

Final Report for Contract
**"Prototype Laser-Diode-Pumped
Solid State Laser Transmitters"**

Contract NAS7-999

For period April 1987 - June 1989

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ABSTRACT: Monolithic, diode-pumped Nd:YAG ring lasers can provide diffraction-limited, single-frequency, narrow-linewidth, tunable output which is adequate for use as a local oscillator in a coherent communication system. We built a laser which had a linewidth of about 2 kHz, a power of 5 milliwatts, and which was tunable over a range of 30 MHz in a few microseconds. We phase-locked this laser to a second, similar laser. This demonstrates that the powerful technique of heterodyne detection is possible with a diode-pumped laser used as the local oscillator.

Laser diode pumping of monolithic Nd:YAG rings can lead to output powers of hundreds of milliwatts from a single laser. We built a laser with a single-mode output of 310 mW. Several lasers can be chained together to sum their power, while maintaining diffraction-limited, single frequency operation. We demonstrated this technique with two lasers, with a total output of 340 mW, and expect that it is practical for up to about ten lasers. Thus with lasers of 310 mW, output of up to 3 Watts is possible. The chaining technique, if properly engineered, results in redundancy.

The technique of resonant external modulation and doubling is designed to efficiently convert the cw, infrared output of our lasers into low duty-cycle pulsed green output. This technique was verified through both computer modeling and experimentation. Further work would be necessary to develop a deliverable system using this technique.

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I. Project Summary

The National Aeronautics and Space Administration (NASA) has the goal of developing free-space point-to-point communication systems using optical radiation. The advantage of free-space communication using optical radiation is due to the small antenna aperture needed for low divergence transmitted beams. Laser transmitters used for optical communication must have power of the order of 1 Watt . The beam must be diffraction-limited to be useful. Three modulation formats which have been proposed are phase modulation, frequency modulation, both known as coherent communication, and pulse position modulation, or PPM. This report describes progress in building lasers useful for free-space communication using these three modulation formats.

Efficient, diffraction-limited all-solid-state lasers with power approaching 1 Watt at the near infrared wavelength of 1.06 microns can be built using the technique of laser-diode-pumping. The reliability of these lasers is essentially equal to that of the laser diode pumps used. Under this contract, we have developed diode-pumped lasers that have capabilities useful for both coherent communication and PPM communication through space.

Monolithic Nd:YAG ring lasers can provide diffraction-limited, single-frequency, narrow-linewidth, tunable output which is adequate for use as a local oscillator in a coherent communication system. We built a laser which had a linewidth of about 2 kHz, a power of 5 milliwatts, and which was tunable over a range of 30 MHz in a few microseconds. We phase-locked this laser to a second, similar laser. This demonstrates that the powerful technique of heterodyne detection is possible with a diode-pumped laser used as the local oscillator.

Laser diode pumping of monolithic Nd:YAG rings can lead to output powers of hundreds of milliwatts from a single laser. We built a laser with a single-mode output of 310 mW. Several lasers can be chained together to coherently sum their power. We demonstrated this technique with two lasers, with a total output of 340 mW, and expect that it is practical for up to about ten lasers. Thus with lasers of 310 mW, output of up to 3 Watts is possible. The chaining technique, if properly engineered, results in redundancy.

The technique of resonant external modulation and doubling is designed to efficiently convert the cw, infrared output of our lasers into low duty-cycle pulsed green output. This technique was verified through both computer modeling and experimentation. Further work would be necessary to develop a deliverable system using this technique.

The research done under this Small Business Innovation Research (SBIR) contract has led to a successful line of commercial products sold by Lightwave. Almost 400 lasers have been delivered to customers in a variety of fields. A significant fraction of the deliveries have been to Japan and Europe. The "Phase III" self-sustaining commercialization program envisioned by the designers of the SBIR program is already well underway.

TABLE 1: LASER PERFORMANCE

A. Local Oscillator	Best Result	Delivered Unit
Wavelength	1.06 μm	1.06 μm
Output power	11 mW	4.5 mW
Oscillating Mode	TEM ₀₀ , single frequency	
Input pump optical power	30 mW	30 mW
Optical Efficiency	37%	15%
Input electrical power	162 mW	162 mW
Electrical Efficiency	6.7%	2.8%
Amplitude Stability (5Hz to 1 MHz, RMS)	0.03%	0.12%
Frequency Stability 1 msec	500 Hz	500Hz
" " 1 sec	20 kHz	20 kHz
" " 1 hour	10 MHz	10 MHz
Thermal tuning range	35 GHz	15 GHz
Thermal tuning response time	0.2 sec	3 sec
Piezo tuning range	200 MHz	30 MHz
Piezo tuning response time	3 μsec	3 μsec
B. High-Power Module	Best Result	Delivered Unit
Wavelength	1.06 μm	1.06 μm
Output power	311 mW	135 mW
Oscillating Mode	TEM ₀₀ , single frequency	
Input pump optical power	527 mW	325 mW
Optical Efficiency	59%	41.5%
Input electrical power	1.8 W	1.32 W
Electrical Efficiency	17.3%	10.2%
Amplitude Stability (5Hz to 1 MHz, RMS)	0.94%	3.4%
Combined Output, 2 modules	340 mW*	260 mW

*340 mW is the combined power of the delivered units when pump diodes are run at a level which will reduce lifetime. 260 mW is the output from the same units at rated power.

II. Introduction

1. Relevant NASA Goals

This contract work had as its goal the development of lasers useful as transmitters for free-space optical point-to-point communication.

NASA has many potential applications for an optical free-space communications link. The specific goal of JPL is for fairly low bit-rate links (several MHz) over extremely large distances, such as those contemplated for proposed deep space exploration probes. Other branches of NASA are interested in links between geo-stationary earth-orbiting satellites. These links require bit rates approaching 1 GHz. Optical links are very attractive because low divergence beams are possible with optical antennas of moderate size. The higher power possible on target with these low divergence beams more than compensates for the increased quantum noise present at optical frequencies.

Four key requirements for a communication laser are beam quality, with a diffraction-limited beam preferred; high power, with a level near 1 Watt being desirable; good power efficiency, with 10% a good goal; and high reliability. Diode-pumped solid state lasers are promising on all four counts. Diode-pumped lasers, when pumped by wide-stripe laser diodes which are many times worse than the diffraction limit, still have output which is diffraction-limited. During this contract, we have built a diode-pumped laser which is diffraction-limited, which has an output power of 311 mW, and which has an output power equal to 17.3% of the input electrical power. These values are in the range required for space communications links.

The output of the laser must be modulated in some manner to be useful for communications. Diode-pumped lasers cannot be modulated directly by simply modulating diode input current, because the dynamics of these lasers are quite slow, with time constants of a few microseconds. Other modulation schemes are required. Two possible modulation formats are phase modulation, where the information is encoded on the optical phase of the transmitter laser, and pulse-position-modulation, where several bits of information are sent in a single pulse, with the information encoded according to the timing of the pulse. The lasers we have developed are applicable to both these types of modulation.

2. Technical Background

a) Diode-pumped solid-state lasers.

Semiconductor laser diodes are now commercially available at very high power levels. The latest high-power laser from Spectra-Diode Laboratories, the largest U.S. manufacturer, operates at an output power of 10 Watts, continuous wave. This compares with a maximum available power of 200 mW only five years ago. These lasers are very efficient compared to other lasers, with an output power of 1 Watt possible with an input current of 1.6 Amperes at 1.7 Volts. This is an efficiency of 37%. The reliability of semiconductor lasers can be good. Lifetimes of greater than 100,000 hours are possible when diodes are operated at conservative power levels. These levels of efficiency and reliability are far better than is possible with any other kind of laser.

Two significant disadvantages of high-power laser diodes are the lack of spatial and temporal coherence. Low spatial coherence is equivalent to a beam divergence which is greater than the diffraction limit. The most power which current laser diodes can achieve in a single diffraction-limited spot is about 100 mW. More powerful laser diodes have correspondingly larger beam size. Low temporal coherence, or wide linewidth, are characteristics of a laser which make it impossible to use phase modulation, or other coherent communication techniques.

The output from laser diodes is can be efficiently matched to the absorption lines of Nd^{3+} in Yttrium Aluminum Garnet (YAG), and used to build efficient optically-pumped Nd:YAG lasers. A very significant advantage of diode-pumping is that it is possible to build a diffraction-limited diode-pumped laser using one or more laser diodes which are not themselves diffraction limited. As long as the diode light from the pumps is mostly absorbed inside the volume of the lowest order spatial mode of the pumped laser, the pumped laser will lase in a diffraction-limited mode. Since conversion efficiency from diode light to diode-pumped output power is typically in the range from 30% to 50%, powerful and efficient diffraction-limited lasers can be built.

One factor which is often ignored when the efficiency of diode-pumped lasers is discussed is the power used for temperature control of the laser diode. The laser diode must be temperature-controlled to within a 1°C range to keep the output of the laser diode at the peak absorption of the solid-state laser material. If the correct temperature of the laser diode is far from the temperature of available heat sinks, the temperature-control power may be significant. If the heat sink temperature is known in advance and does not fluctuate, then lasers can be specially selected at the desired wavelength, and the power needed for temperature control kept small. This may be the case for satellite-based systems. In field systems, where ambient temperature is variable, the diode temperature controller may be the largest user of power in the laser system.

b) Diode-pumped single-frequency ring lasers

The local oscillator studied in Phase I of this SBIR contract was based on the MISER, a monolithic, isolated, single-mode, end-pumped ring laser. It was invented at Stanford University by Kane and Byer [1] during a successful effort to demonstrate a coherent laser radar system utilizing Nd:YAG lasers operating at 1.06 micron. The MISER ring laser, for which Lightwave has a license from Stanford, was invented to overcome two unavoidable problems with linear diode-pumped solid state lasers: multimode oscillation and sensitivity to optical feedback. Unidirectional-ring solid-state lasers were known to overcome these problems, but had the disadvantage of being complex devices with numerous discrete optical components. The MISER invention replaced all of these components with a single four-faceted crystal. This is a single crystal of Nd:YAG (neodymium doped yttrium aluminum garnet) cut and polished to form a complete resonator. Three of the reflections in the round-trip lasing path are total internal reflections, and the fourth reflection, the input/output surface, is dielectrically coated. Unidirectional oscillation is possible due to the nonplanar path. When placed in a magnetic field and pumped with a properly aligned diode laser, the MISER will oscillate unidirectionally in a single mode of very narrow linewidth, with a natural resistance to optical feedback. The MISER produced by Lightwave with Phase I support provided 2 mW of output when pumped with an inexpensive single-stripe diode laser. A major goal of the Phase II program was the further development of powerful single-frequency diode-pumped lasers.

c) Coherent communication

In a coherent communication link, the phase or frequency of the transmitted beam contains the information. This contrasts with an incoherent system, where the intensity (or the presence or absence) of the transmitted beam carries the information. This is similar to the distinction between FM and AM radio transmission. Coherent communication has significant advantages when working against the noise of a bright background, or when more than one channel must be overlapped in space. Coherent communication requires that the transmitting laser be oscillating in a single frequency of narrow linewidth. At the detection end of the link a second, less powerful laser is used as a reference to detect phase or frequency changes in the transmitter laser. This laser, known as the local oscillator, must be a single frequency laser of narrow linewidth. In addition, this local oscillator laser must be tunable, so that its frequency can track that of the transmitter. Under this contract we have made developments which have brought coherent diode-pumped space communication much closer to reality.

d) Pulse Position Modulation

The technique of pulse position modulation (PPM) requires less average power than a binary code to transmit information. This is done at the cost of requiring more peak power. A PPM system operates at a low duty cycle. The time between pulses carries the information. If the pulse is short and the arrival time is measured precisely, then many bits of information are carried on a single pulse. Against a dark background, a PPM system requires received powers which may be lower than one photon per bit of information. These systems are attractive for deep space probes. The problem with PPM is that it is only advantageous if it makes use of power efficiently. If power is wasted during the "off" part of the cycle, then a simple binary code may be better. Since laser diodes can not be run at peak powers significantly above their cw limit, there is a need for a technique for converting the cw or high-duty-cycle output of diodes into the low duty cycle needed for PPM. We investigated a technique for converting the output of our powerful single-frequency lasers into randomly pulsed, frequency-doubled output appropriate for PPM. We call this technique Resonant External Modulation and Doubling. Our experiments and modelling convinced us that our technique is valid, but much more work is required to build a practical system based on this approach.

3. Objectives Summary

a) Completion of Local Oscillator

The first objective was the completion of the low power local oscillator begun in Phase I. Although the device developed in Phase I was acceptable for some applications, there were several problems that needed more attention. Its sensitivity to feedback, the lack of fast tunability, and the significant amplitude noise due to relaxation oscillations were all areas that could be improved. The soldering and assembly techniques studied in Phase I needed improving as well.

To accomplish these goals, the following tasks were to be performed.

- a. Develop a theoretical understanding and computer model of the monolithic nonplanar ring.
- b. Design miniaturized electronics for stabilization of MISER.
- c. Design and fabricate MISER resonator optimized for beam quality and power.
- d. Redesign of mechanical assembly and alignment hardware.
- e. Design electrical connectors and mechanical mounts for finished assembly.
- f. Test finished unit for power and stability.
- g. Deliver 1 unit to NASA.

b) Development of Modular High Power Single-Mode Transmitter

The second objective was the development of a laser-diode-pumped, solid-state laser module with high output power. Two or more of these modules combined would be suitable as a transmitter with powers nearing one Watt. The high power module should have the desirable characteristics of single-longitudinal mode, fundamental spatial mode, 1.06 micron output. The program to develop this module was as follows:

- a. Study and choose an optical beam combining geometry.
- b. Design pump module mechanics and optics.
- c. Design resonator structure.
- d. Design base plate and alignment jig.
- e. Acquire and assemble components.
- f. Test and evaluate system.
- g. Deliver to NASA.

c) Resonant External Modulation/Doubling

The third objective was to theoretically investigate, computationally model, and experimentally verify the technique of resonant external modulation and doubling. The intended steps to carry this out were as follows:

- a. Develop theory of coupled, modulated nonlinear resonators.
- b. Develop computer model based on theory.
- c. Experimentally verify theory and model.
- d. Test and characterize output of experimental system.
- e. Compare experimental results with computer model.

III. Local Oscillator

1. Improved MISER resonator design

High resistance to optical feedback is a valuable trait for a laser to be used in a coherent communication system. This factor also improves the performance of the resonant doubling system, described later in this report. In cooperation with graduate students at Stanford, a mathematical model was developed which calculated the sensitivity to feedback of various designs of monolithic ring resonators. This work was recently published.[2] This model showed that the Phase I design was far from the theoretical optimum in regard to feedback resistance. Therefore, a

new design was developed and fabricated. New fabrication tooling had to be designed and constructed.

Feedback resistance was not the only goal, however. Additional constraints were that the ring resonator fit into the previously designed package and that it be not too sensitive to small errors in fabrication and to errors in the phase of the reflectivity of the output coupler. Also, the new resonator was designed to be tuned with a mechanical force, which meant that the top of the crystal had to be a non-optical surface. The resulting design, shown in Figure 1, had a resonator that was barely nonplanar compared to the old design. Table 2 gives the design parameters of all the nonplanar rings which we know of, including the two designs developed at Lightwave under NASA support. The definitions of the parameters are from Ref. 2. The half-size laser was developed under a different contract, but is included for completeness.

