injection locked to  $A_1$ . A polarizer between the grating and the detectors was used to ensure that only light of a single linear polarization was detected.

Figure 3 shows the results of beam summation with the master laser operating above threshold and the slave laser well below threshold (i.e.,  $A_2 = 0$ ). The master light reflected by the output coupler of the slave laser ( $A_1$ ) was combined with light taken directly from the master ( $B_1$ ). The polarizer was adjusted so that with either beam blocked the power at  $D_0$  was the

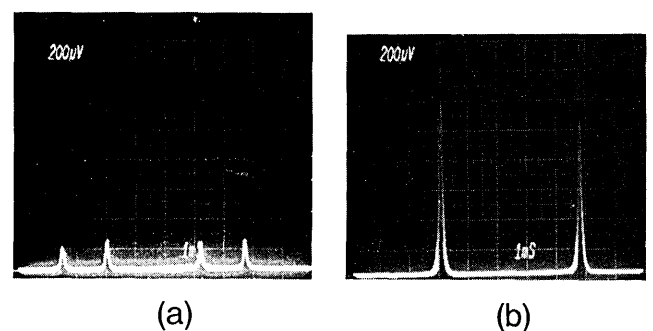


Fig. 2. Transmission of a Fabry-Perot interferometer (150-MHz free spectral range) with master and slave lasers (a) unlocked and (b) injection locked. Photographs show the output of 150 consecutive scans over 4 sec.

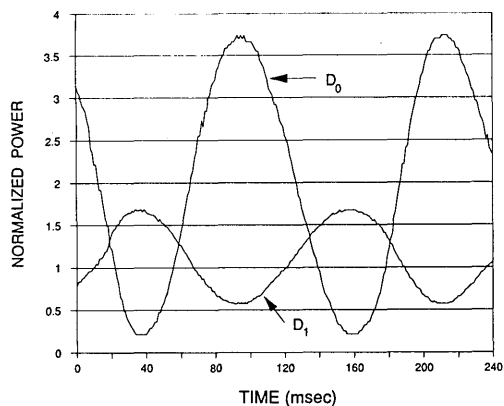


Fig. 3. Summation of two equal-intensity beams derived from a single laser. The powers at detectors  $D_0$  and  $D_1$  are displayed versus time as the phase of one beam was varied. The theoretical limits are 0.0 and 4.0.

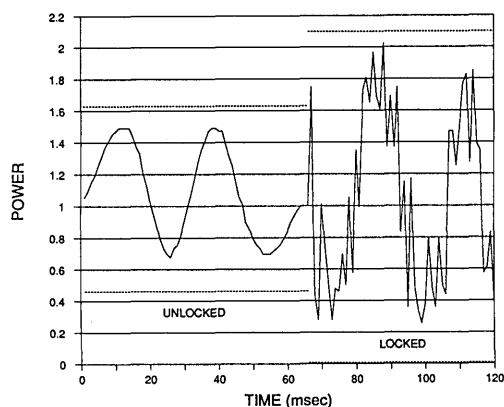


Fig. 4. Summation of the master and slave lasers. The power at detector  $D_0$  is displayed during unlocked (0–65 msec) and injection-locked (65–120 msec) operation. Dashed lines indicate the corresponding theoretical limits.

same ( $A_1 = B_1$ ). With that power equated to unity, the theoretical minima and maxima powers were 0.0 and 4.0 at  $D_0$  and 0.44 and 1.7 at  $D_1$ . The data were obtained by alternately sampling the two detector outputs at intervals of 1 msec with a waveform digitizer. The normalized power 4.0 at  $D_0$  represents the theoretical maximum of 81% of the energy in the two equal-intensity input beams combined in a single outgoing beam.

Figure 4 is the result obtained with both master and slave lasers operating above threshold. The power measured at  $D_0$  is shown in arbitrary units, for both unlocked and injection-locked operation. The unlocked input intensities at  $D_0$  were  $A_1 = 0.17$ ,  $A_2 =$

0.37, and  $B_1 = 0.50$ . When the slave laser was injection locked, its output and the reflected collinear master light were indistinguishable, and their combined power ( $A_1 = 0.54$ ,  $A_2 = 0$ ) was nearly equal to the unlocked sum. In this case the theoretical minima and maxima were 0.46 and 1.6 unlocked and  $7.8 \times 10^{-4}$  and 2.1 locked, respectively. The difference between theory and this experiment is somewhat greater than that observed in the experiment of Fig. 3. This is primarily the result of imperfect mode matching that limits the area at the grating over which the phase difference between the slave-laser output and the collinear reflected master light remains negligible. The power fluctuations that are apparent in the injection-locked data reflect the sensitivity of the injection-locking system to cavity frequency fluctuations induced by ambient acoustic noise.

In summary, diode-pumped Nd:YAG ring lasers have been operated in a single direction and frequency at output powers in excess of 25 mW. Two such lasers have been injection locked in a master-slave configuration. With these sources, efficient coherent beam summation has been achieved at  $1.06 \mu\text{m}$ , in good agreement with theory. These experiments could be extended to combine many sources either by chaining the ring cavities so that each device is injection locked to an immediate neighbor or by injection locking all the lasers to a single master oscillator.

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## References

1. W. B. Veldkamp, J. R. Leger, and G. J. Swanson, *Opt. Lett.* **11**, 303 (1986).
2. J. R. Leger, G. J. Swanson, and W. B. Veldkamp, *Appl. Phys. Lett.* **48**, 888 (1986).
3. H. Dammann and K. Görtler, *Opt. Commun.* **3**, 312 (1971).
4. U. Killat, G. Rabe, and W. Rave, *Fiber Integ. Opt.* **4**, 159 (1982).
5. H. L. Stover and W. H. Steier, *Appl. Phys. Lett.* **8**, 91 (1966).
6. C. L. Buczek, R. J. Freiberg, and M. L. Skolnick, *Proc. IEEE* **61**, 1411 (1973).
7. C. N. Man and A. Brillet, *Opt. Lett.* **9**, 333 (1984).
8. S. Kobayashi and T. Kimura, *IEEE J. Quantum Electron.* **QE-17**, 681 (1981).
9. C. L. Tang and H. Statz, *J. Appl. Phys.* **38**, 323 (1967).