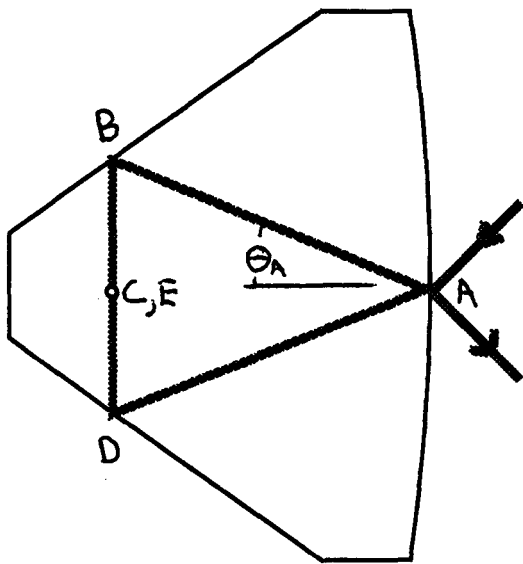
TABLE 2: DIFFERENT RING DESIGNS

<u>Design</u>	Θ_A	β	AE	CE	Round-trip
First Stanford Design	7.8°	90°	36.5 mm	1.8 mm	84.3 mm
Second Stanford Design	16°	90°	10.5 mm	1.5 mm	28.6 mm
Hewlett-Packard Design	30°	1.25°	4.23 mm	1.77 mm	15.8 mm
Third Stanford Design	30°	1.05°	4.0 mm	2.33 mm	15.8 mm
Lightwave "Old-Style"	22.9°	90°	3.5 mm	1.03 mm	11.2 mm
Lightwave "New-Style"	22°	4°	3.5 mm	1.41 mm	11.5 mm
New-Style, Half-Scale	22°	4°	1.75 mm	0.71 mm	5.8 mm

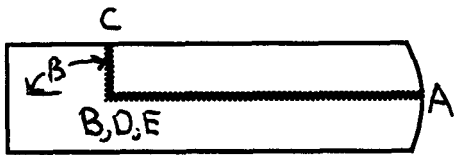
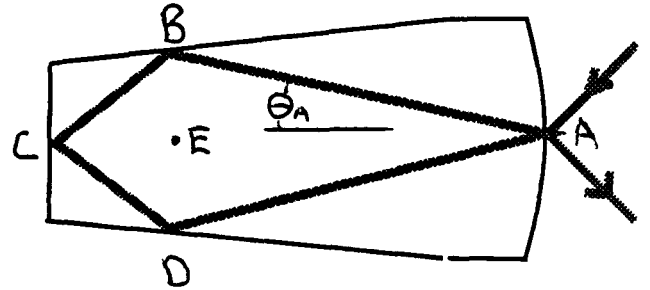
2. Jigging

New tooling had to be designed to fabricate ring resonators crystals of the new, feedback resistant design. The tooling parts were machined in the same manner as the previous tooling used for the highly non-planar design. The precision-ground block holds the smaller pieces at a precisely-defined angle. There are three distinct sites on the large block, one for each of the flat surfaces which must be ground onto the ring resonator. The laser crystals are bonded to the smaller pieces throughout the process, so the relative angles are those of the smaller pieces on the large block. This tooling has been quite successful. Yields for most types of crystal built have been good. The exceptions are described later in this report.

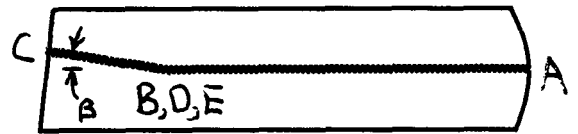
We also built a system for permanently aligning lasers with the pump beam. During alignment, the crystals are held with a vacuum chuck and positioned with all six degrees of freedom. A heater pad under the crystal keeps a blob of solder melted while aligning the laser, and when the solder freezes the crystal remains in the desired alignment. This soldered alignment technique has been quite successful. A person skilled in alignment can get a crystal lasing in about



top view



side view



original highly non-planar design

optimized design for maximum feedback resistance

Figure 1 depicts both designs of the MISER crystal. The design on the left has a highly non-planar beam path. The design on the right was optimized to minimize feedback sensitivity. Some features common to both designs are: the input/output mirror (curved surface) has a highly reflective dielectric coating; the three other bounces are total internal reflections, and the input and output beams are 90° apart.

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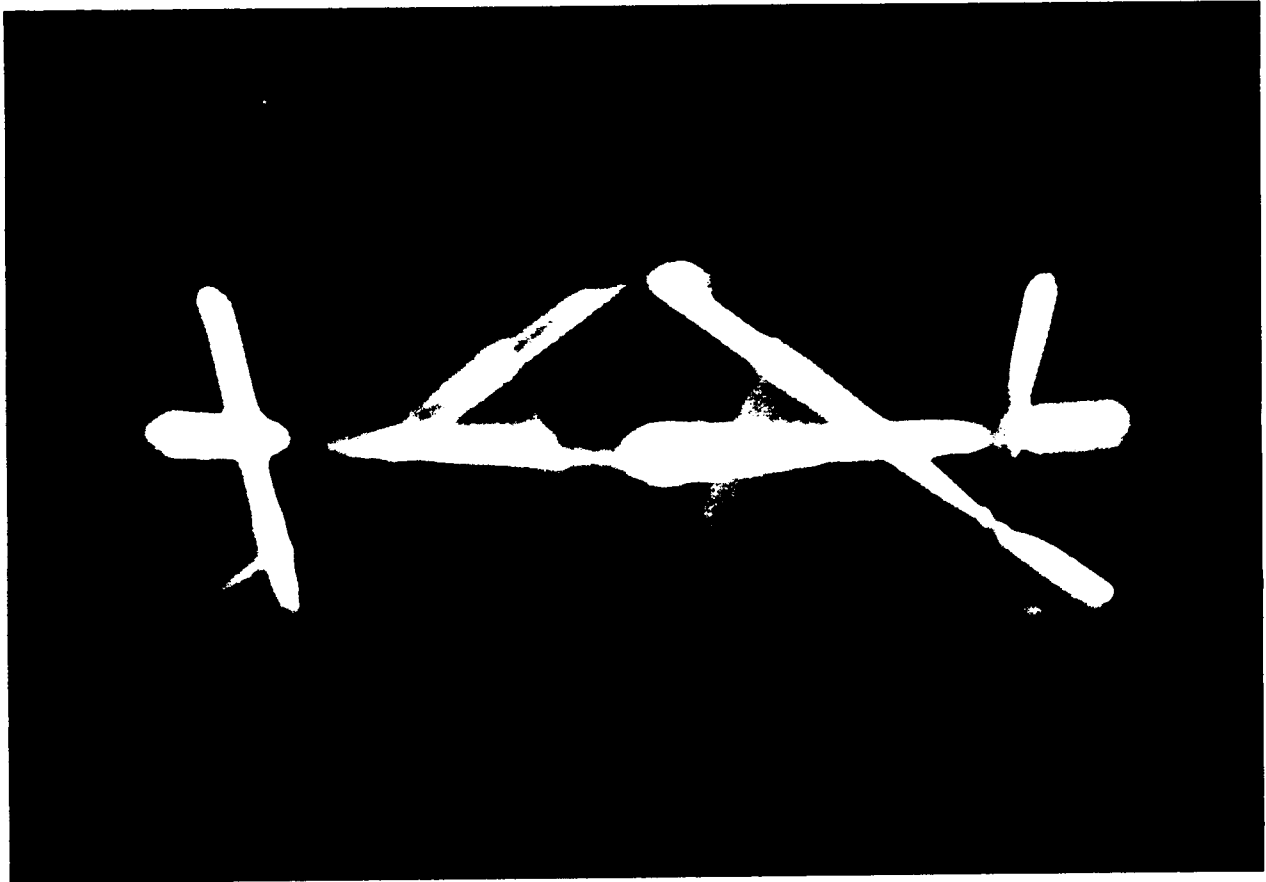


Figure 2. Fluorescence path in a lasing crystal, viewed from the front curved surface of the resonator. This photograph was taken with an infrared-sensitive video camera, used during laser alignment. The top vertex is a total internal reflection from the top, polished surface of the crystal. The bright spot in the center of the lower side of the "triangle" is the input/output point on the front, coated surface. The additional lines on the right and left edges of the triangle are merely secondary reflections in the crystal when viewed from this angle.

five minutes. The use of infrared-sensitive video cameras to allow the aligner to see the fluorescence path in the crystal is a valuable technique, which allows skilled aligners to quickly make adjustments which lead to lasing. Fig. 2 is a photograph of the fluorescence in a crystal which is being aligned.

3. Feedback Measurements and Results

Feedback degrades the performance of all types of lasers. In a linear laser, even a very small amount of feedback will pull or split the frequency of the laser, reducing its coherence. These effects are not observed in our ring resonators. In a unidirectional ring laser, the feedback injects power into the ring resonator which travels in the opposite direction from the laser. True oscillation in the wrong way is not possible, since the threshold for the right way is slightly lower, and it oscillates first and saturates the gain. Still, the wrong-way resonator has a very high Q-factor, so power injected from outside the laser into the wrong direction will build up. This power competes with the oscillating right-way power for the excited atoms. When the wrong-way power is of the same order as the oscillating right-way power, there must be a reduction in the right-way laser output. Thus we observe that at feedback levels above a certain amount, the laser output is reduced. Amplitude stability is also reduced, since the amount of feedback will be fluctuating.

We measured the effects of feedback on Nd:YAG monolithic ring resonators of both types. The set-up for measuring feedback is shown in Figure 3. This setup takes advantage of the fact that only light spatially matched to the laser resonator will build up in the resonator. Light reflected from a mirror at a beam waist will be spatially overlapped nearly perfectly with the incoming beam. As the distance from the beam waist to the mirror is increased the overlap of the two beams will be reduced in a well-defined way. The exact amount of feedback is difficult to know exactly. The virtue of this setup is that feedback is precisely controlled by mirror position in a way that is the same for both lasers.

The focussing lens was AR coated for $1.06\ \mu\text{m}$. A 99% reflecting mirror at normal incidence was moved along the axis of the beam, changing the amount of light spatially matched back into the laser. Feedback affected the highly nonplanar and the slightly nonplanar lasers differently as a function of mirror position. The old highly-nonplanar design showed effects at a feedback level of 0.1%. The newer barely-nonplanar design was substantially more resistant to feedback. Nevertheless, significant effects are seen at a feedback level of 1%. We will experiment with materials other than Nd:YAG which may yield more feedback-resistant designs.

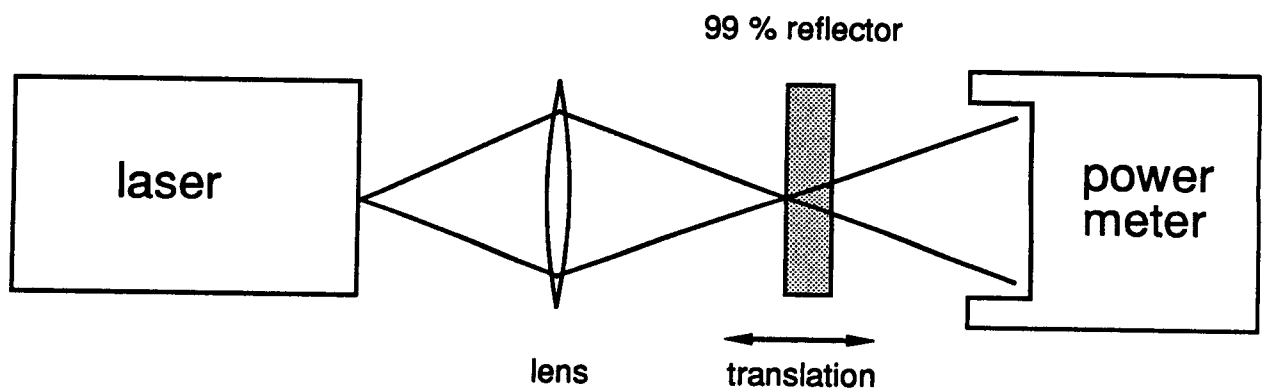


Figure 3 shows the experimental set-up for feedback measurements. The beam from the laser is focused onto a 99% reflecting mirror. The amount of feedback varies with the position of the mirror, with the greatest amount of spatially-matched feedback occurring when the mirror is at the focus. The feedback drops off in a calculable way as the mirror is translated.

4. Frequency Stability

Many times in the development of the ring lasers, experiments such as those shown in Fig 4 were set up to measure the frequency stability of the lasers. The experiment shown is a beat note, or heterodyne, experiment, where the beams of two lasers are combined and the frequency difference between the two lasers is observed in order to measure the frequency stability of the frequency difference between the two lasers. The beams from the two lasers are collimated with 50 mm focal length lenses and crossed at a 50-50 beamsplitter. The transmitted beam from one laser and the reflected beam from the other are carefully overlapped. This can be done with either of the two sets of beams that leaves the beamsplitter. The aligned beam is then detected on a photodiode, the output of which is connected to an oscilloscope or a fast frequency counter. When the frequency of one laser is tuned close enough to the other, the beat frequency of the two lasers can be observed.

Initially, it was suspected that the long term frequency drift was due to air currents in the laser head package. The laser diode is run considerably below room temperature, while the MISER crystal is above room temperature, and so thermal gradients are expected to cause convection currents. To test this theory, a roughing pump capable of pulling a 20 mTorr vacuum was used to evacuate the hermetic laser assembly enclosure. A sealed, evacuated unit and a standard, nitrogen purged unit were set up in a heterodyne configuration described in the previous section. The long term frequency stability was measured and compared to that of two standard units. There was no noticeable improvement due to the evacuation of the laser enclosure. Other sources of frequency drift predominate.

We found that a major source of long term frequency drift for the Phase I design was aging of the temperature sensor. We were using an unencapsulated thick film thermistor, which we found to be quite noisy, and to exhibit substantial long term drift. We replaced these devices with platinum thermistors. These commercially-available devices use platinum sputtered onto a ceramic substrate as a temperature sensor. The platinum is inert, so it has excellent long-term stability. Long-term frequency stability was improved from 50 MHz/hour drift to less than 10 MHz/hour by this replacement.

We reported on the frequency stability of the laser we built in a paper published in Optics Letters in April 1988. This paper is included as Appendix 1. We used a measure of frequency stability known as the Allan Variance. The Allan variance gives expected frequency change as a function of delay time. To measure the Allan Variance, the frequency of an oscillator is measured once with a frequency counter, and then again after the delay time. The expected square of the frequency change is the Allan Variance of the oscillator for the specified delay time. Plotted in Fig.

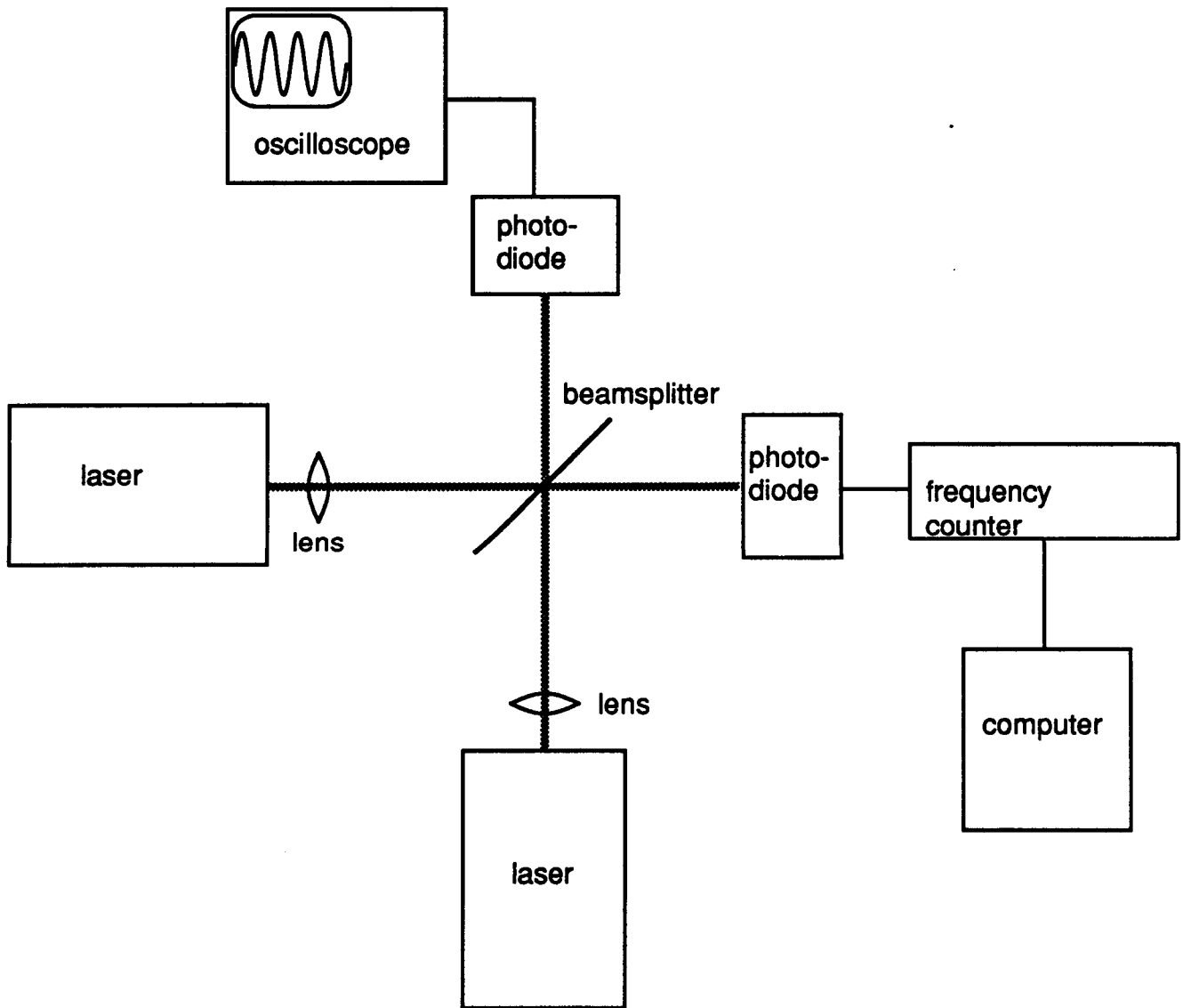


Figure 4 shows the experimental set-up for measurement of frequency stability. The beams from two lasers are combined at a 50-50 beamsplitter and detected on a silicon photodiode. When the beams are spatially overlapped correctly, modulation depth of the detected beat frequency is in excess of 85%. The signal was analyzed by a frequency counter and accumulated on a personal computer.

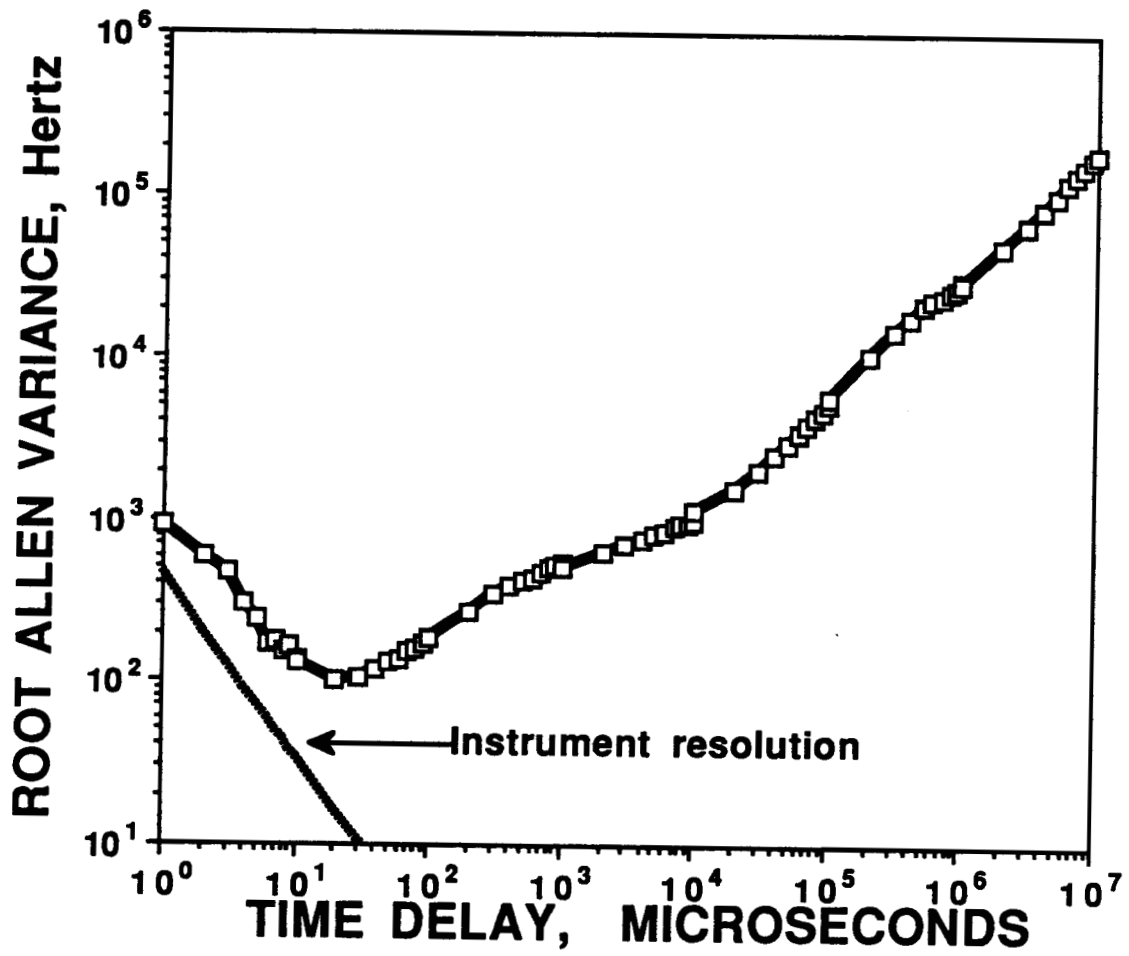


Fig. 5. Root Allan Variance is a measure of how much laser frequency is expected to change (RMS) in a given time. For times between 1 μ sec and 1 msec the frequency change is below 1 kHz.

5 is the square root of the Allan Variance for two of our low-power oscillators. The short, medium, and long term frequency stability are defined by the frequency variation of the beat frequency over 1msec, 1 sec, and one hour. These values, plotted in Figure 5, are given in Table 3.

TABLE 3: FREQUENCY STABILITY OF LOCAL OSCILLATOR LASERS

1 msec	500 Hz
1 sec	20 kHz
1 hour	10 MHz

5. Tests for Single Mode

One of the most important requirements of coherent communication is that the laser oscillators used oscillate in a single mode. We used sets of fixed-length solid etalons to determine the number of laser modes oscillating. The arrangement shown in Figure 6 is used. The laser beam passes through a diffusing element, such as teflon tape or frosted glass, and then through a solid Fabry-Perot etalon. An etalon is an interferometer composed of two flat and parallel partially mirrored surfaces, on a piece of optical glass [3]. Light of a single frequency passing through an etalon creates a set of bright and dark fringes as the angle from the axis changes. This gives rise to a pattern of circular rings as seen in Figure 7. If the laser is not single mode, this pattern changes to grouped sets of rings, instead of the sharp, single concentric circles. With this method of mode detection, another mode at 1% of the power of the main oscillating mode is detectable.

We found that the vast majority (>95%) of ring lasers produced from Nd:YAG at the 1.06 micron wavelength lase at a single frequency without difficulty. There are problems at the 1.32 micron wavelength of Nd:YAG, but that is beyond the scope of this report. When multiple lasing frequencies are observed, it is due to either the presence of multiple axial modes, or to the presence of multiple transverse modes.

The usual cause of multiple axial modes is that the laser is near a mode-hop. Figure 8 shows the wavelength of a typical ring laser as a function of temperature. The linear scan occurs in regions where a single mode is oscillating, and the frequency of that mode is being changed by thermally expanding the monolithic resonator cavity. As the laser gets warmer, the resonator expands, and the wavelength of the resonator mode expands accordingly. This increase in wavelength with temperature corresponds to a decrease in laser frequency. The coefficient is -3.1 GHz/°C for Nd:YAG at 1.06 microns. Eventually the mode scans to a point where it is off the peak of the Nd:YAG gain, and another mode on the other side of the gain peak has almost the same gain. Over a narrow range of temperatures, both will lase. The single-mode region is about 5 °C wide, so it is quite easy to regulate the temperature for single mode operation. The overall slope of

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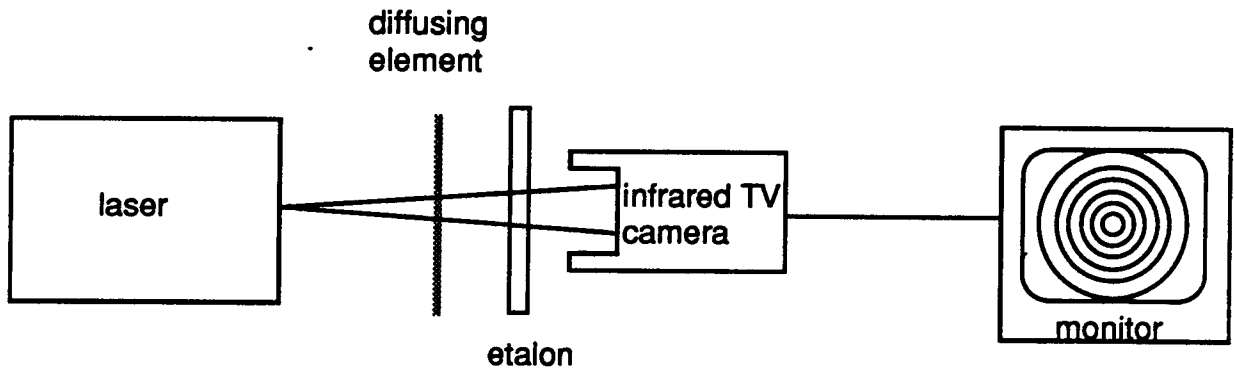


Figure 6. Experimental set-up for determining the mode quality of a laser.



Figure 7. Fabry-Perot interferograms. When a laser is running in a single mode, the sharp concentric rings as shown on the left appear. The fringe pattern on the right indicates laser oscillation in two adjacent modes.

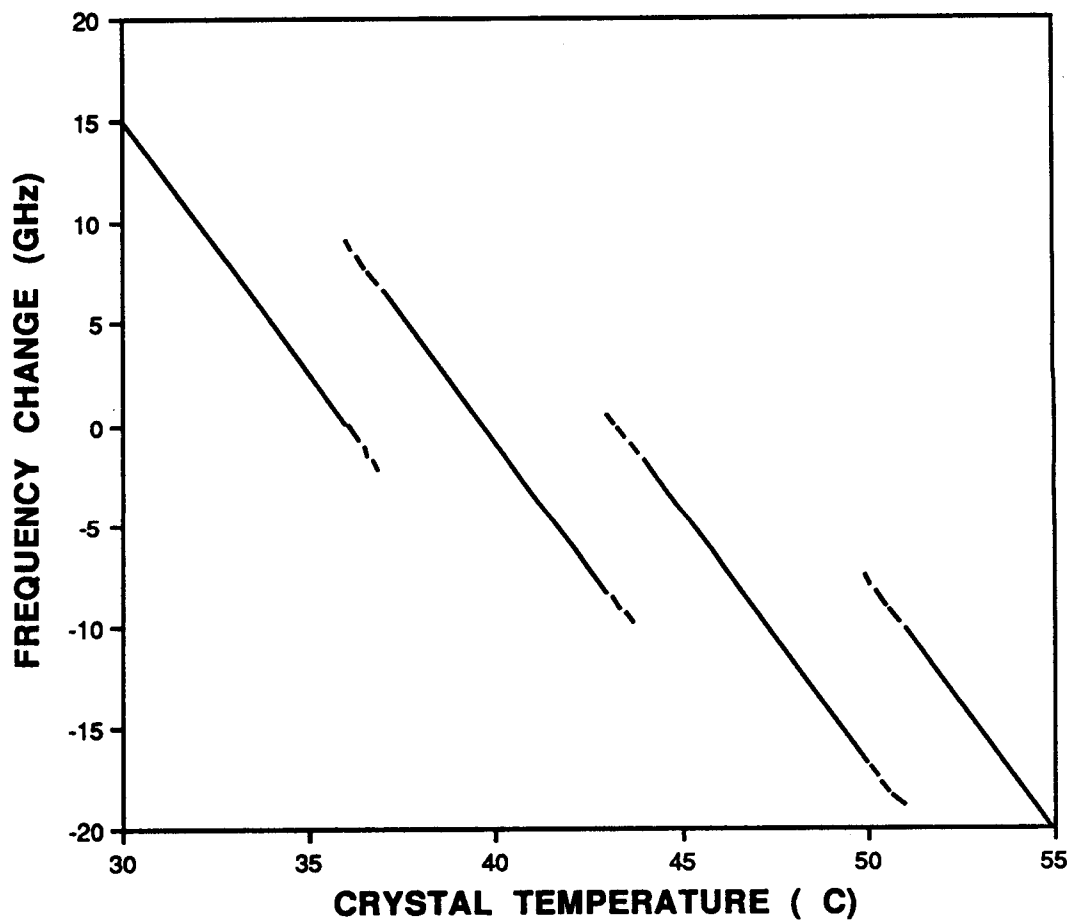


Fig. 8. Temperature tuning of monolithic Nd:YAG resonator. In straight segments laser frequency tunes at -3.1 GHz/C. Discontinuities are mode-hops. In dashed regions near mode-hops two frequencies are oscillating.

the Nd:YAG gain curve causes each successive mode to scan over a lower range of frequencies as temperature is raised.

The usual cause of multiple transverse modes is that the pump beam is too big, or that it is not aligned properly with the monolithic resonator. Either problem will lead to significant energy storage and gain outside of the TEM₀₀ mode volume of the laser resonator. Higher order spatial modes will oscillate. At high levels of power this will cause the beam to look bigger. Proper alignment, and proper choice of laser resonator parameters, will eliminate higher order transverse modes. Later in this report we will discuss the techniques we used to maximize the size of the TEM₀₀ mode in our ring resonators, and thus to achieve TEM₀₀ output with high power laser diodes and their correspondingly large pump beams.

6. Amplitude Noise Reduction

Amplitude fluctuations in solid state lasers are predominantly due to a mechanism known as relaxation oscillations. These oscillations are due to a resonance between energy stored in the laser cavity as photons and energy stored in the laser medium as excited atoms. The frequency of relaxation oscillations for lasers of our design is between 200 kHz and 400 kHz. For a given laser at a given level of power the frequency is constant, and the bandwidth of the fluctuations is about 10 kHz. At frequencies above the relaxation oscillation frequency the amplitude fluctuations drop off quickly, so that the laser output is quantum-noise-limited at frequencies above 40 MHz. The total amplitude fluctuation in a band from 5 Hz to 1 MHz is 0.2% RMS. This is improved from a typical level of 0.5% RMS in the lasers made in Phase I. This improvement was brought about by reducing the output coupling of the lasers to a point slightly below the level which optimizes power. This brings the laser more times above threshold and thus reduces amplitude fluctuations.

We decided that for ultimate control of noise an active feedback system would be necessary. A circuit was designed to monitor a portion of the 1.06 μm output beam and adjust the laser diode to correct for fluctuations. Any increase in 1.06 μm laser output was countered by decreasing the diode current. Another method was investigated in which the diode light was monitored and used to generate a correction signal to the diode current. However, this method was discarded because the fluctuations in diode power were very small, even though this caused most of the amplitude noise in the ring laser. The 300 kHz relaxation oscillations are easy to detect and provide a larger signal with which to correct the diode power. Therefore, the best design incorporated the large gain which the relaxation oscillations provided to this negative feedback loop.

To test this method, a small amount of the laser output is diverted with a beamsplitter to a photodiode, which is connected to a high-gain, low-noise amplifier, as shown in Figure 9. The rest of the laser output was monitored on an independent photodiode. The amplifier was AC coupled to the laser diode, while the DC current to the diode came from the standard power supply. With

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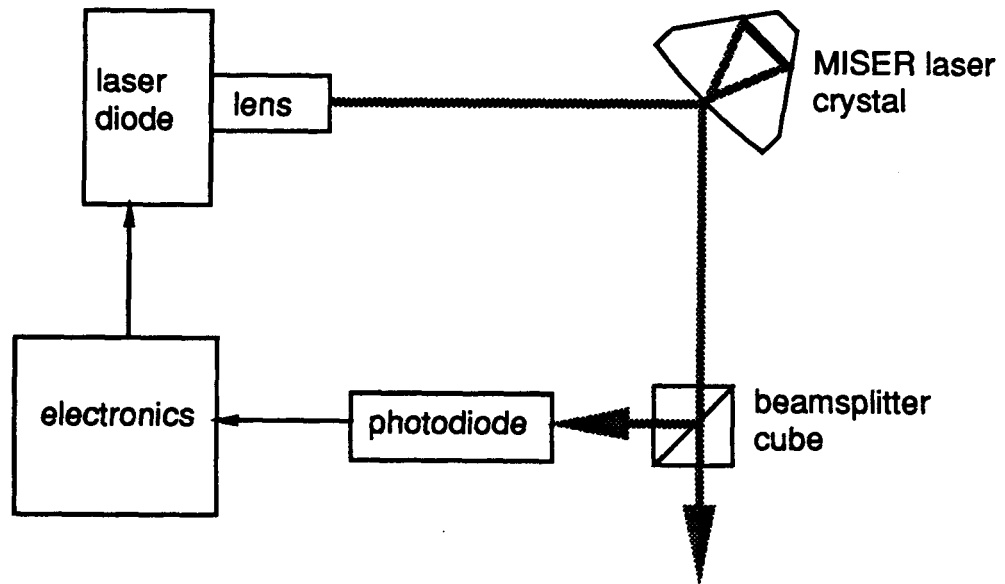
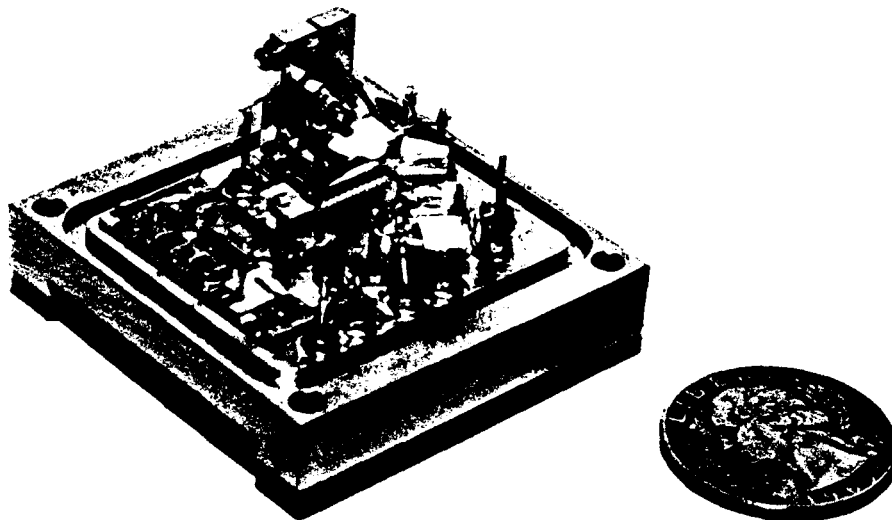


Figure 9. The local oscillator with quieting electronics in schematic and photographic form. The diode pump beam is focused into the MISER crystal with a Selfoc (graded-index) lens. Most of the $1.06 \mu\text{m}$ output beam passes through the beamsplitter, but a small amount is diverted to the photodiode. The electronics then provide a correction to the laser diode current to reduce any amplitude fluctuations.



the amplifier turned off, the $1.06 \mu\text{m}$ amplitude modulation was 0.3% RMS. With the amplifier turned on, the modulation was reduced to 0.05% RMS. This modulation was spread out over frequencies up to 1 MHz, instead of being concentrated at the relaxation oscillation frequency.

The circuit used in these initial tests was then hybridized by Hybrid House, a San Jose manufacturer of custom hybrid circuits, on a 1" by 0.5" alumina substrate and placed in the laser head. Miniature optics, such as the beamsplitter and focusing lens, were used. The standard package which houses the laser head assembly was modified to provide room for the hybrid circuit and associated optics. The first laser built using the hybrid electronics had RMS noise in a 5 Hz to 1 MHz bandwidth of 0.28% with the hybrid circuit turned off, and 0.03% with the electronics turned on. Figure 10 shows the spectrum of amplitude fluctuations with and without the quieting circuit in operation. The unit packaged for shipment to JPL had a noise level of 0.12%. The finished unit was delivered to JPL in February 1989.

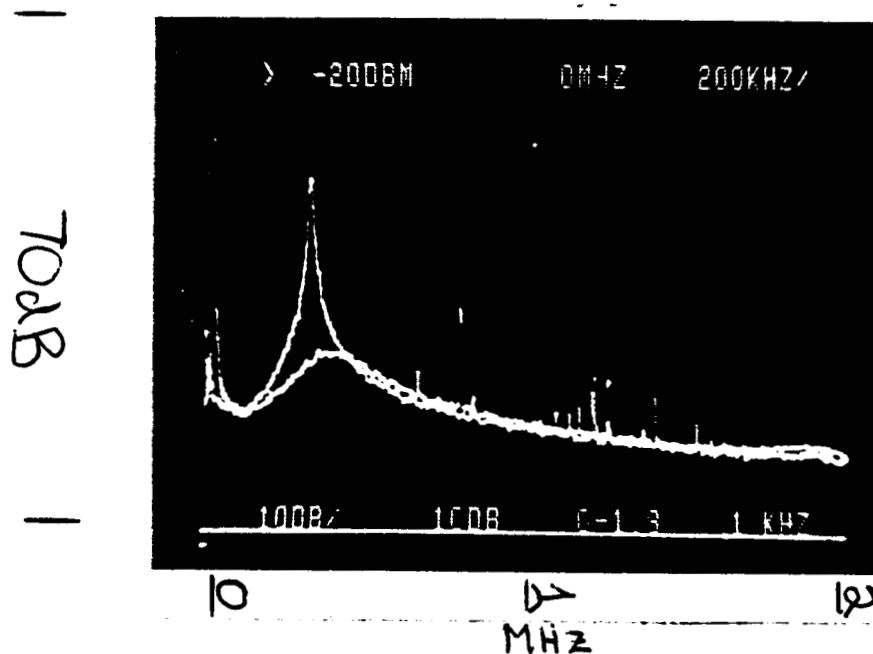


Figure 10. Spectrum of amplitude fluctuations with and without the noise quieting circuit in operation. The relaxation oscillation frequency can be easily seen as a sharp peak in the unquieted spectrum.

7. Fast Tuning and Phase Locking

The non-planar design of the new feedback resistant MISER resulted in a large non-optical surface on top of the crystal. This allowed a piezo-electric element made out of PZT-5H ceramic material to be bonded to the resonator, as shown in Figure 11. This piezo-electric tuner, a .01" thick, .20" square plate, was purchased from the Vernitron Corporation of Bedford Ohio. The PZT material was poled in its thin dimension, and electrodes were plated on its large surfaces. When a voltage is applied across a PZT plate, its area changes. In this case, the PZT is epoxied to the rigid Nd:YAG crystal, and cannot move. Instead, it applies a force to the Nd:YAG, which then undergoes a very small expansion or contraction. This causes a change in the optical path length of the laser cavity, so that the resonant frequency of the single oscillating mode changes as well. Lightwave received a patent on this laser tuning technique [4].

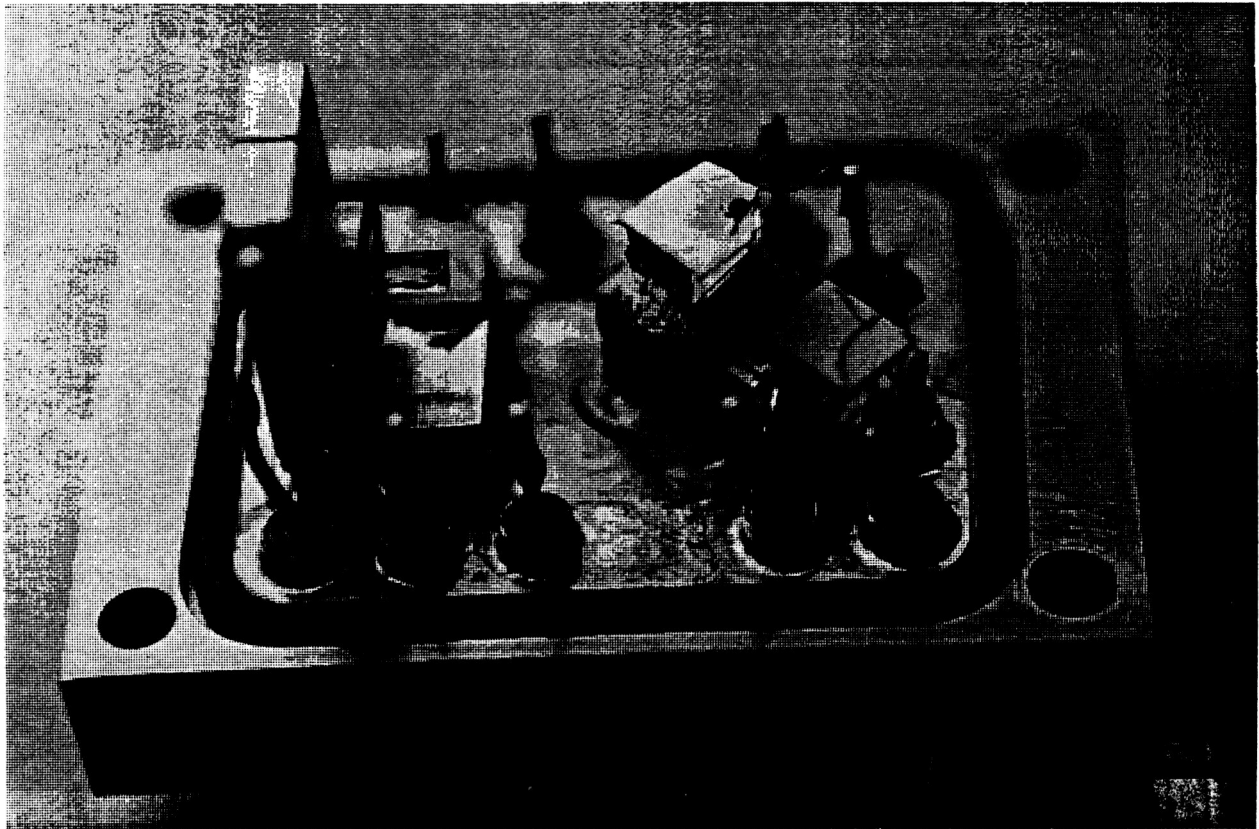


Figure 11. Local oscillator with a piezo-electric tuning element bonded directly to the top, non-optical surface of the resonator. When a voltage is applied to the tuner, the PZT material expands or contracts in the flat direction, applying a force to the crystal, thus changing the optical path length of the resonator.

With a standard unit and this PZT-tuned unit configured in a beat note experiment, the tuning rate per volt applied to the PZT was measured at 1 MHz/volt. With a +15 Volt step function applied to the PZT the tuning range was 15 MHz, and the response time was less than 10 μ sec, as shown in Figure 12. The rate of modulation is limited by the mechanical resonance of the YAG crystal. Ringing occurs when voltages with Fourier frequency components higher than 400 kHz are applied, which can be seen in Figure 12a. The maximum voltage that can be applied to the piezo-electric transducer is around 100 Volts, which gives a tuning range of +/-200 MHz. At larger voltages, the piezo element starts to become depoled and the tuning rate per volt decreases.

This fast, precise tuning made it possible to phase lock two lasers with a simple, electronic feedback loop shown in Figure 13. The difference frequency of two lasers, one piezo-electrically tuned, is detected on two independent photodiodes. The output of one of these is filtered with a 1 k Ω resistor and a .47 μ f capacitor, and applied to the PZT element. The other photodiode is used to independently monitor the optical signal. The lasers stayed phase-locked together for periods of minutes with RMS phase noise of 29 milliradians. Our work with fast tuning and phase locking was reported in the Optics Letters paper [5] which is included as Appendix 1.

Bonding the piezo element to the bottom of the YAG crystal was tried, to allow this method of tuning to be applied to the original resonator design, which has an optical surface on top. The tuning rate decreased to 300 kHz/volt. This was probably due to the expending of force on the copper base which was bonded to the other side of the transducer.

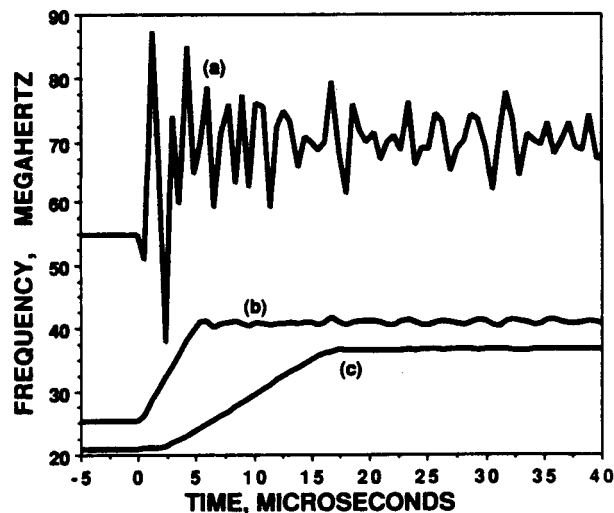


Fig. 12. Frequency as a function of time following a voltage step applied to the PZT-tunable laser. a) a 1- μ sec voltage rise leads to ringing of the crystal. b) 5- μ sec and c) 15- μ sec rise leads to clean tuning of frequency.

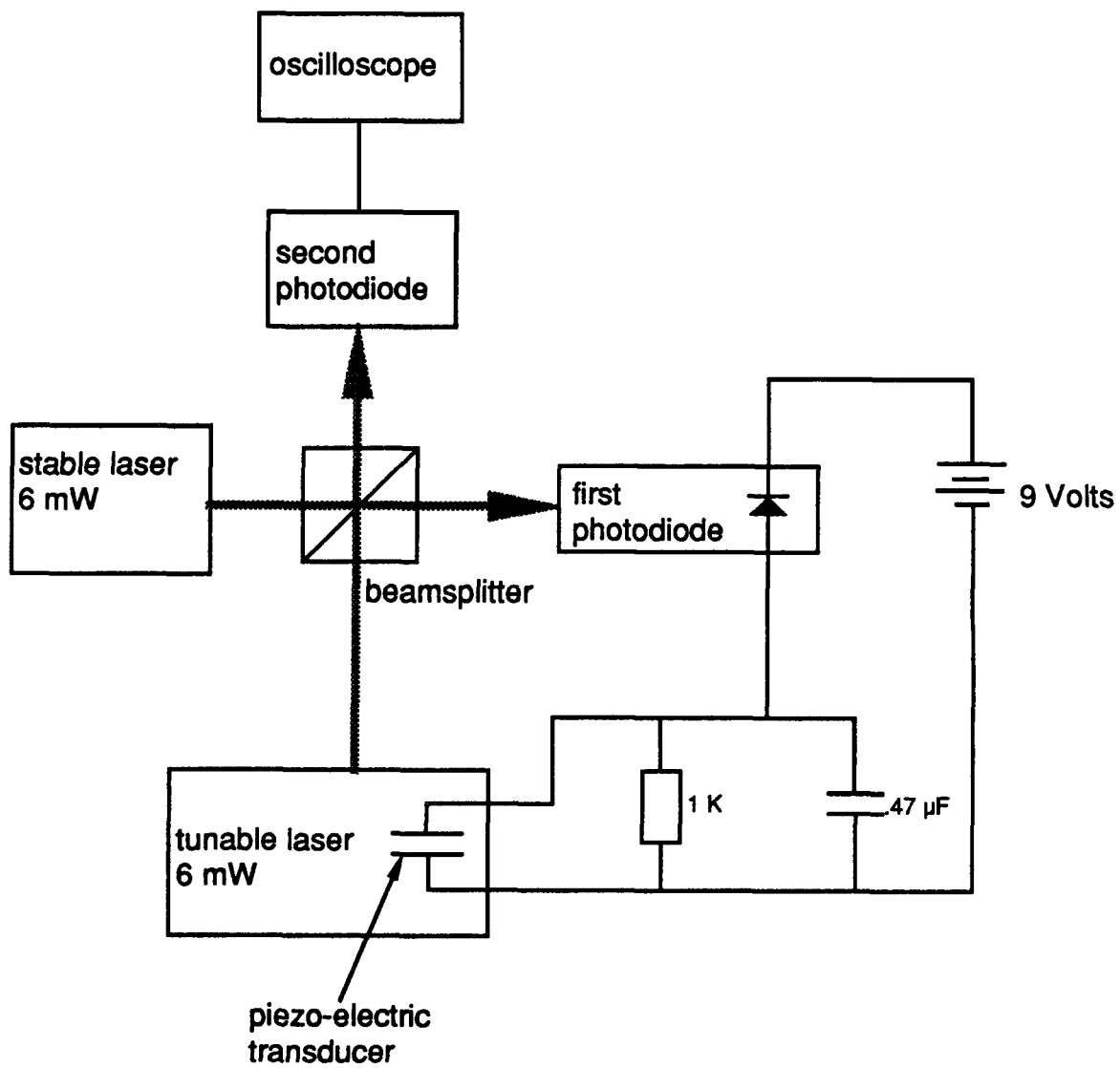


Figure 13: Two lasers phase locked by feeding a filtered signal from a photodiode directly to the piezo-electric element that tunes one of the lasers.

8. Laser Delivered to NASA

The local oscillator laser delivered to NASA in February 1989 met the following specifications:

Power	4.5 mW
Frequency stability:	
1 msec	500 Hz
1 sec	20 kHz
1 hour	10 MHz
RMS Amplitude noise, 5Hz-1MHz	0.12%
Single-mode tuning range, thermal	15 GHz
PZT tuning range with +/- 15 Volts applied	30 MHz
Polarization	99% linear
Beam Quality	TEM ₀₀ , elliptical, 1.25:1

This laser has essentially all the properties required of a laser to be used as the local oscillator in a coherent communication system. The only property of this laser which may not be adequate is expected lifetime and probability of failure. Further work will be required before these lasers have the very high reliability required for communication in space. Diode manufacturers currently estimate 50,000 hours mean time between failures. However, a large MTBF is not all that is required - a very low probability of premature failure is also important. We do not currently use diodes which are space qualified. More reliable diodes would have to be used in any space system. We believe that all the components of our system other than the diodes are very unlikely to degrade. A possible exception to this is the glue used for purposes such as attaching the fast-tuning piezo-electric element to the laser crystal. These aspects of the laser must be studied further before use in space becomes a reality.

IV. High Power Module

1. Investigated Pumping and Resonator Geometries

The goal of this part of our research and development program was to find a way to combine the output of a number of laser diodes in a way that could reach an output power of 1 Watt at 1.06 microns. We proposed to find a "modular" approach, meaning that additional increments of power could be added by combining "modules" in some configuration. In addition to high power, an additional goal of the modular approach was to provide redundancy. We initially examined some approaches which involved a number of laser diodes pumping a single piece of YAG. One way to do this is by polarization-combining. Laser diodes are fairly well polarized, so it is possible to perfectly overlap two beams in space by placing one pump laser so that it passes through a polarizing beam splitter before reaching the YAG, while the other, oppositely polarized pump is reflected by the same beam splitter before reaching the YAG. It is also possible to pump a rod from both ends, so that when used with polarization-beam-combining up to four lasers can be incident on the same rod. It might seem that a four-faceted ring of the type we use could be pumped at all four facets, but this is not the case. Three of the reflections are total internal reflections, so no external beam is colinear with the internal beam. However, at the reflection point where pumping and output coupling occur, it is possible to pump from two directions, with one of them being along the path of the output beam, but directed oppositely from the output beam. A piece of optics which reflects at the pump wavelength and transmits at the lasing wavelength is required to keep the output beam from being directed back to the pump laser.

A modification of our standard ring design was considered, which would have more surfaces reflected by dielectric coatings rather than by total internal reflection. Four pump beams could enter at each (non total-internal) reflection point. End-pumping is possible not only with rod and ring resonators but also with zig-zag slabs as well. In Figure 14, each reflection point of the zigzag slab can be pumped with four diodes. Each pair of diodes is polarization coupled, and each direction of the bounce is pumped. In theory, this would allow large amounts of pump power with which to excite a high power laser.

Lightwave has had experience with geometrical and polarization pump beam combination techniques. These techniques work well, but they require a substantial amount of mechanical engineering in order to be successful. Our experience had been that by the time a product is engineered for use with two diodes of a particular power, a single diode was available with the same power. This new, more powerful diode was not compatible with the carefully engineered beam combining optics. Lightwave essentially threw away a completely engineered Q-switched

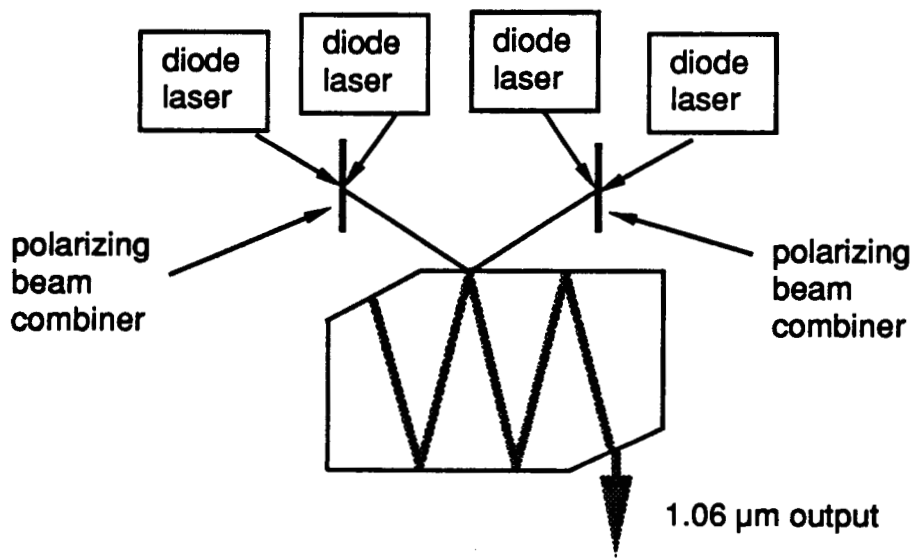
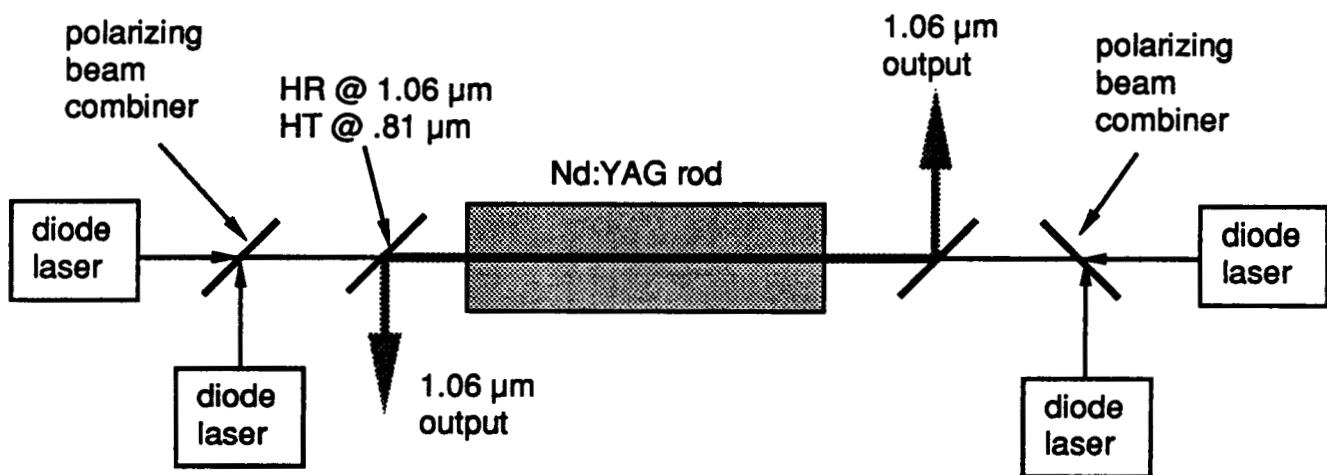


Figure 14 shows two possible configurations for end-pumping YAG with multiple laser diodes. A linear laser rod is pumped with four laser diodes using polarization combining. The zig-zag slab on the bottom is shown end-pumped with four laser diodes at one of the non-total internal reflection points, but could be pumped at the other vertices, in both directions, as well.

laser design using beam-combining optics. The design was obsolete by the day it was complete, due to the availability of 1-Watt diodes. That system used two 200-mW diodes. This experience led us to take the following approach: We would seek to build the biggest possible laser using a single diode pump before we started using beam-combining techniques.

Due to the previous success of the MISER, the nonplanar monolithic ring resonator was studied for use at high powers. The first experiment was to pump one of the monolithic rings designed for use with a 30-mW laser diode with a larger pump laser diode. We obtained a laser diode from the Sony Corporation with an output of 175 mW. This laser diode had an emitting aperture of 50 microns, rather than the 2 or 3 micron aperture of a 30 mW "single-stripe" laser. The light from this extended aperture cannot be focused to a small spot as easily as the light from the single-stripe diode. A simple single-lens imaging system such as is used for our single-stripe laser will lead to a pump beam substantially larger than the fundamental mode of the laser resonator. If the pump beam is larger than the lasing mode, higher-order spatial modes will oscillate. We designed an imaging system which used a pair of spherical mirrors to reshape the beam in a way that minimized the spot size of the light from the 50- μm aperture of the Sony laser diode. The ellipticity of the pump beam was reduced by a factor of four, and the astigmatism eliminated. A patent on this imaging system has been applied for. Using this reshaped pump beam and a standard design ring laser, we were able to obtain an output power of 55 mW. However, the output was not in a single transverse mode. Additional transverse modes were clearly visible as additional rings when the laser beam was passed through an etalon.

These early ring experiments did not lead to single mode power, but the laser was unidirectional and there were no multiple axial modes. We decided that the MISER approach would be workable if the TEM_{00} mode volume could be expanded to include all of the pumped volume. Our efforts were concentrated on designing monolithic rings with greater TEM_{00} mode volume.

2. Monolithic Rings with Curved Surface

The matching of the pump beam to the TEM_{00} mode volume is one of the critical aspects of the design of diode-pumped lasers. If the pumped volume extends beyond the TEM_{00} mode volume, then the TEM_{00} mode cannot extract all the stored energy. Gain remains in the laser material, which pumps higher order transverse modes. The laser will not be diffraction-limited or single frequency. If the TEM_{00} mode volume is too large, then there may not be adequate gain. When designing for low power pumps, the problem of low gain is important. With high powered pumps, the problem of multiple transverse modes is much more serious. The primary problem in the design of diffraction-limited high-powered diode-pumped lasers is the problem of minimizing

the pumped volume while maintaining a TEM₀₀ mode volume big enough to avoid higher order modes.

The beam reshaping geometry described in the previous section minimizes the cross-sectional area of the pump beam from 50 μm aperture laser diodes over the absorption length of 806 nm light in Nd:YAG (about 2 mm.) The pumped volume is thus minimized. The design problem is to maximize the cross-sectional area of the TEM₀₀ mode.

The square of the beam radius w for the mode of a monolithic ring laser, for the case where $R \gg L$, is

$$w^2 = (\lambda/\pi n)[(RL/2)^{1/2}] \quad (1)$$

where λ is the wavelength of the laser in air, n is the index of refraction (1.82 in YAG), R is the radius of curvature of the curved surface of the resonator, and L is the round-trip path in the resonator. To increase w , it is necessary to increase either R or L . We have tried to increase R rather than L in order to maintain the small size and resultant large mode separation of our rings. All the rings built under this contract have path length L equal to 11 mm. The three values of R and the corresponding values of w are given in Table 4.

TABLE 4: Radii of curvature and mode radii of monolithic rings

<u>R</u>	<u>w</u>
16 mm	42 μm
60 mm	59 μm
160 mm	75 μm

The mode radius increases very slowly as the radius of curvature of the resonator is increased, in fact, Eq. 1 shows that w increases as the fourth root of R . The 16-mm curvature resonator was used with the 30 mW pump. This resonator did not run single mode with the 175-mW Sony laser. The 160-mm curvature resonator lased single mode at maximum power with that pump. The best output obtained with the Sony pump was 70 mW. Our commercial laser, the Model 120-03, makes use of Sony pumps and 160-mm radius-of-curvature resonators. The specified output power is 40 mW, which is obtained without difficulty.

We have fabricated monolithic resonators of both the old (90° out-of-plane) and new (4° out-of-plane) designs, at radii of both 16 mm and 160 mm. All of the 16-mm resonators lased successfully, and all of the old-style resonators lased successfully. Many of the 160-mm, new-style resonators failed to lase. Those that did had beam paths which were asymmetrical, though the design path has perfect symmetry. The greater difficulty of fabricating longer radius resonators is not surprising. As the radius of curvature is increased, the shift in the lasing path due to a mis-centeration of the center of curvature was expected to grow proportionally. The change in position

Δp of the self-replicating ray in a two-mirror resonator, with one mirror flat and the other of radius of curvature R , is given by

$$\Delta p = R \sin^{-1}(\Delta C) \quad (2)$$

where ΔC is the error in angular alignment of one of the mirrors. Our resonators have a thickness of 2 mm, with the nominal lasing path exactly centered, 1 mm from each surface. Thus if the sphere center moves by 1 mm, the beam path moves out of the laser crystal, and the laser will not lase. For a radius of curvature of 16 mm, the angular centration error corresponding to a 1 mm motion is $\sin^{-1}(1/16)$, or 3.5° , which is not difficult. For a 160 mm radius, we get 0.35° . This is a demanding tolerance.

Thus a simple two-mirror resonator with both faces perfectly flat is nearly impossible to build, since unless fabrication is perfect, no ray will have a closed path. What was surprising was the fact that old-style resonators of both radii showed essentially no evidence of fabrication error. We discovered that it had been theoretically predicted that highly out-of-plane ring resonators with an even number of reflection points would exhibit high tolerance for fabrication error [6]. Equation (2) is approximately valid for planar resonators, but for nonplanar resonators the change in the position Δp of the resonator beam is smaller. According to [6], the tolerance for highly out-of-plane resonators is given by an equation similar in form to Eq (2), but with R replaced by L , the round trip path length. This means that for our design, with $L=11.5$ and the maximum value of $\Delta p=1$ mm, we can have an angular error as large as 5° , no matter how large R is. Thus in theory very large values of R can be used, with correspondingly larger values of beam radius w .

3. All flat MISER

In order to obtain higher output powers, larger pump diodes are needed. Unfortunately, higher power diodes usually have larger emitting apertures, and thus can not be focussed to spots as small as are possible with lower power diodes.. This means that the mode volume of the chosen resonator must also be larger if oscillation in the TEM_{00} mode is to be maintained. One means of increasing the mode volume in a cavity is to lengthen the resonator. We preferred to use a short resonator, because the laser remains small and the mode spacing and range of tunability correspondingly large. Another way to increase the mode volume is to increase the radius of curvature of the output coupler. The radius of curvature of Lightwave's commercial low power laser is 16 mm, while for the commercial high power (40 mW) laser the radius is 160 mm. Larger radii of curvature at first did not seem practical, for the reason described above, that is, because the tolerances on angular centration become extreme. Once we understood the tolerance-reducing effects of highly nonplanar ring resonators, we became interested in resonators with very large curvature. The limit of large curvature is, of course, a planar surface. According to Eq. (1), a resonator with planar surfaces will have an infinite value of the mode radius w , and the mode will

be unconfined and unstable. Any small effect which corresponds to a positive radius will stabilize the resonator; any negative effect will destabilize the resonator, so that no laser is possible.

The predominant effect, which turns out to have a positive, or stabilizing effect on the laser resonator, is the effect of temperature gradients on the laser material. When high-power laser diodes are focused inside the YAG crystal, thermal gradients are created, with a higher temperature on the axis of the pump beam. A higher temperature leads to an increase in the index of refraction of the material, which gives rise to a positive lensing effect, equivalent to a positive radius of curvature. We have developed a simple model of this lensing effect. This thermal lensing effect is important because it limits the power available from a single ring resonator. If the lensing is too strong, the TEM₀₀ mode radius w will shrink, to the point where some of the pumped volume is outside the mode. This will lead to higher-order transverse modes.

The assumption which permits an approximate understanding of thermal focusing in diode-pumped lasers is that the thermal focusing that determines mode volume is due to the effective lens which exists right on the axis of the mode. Focusing is due to a quadratic index variation, so it is assumed that the parabolic index of refraction gradient that fits at the center of the mode is the one that determines the focussing. Thus we ignore the complex temperature distribution which exists in the pumped crystal, and pay attention only to the second derivative of the temperature field right at the center of the mode. This simplifies calculations greatly, and is probably not too far off, since most of the optical power is at the center of the mode.

The thermal lensing depends on the heat deposited in the crystal per unit cross-sectional area. The distribution along the axis is not significant - only averages along the axis. If the pump laser has a power P , then the heat deposited per unit cross-sectional area, Q , is given by

$$Q = 2 \eta_H P / \pi w_p^2 \quad (3)$$

where w_p is the radius of the pump beam and η_H is the fraction of the pump power which is converted to heat, typically 25%. According to Koechner [7], the focal length of a rod uniformly heated by a steady-state heat per unit area of Q is

$$f = 2 k / (Q dn/dT) \quad (4)$$

where k is the thermal conductivity of the material (0.13 Watts/cm-K for YAG) and dn/dT is the coefficient of change in index of refraction of the material ($7.3 \times 10^{-6} \text{ K}^{-1}$ for YAG.) A lens of focal length f has the same focussing power as a curved mirror of radius $R=2f$, so the effective radius of curvature for a resonator which has only a thermal lens stabilizing it is

$$R = 2 k \pi w_p^2 / (\eta_H P dn/dT) \quad (5)$$

For a 400 mW pump, focussed into a $w_p=100$ mm spot, with 25% conversion to heat, the effective radius of curvature is 1.12 meters. Substituting into Eq (1), we find that the spot radius of the mode, w_m , for this resonator is given by

$$w_m^2 = \lambda w_p \sqrt{L k / (\pi \eta_H P dn/dt)} / n \quad (6)$$

This equation shows that the mode radius w_m changes more slowly than the pump spot size w_p . It is desirable to have $w_p < w_m$ to avoid transverse modes. If this condition is not met, Eq. (6) indicates that it may be possible to achieve it by reducing w_p , reducing power P , or increasing resonator round trip path length L . Equation (6) can be solved for the power at which $w_p = w_m$. This solution is

$$P = L k (\lambda / w n)^2 / (\pi \eta_H dn/dT) \quad (7)$$

This indicates that with the same pump beam geometry, the TEM₀₀ power is proportional to resonator length. Longer resonators may be a means of increasing power. The disadvantage is slightly higher cost, and lower tunability, since mode spacing is smaller.

We built all-flat-surface ring resonators of the highly nonplanar old-style design. These lasers performed in a manner consistent with the thermal focussing calculations above. The effective radius of curvature of the resonator as a result of thermal lensing was experimentally determined. The spot size of the output 1.06 μ beam was measured as a function of the power of the incident diode pump beam. Solving Eq. (1) for R , we get

$$R = w_o^4 (n\pi/\lambda)^2 (2/L) \quad (8)$$

where n is the index of refraction (1.82 for Nd:YAG), λ is the wavelength (1.06 μ m), and L is the resonator length (11.5 mm).

The inverse of the effective radius of curvature is plotted as a function of diode power in Figure 15. The linear relation is in accordance with Eq. (5) up to a pump level of one watt of diode power. At this point, it was very difficult to maintain oscillation in the fundamental spatial mode. Too much focusing occurred, the mode volume decreased, and higher order modes were excited by the pump beam.

4. Efficiency of flat resonator

The amount of single-mode 1.06 μ m output is plotted versus the amount of incident diode power in Figure 16. The slope efficiency is 59%, compared to the theoretical maximum of 67%, the ratio of the output photon energy to the input photon energy. The threshold could not be measured exactly, since the resonator itself was a function of the incident pump power. These results were made with a monolithic YAG crystal that had a Nd doping concentration of 1.1%. A higher doped crystal was also tried, 1.4% Nd, but the efficiency was less; only 45%. The output coupler in both cases was about 1.2% transmissive.

The greatest amount of single-mode 1.06 μ m light was obtained by pumping a flat MISER crystal with a 2 W diode. 379 mW of TEM₀₀ light was observed, but the diode was turned down to 947 mW due to its large (100 micron) emitting aperture.

Effective thermal focusing vs input power

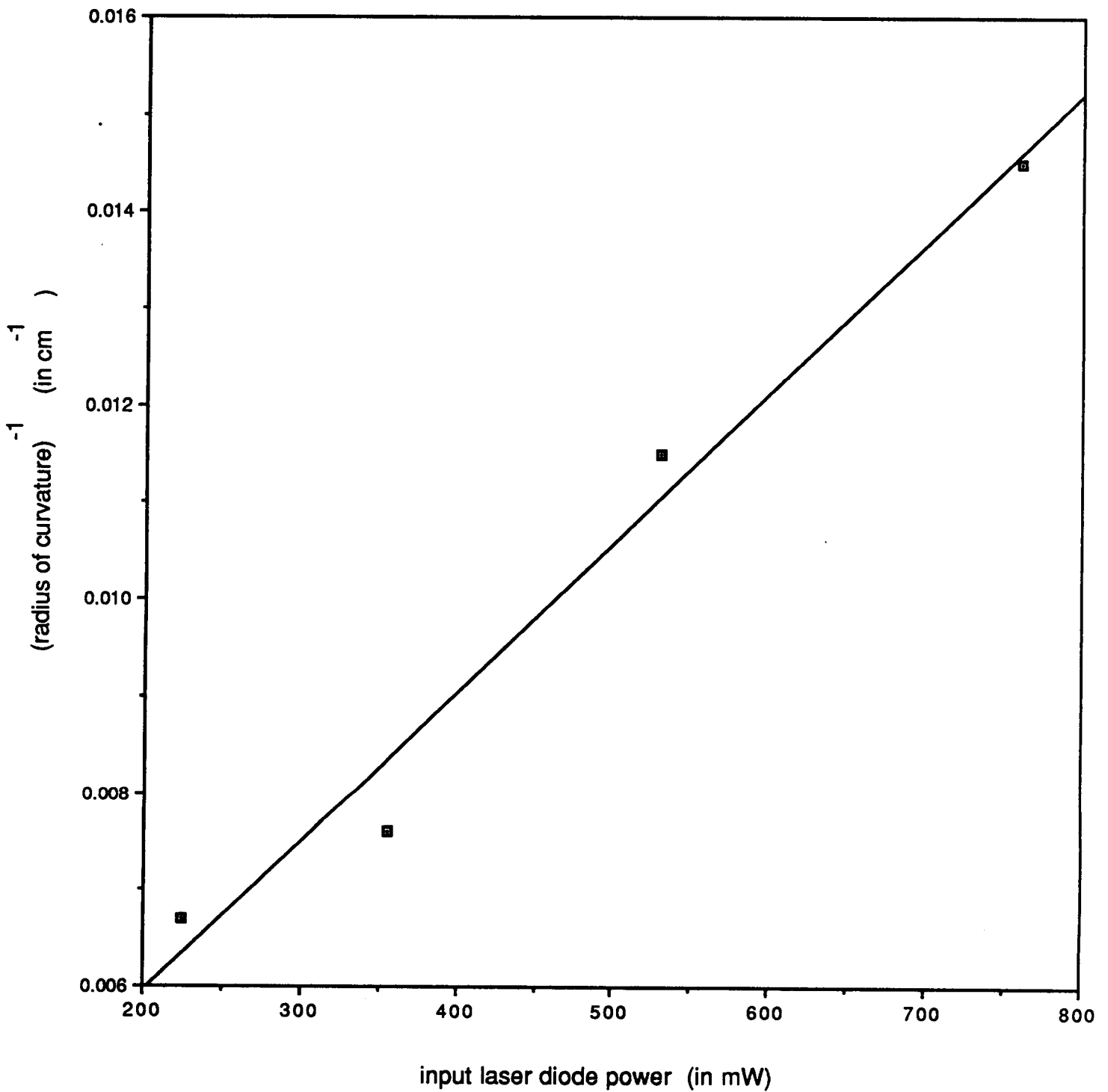


Figure 15. Inverse of the effective radius of curvature in an all-flat resonator as a function of the input diode power. As the diode power increases, the thermal focusing increases linearly, until about the one watt level of input diode power.

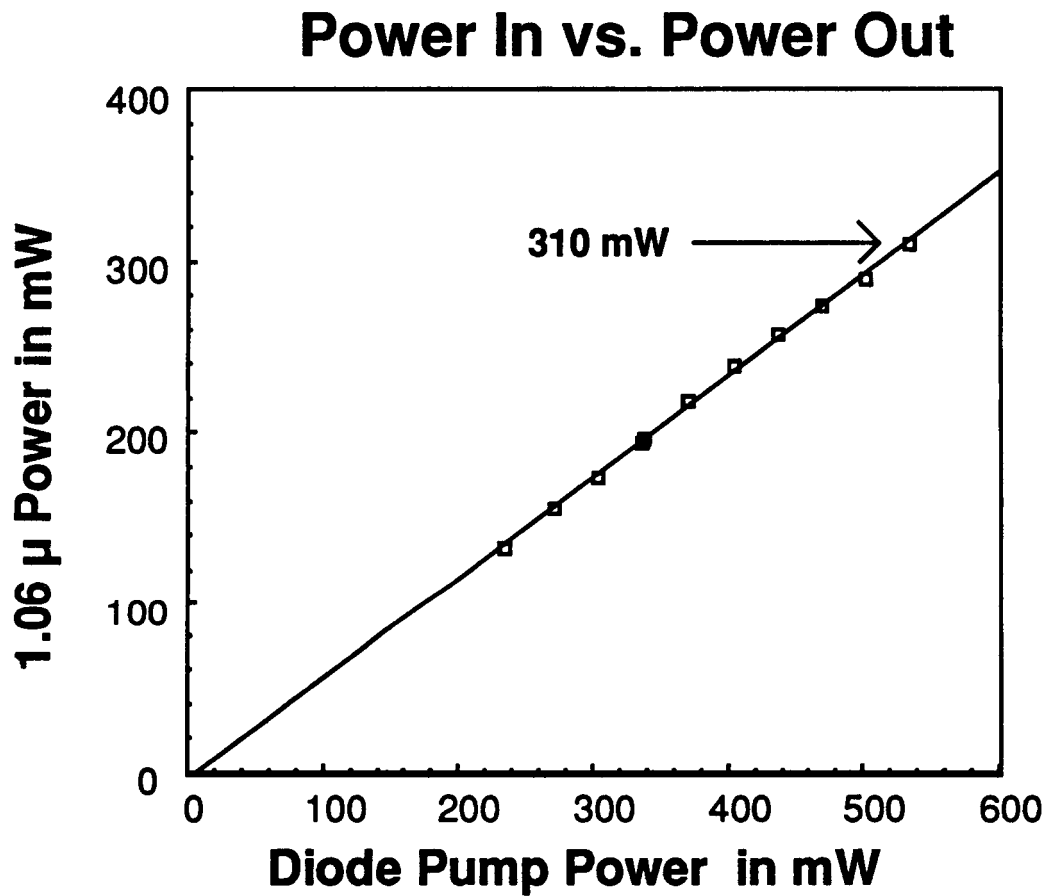


Figure 16. Optical efficiency of the all flat MISER resonators. 59% optical conversion efficiency is achieved from the input diode power to the 1.06 micron, single longitudinal mode output power. The pump used was an experimental low divergence Spectra Diode Labs diode with a 60 micron stripe width. This was critical to keep oscillation in the fundamental spatial mode.

5. Injection Locking and Chaining

In order to achieve higher output powers than would be possible with one laser, and to provide redundancy, we studied techniques for combining the power of a number of lasers into a single beam. A technique which works quite well for a moderate number of lasers is diagrammed in Fig. 17. This technique, which we call injection chaining, is only possible when the laser resonator is a ring. The output coupling face of a ring can be used as an injection point for light from another laser. Light from the other laser is reflected off the face of the resonator, and after the reflection, output from both lasers is co-linear. If the spatial matching between the lasers is good, then the power from both lasers is now combined in a single beam, which is diffraction-limited. The light will not in general be single-frequency, as the frequency of both lasers will be present. This technique of power-summing is practically limited to a few lasers by the excess complexity which results otherwise. A fundamental limit is due to the amount of power lost to imperfect optics in each stage. The power after N stages is

$$P_N = P + rP + r^2P + r^3P + \dots + r^{N-1}P \quad (9)$$

where P is the power of each stage and r is the effective transmission from stage to stage. For an infinite number of stages, the power is

$$P_{\max} = P/(1-r) \quad (10)$$

Thus it makes no sense to go much beyond $(1-r)^{-1}$ stages.

There is a well-studied technique, known as injection-locking, where a weak "master" laser is injected into the resonator of a more powerful "slave" laser. When the frequency of the master laser is tuned within a certain range of the free-running slave oscillator, the master laser locks the slave laser to its frequency and dominates the subsequent oscillation behavior. Traditionally, the power of the master laser is negligible compared to the slave laser, as in the case when a stable, low power laser is used to improve and quiet the output of a high power laser. For this study, the goal was to obtain high output powers by combining similar lasers of intermediate power while maintaining single-mode output. Therefore, this technique will be referred to as injection chaining.

When the frequencies of the two lasers fall within a narrow range of each other, locking occurs. This locking range is determined by the relative powers of the two lasers. From [8],

$$f_{\text{lock}} = 2a [\text{power of master laser} / \text{power of slave laser}]^{1/2} \quad (11)$$

where f_{lock} is the total frequency range over which the lasers are locked together, and a is the cold cavity bandwidth.

In normal injection locking, the power of the master laser is negligible to that of the slave laser. In the case of injection chaining, the powers of the two lasers are comparable. The power

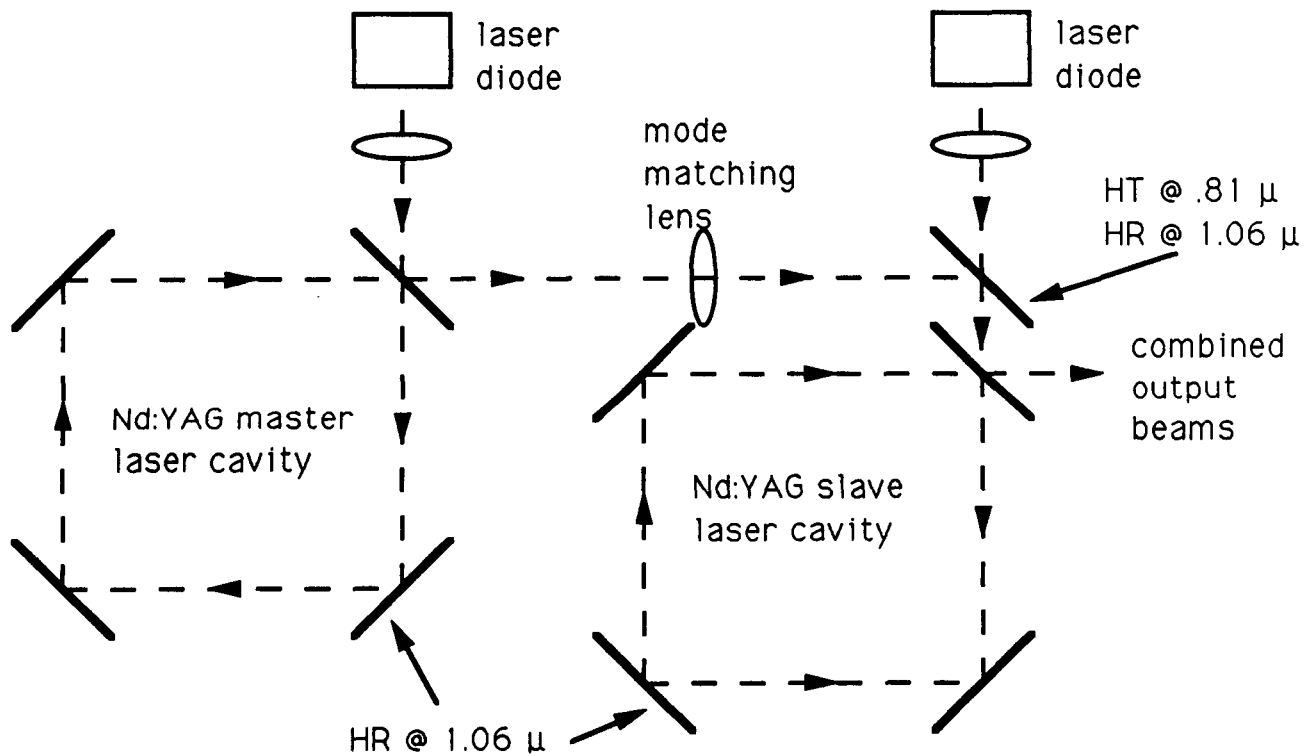


Figure 17 shows a basic diagram for injection locking. The output from the master laser is fed into the slave laser cavity. When the frequency of the injected signal is within a narrow range around the free-running frequency of the slave, the master "locks" and controls the subsequent oscillation behavior. When the two lasers are Lightwave's monolithic nonplanar ring lasers, unidirectional oscillation is established in the presence of a strong magnetic field.

of the combined output beam should therefore be the sum of the individual lasers. However, there are actually fluctuations in power in the locked range. When the two lasers are exactly the same frequency (no detuning) there is actually less power than the sum of the individual lasers. This is due to the master laser being resonant in the cavity of the slave laser. When the master laser is detuned from the center frequency of the slave laser, there is an increase in power above the simple sum due to the saturation in the slave's gain medium by the injected beam. At points outside the locking range, the power is simply the sum of the master and slave lasers.

The experimental set-up for injection chaining is shown schematically in Figure 18. The master laser, a MISER with a 100mW output, is mode matched with a 135mm lens AR coated for 1.06 μm into the slave laser cavity. This cavity is pumped with an experimental 500 mW SDL laser diode. The laser diode is temperature stabilized to control its wavelength. The monolithic crystal of the master laser has a piezo-electric element bonded to the top surface (as described previously in the local oscillator section of this report). With voltage applied across this transducer, the laser can be quickly tuned. The beam of the master laser is reflected off of a beamsplitter that is highly reflective at 45° for 1.06 μm and highly transmissive for 0.81 μm . The beams from the two lasers are carefully aligned for the best spatial overlap and detected on a silicon photodiode. The slave laser is temperature controlled to keep its wavelength stable, and the master laser's frequency is tuned until beat notes can be observed on the oscilloscope. As the master laser frequency is tuned even closer to that of the slave, the beat notes suddenly disappear as the difference frequency falls within the locking range. A completely flat DC signal is observed while the master laser is tuned in frequency through the entire locking range. Figure 19 shows the locking range sandwiched between unlocked regions, as a 60 Hz sine wave (about 40 volts peak-to-peak) is applied to the piezo-electric tuner. The master laser is being tuned more than the total locking range, and so the beat frequencies characteristic of unlocked regions are visible (they appear as thick white areas of the oscilloscope trace). The varying height of the unlocked regions is an indicator of the detection system response. The changing DC level of the locked regions shows the power variation with detuning as described in the previous paragraph.

The locking range can be measured by correlating the voltage needed to scan the entire locking range with the tuning coefficient (in this case, about 1 MHz per volt) of the piezo-tuned laser. This locking frequency range is plotted versus the square root of the ratio of the powers in Figure 20. These experimental results followed the same slope as the theoretical curve also shown on the graph. The deviation of the data from theory is due to incomplete coupling of the two cavities. Less power from the master laser is injected into the slave resonator than is theoretically possible, and so the master laser appears to be of a lower power rating. Since the locking frequency is proportional to the square root of the power of the master laser, the locking range depends on how well mode matched and aligned the two cavities are.

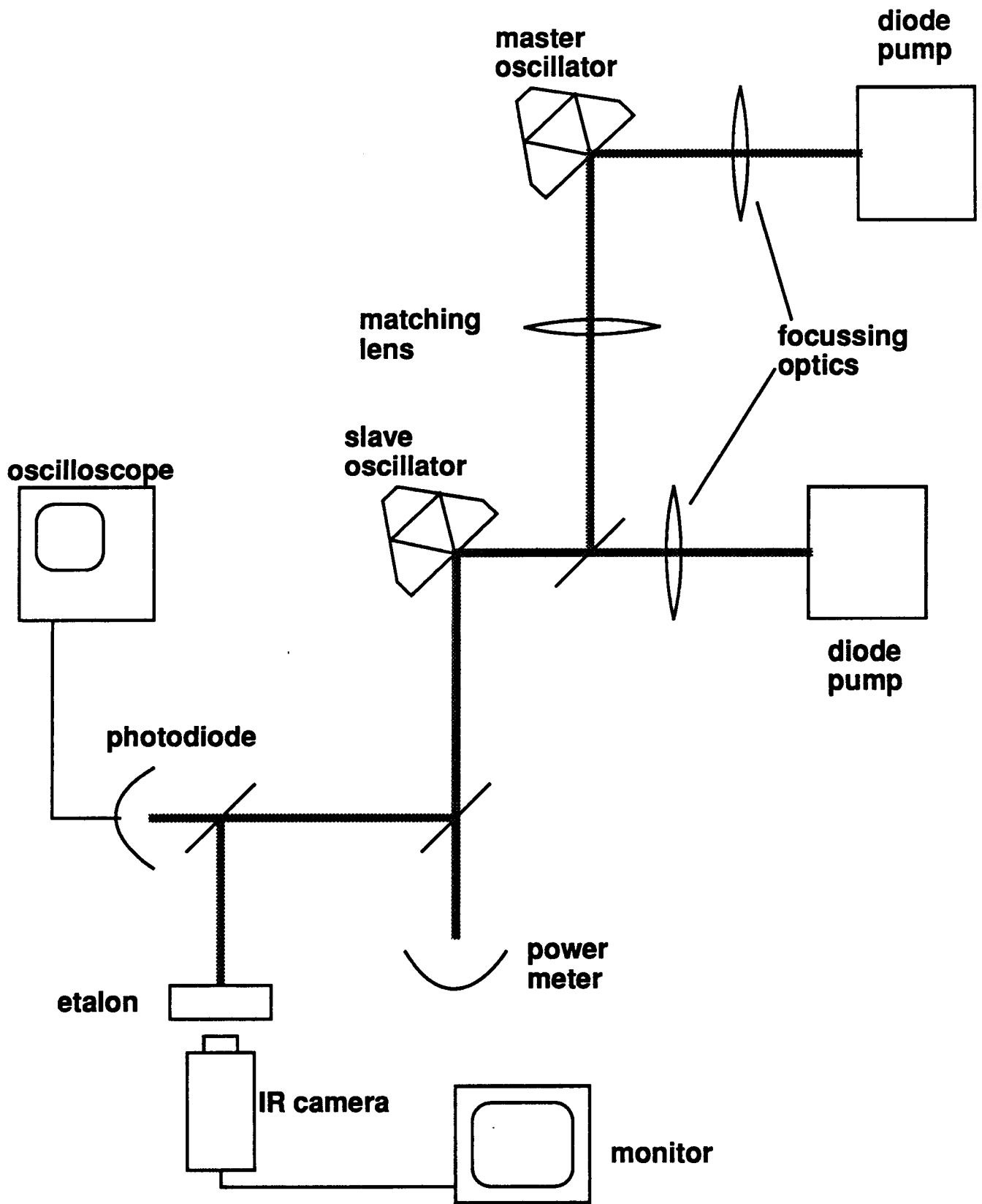
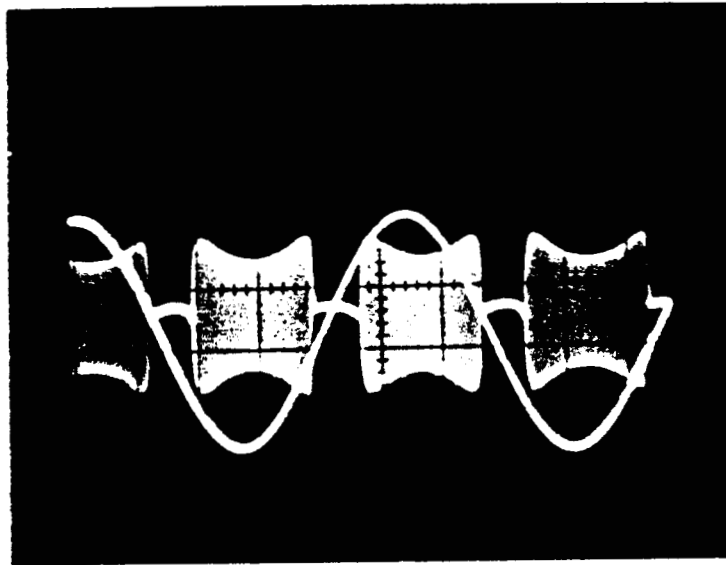


Figure 18. Experimental set-up for injection chaining. With this arrangement, the power output, mode quality, and locking range can be monitored simultaneously.

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modulating voltage 5 V/div
photodiode voltage 10 mV/div



2 ms/div

Figure 19. The injection locked regions can be seen as lines sandwiched between the thick white areas which are the unlocked beat frequencies. To obtain this photograph, the master laser was scanned at 60 Hz over a range of frequencies greater than the locking range. A 40 volt peak-to-peak sine wave was applied to the piezo-electric tuner on the master laser.

Locking Range vs. Field Strength Ratio

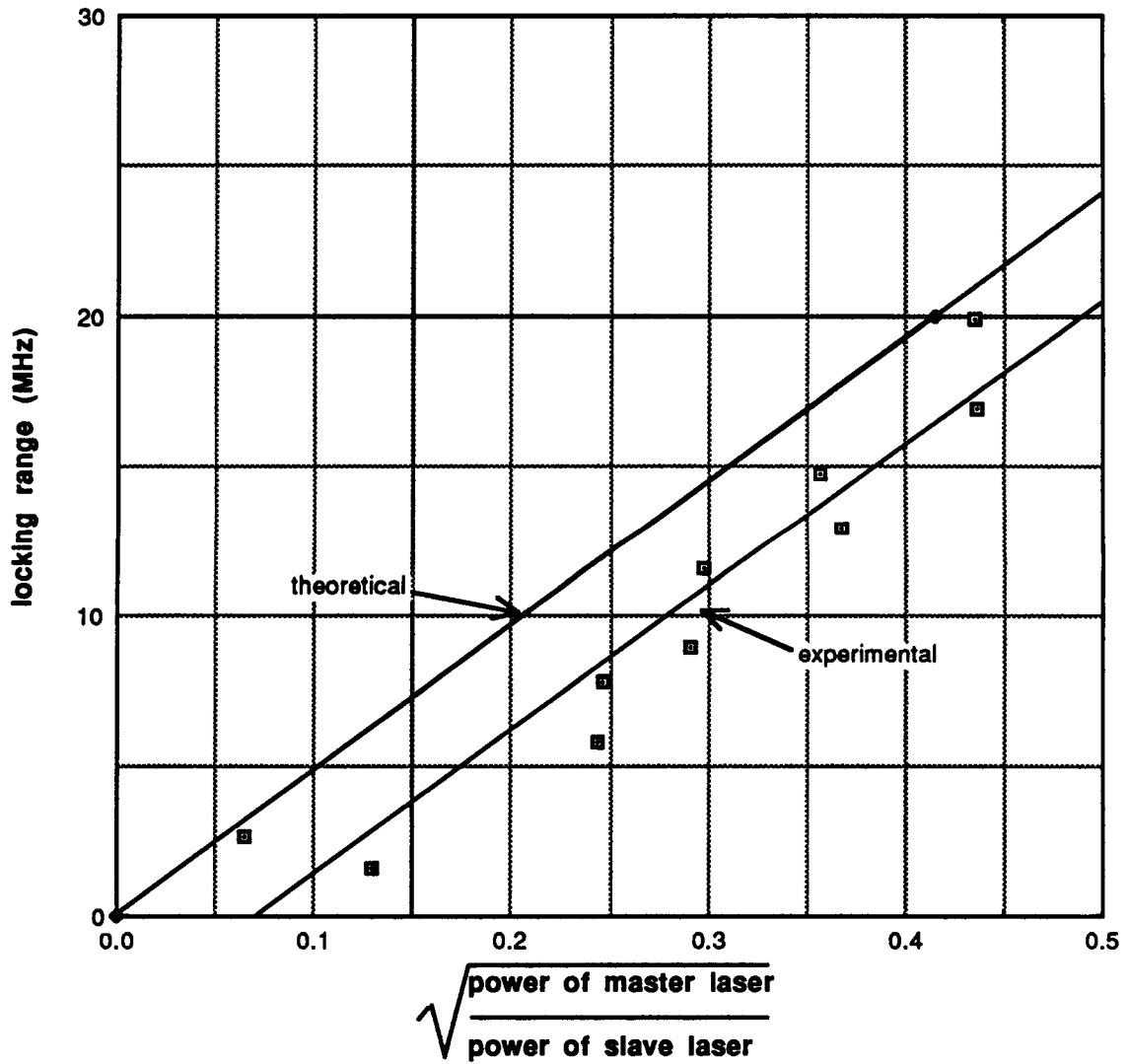


Figure 20. Locking frequency range versus the square root of the ratio of the master laser power to the slave laser power. Greater locking ranges are obtained with higher injected power from the master laser. The deviation from theory is due to imperfect mode matching between the two lasers and thermal effects.

Once the lasers are tuned within the locking range, they will remain locked for minutes at a time without any active feedback. Eventually, the two lasers will drift apart, since the usual drift rate is about 50 MHz per hour. Investigation into possible techniques for actively locking the lasers together was also undertaken. This revealed a promising discriminant to provide a correction signal to the master laser. The set-up for this experiment is shown in Figure 21. The combined output of the two lasers passes through a half-wave plate and then reflected off of a microscope slide placed approximately at Brewster's angle. The reflected beam, which is now mostly vertically polarized, passes through a quarter-wave plate which is set to rotate the polarization by 45° . The polarization is now 45° to the axis of a polarizing beamsplitter cube which the beam then passes through, splitting the beam into two orthogonal polarizations. The two beams are then detected on matched silicon photodiodes. One of the signals is inverted and then the sum of the two is displayed on an oscilloscope. Scanning the frequency of the master laser by applying a sine wave to the piezo-electric tuning element results in a highly dispersive waveform that can be seen on the oscilloscope trace in Figure 22. The "folding" at the top and bottom of the waveform is due to saturation of the detectors. This discriminant is based on the phase change of the master laser beam on reflection from the slave cavity while in resonance [9].

6. Modular laser delivered to NASA

Two high-power laser modules were delivered to NASA in June 1989. Both units of the pair contain all-flat highly-nonplanar resonators pumped by a single laser diode. The laser diode is a developmental type produced by Spectra-Diode Laboratories of San Jose, California. The diode is specified as S8106. This diode has an emitting aperture of $60\ \mu\text{m}$ and a divergence of 30° . Both of these numbers are very low for a high-power diode, and that is good. Low emitting aperture and low divergence make it much easier to focus the light to a small spot. This type of laser diode can be operated at 500 mW output for short times, but lifetime is shortened for powers greater than 300 mW.

These low-divergence diode pumps led to extremely efficient diode-pumped lasers. We have never seen efficiency greater than 40% with any other type of diode, and we achieved 59% using the low-divergence type. The high power and small spot allows us to build lasers which are many times above threshold, and which absorb the pump power totally inside the TEM_{00} mode. Both of these factors lead to high efficiency.

A problem with this type of laser diode is the high level of amplitude noise. This amplitude noise in the laser diode leads to a high level of relaxation oscillation noise in the diode-pumped laser. The highly efficient diode-pumped lasers built with these diodes have RMS amplitude fluctuations of 3.4%, compared to a typical level of 0.3% in the standard diode pumps we use for

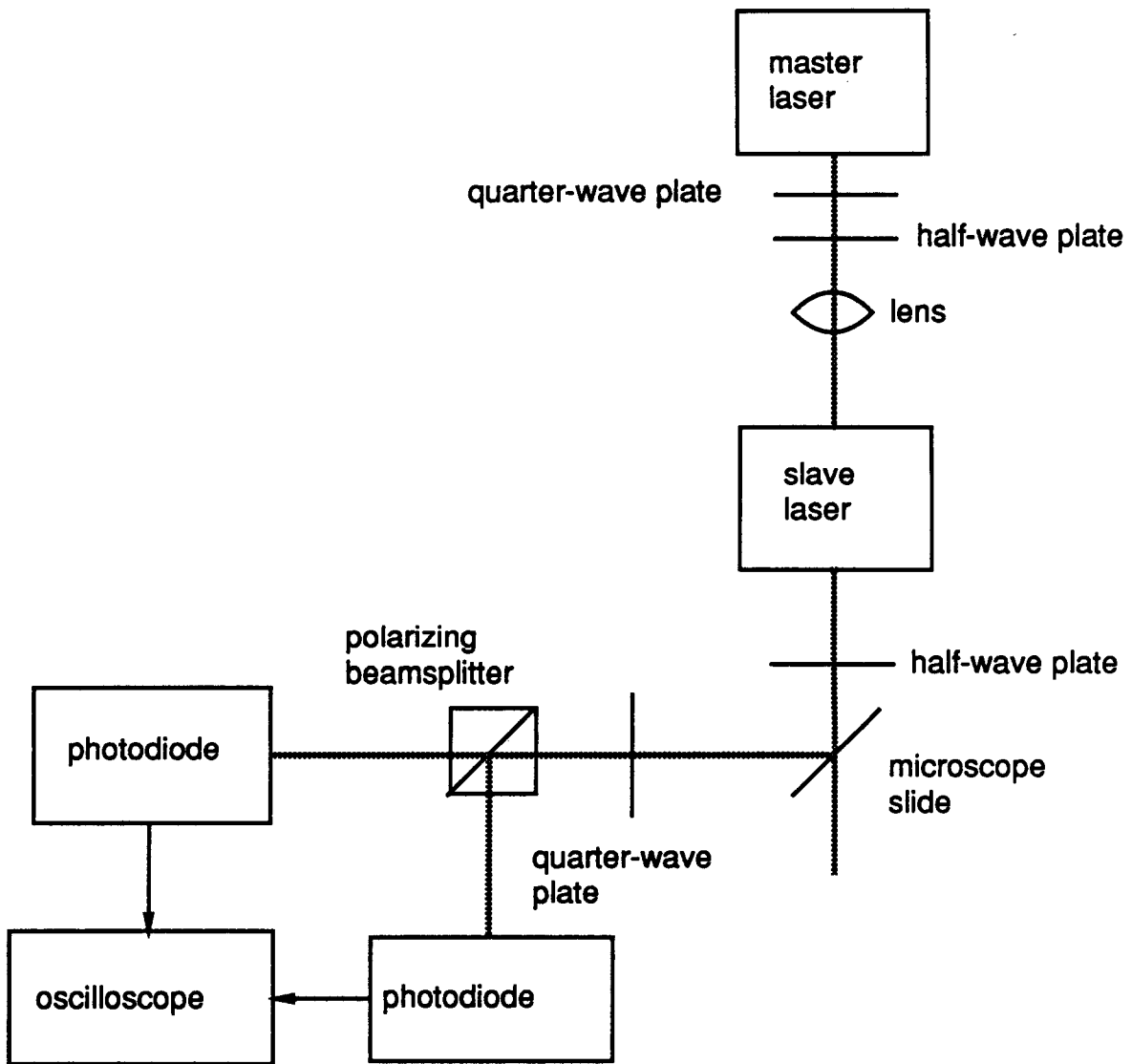


Figure 21. Set-up for creating a discriminant with which to actively lock the two lasers together, based on a phase change between the two lasers.

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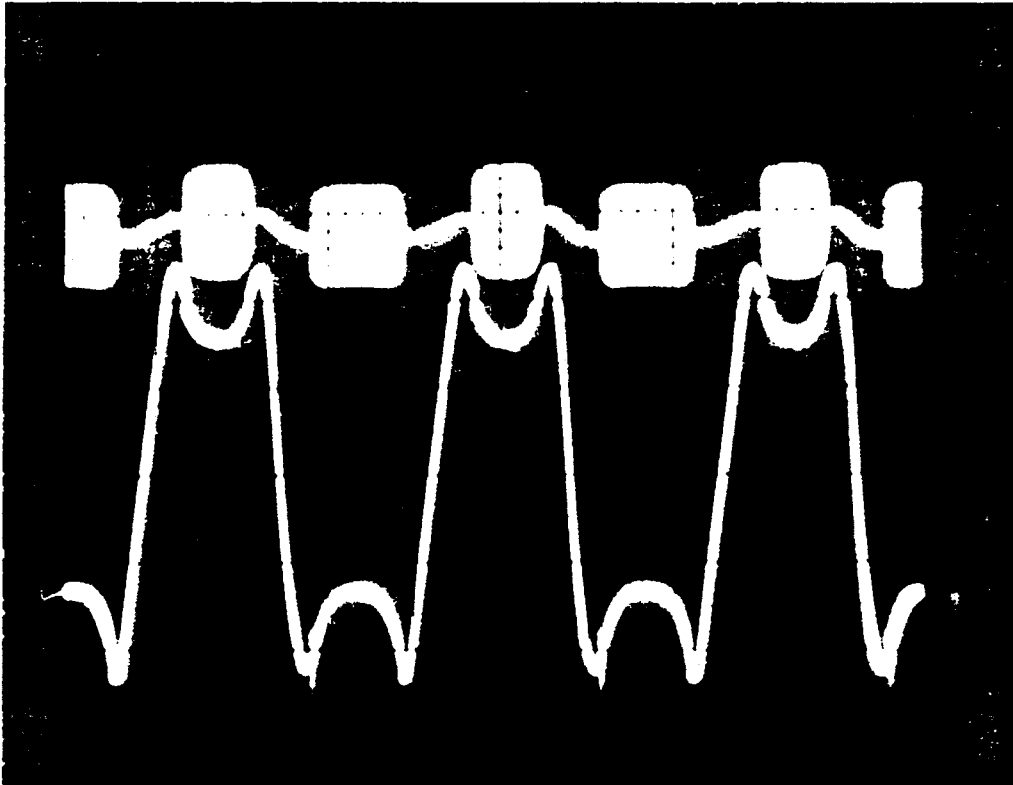


Figure 22. Highly dispersive waveform resulting from the difference in phases of the two lasers during the injection locked region.

commercial products. Whether or not this noise is a serious problem depends on how the laser is used. The diode manufacturer is working to reduce the noise. We may try to use our noise reduction electronics to reduce the noise, because the efficiency of these lasers is so good.

The two delivered modules are package in an injection-chained configuration. The first, or master, laser is of the same design as Lightwave's "Model 120-03" 40-mW laser. Figure 23 is a photo of the delivered laser. The diode laser power supply is set for maximum output from the laser diode of 425 mW. At this level of pump power the output from the YAG laser is 170 mW. This high level of power should not be used for more than a few minutes at a time. The long-lifetime level of power from the diode is 325 mW. At this level of pumping, the output is 135 mW.

The second, or slave, laser has only one design difference from the master laser. The slave has an input window and lens as well as an output window and lens. This "input port" is exactly equivalent to an "output port" designed for the ring laser when it is lasing in the wrong way. In fact, the input port was aligned by forcing the laser to run backwards and aligning components to that backward beam.

The assembly containing both lasers has an adjustable mirror which is used to direct the beam from the master laser into the input port of the slave laser. This beam strikes the laser resonator and is directed through the output port of the slave laser. The transmission from the output of the master to the output of the slave is 93%. This is the fraction of the master laser which will be added to the power of the slave when it is turned on.

The maximum combined power from master and slave, with both pumps putting out 425 mW, is 340 mW. With the pump power turned down to a long-lifetime level, the combined output is 260 mW. The optics included in the delivered system assure that the combined output of the two lasers is TEM₀₀. The output will also be single frequency if the two lasers are frequency-matched to within 40 MHz. This matching is possible by adjusting the precision temperature controller on each laser. The temperature controller is stable enough that locked, single-frequency operation is possible for 75 minutes without adjustment. After longer time, the two lasers drift out of lock, and the frequency difference between the two lasers is observed.

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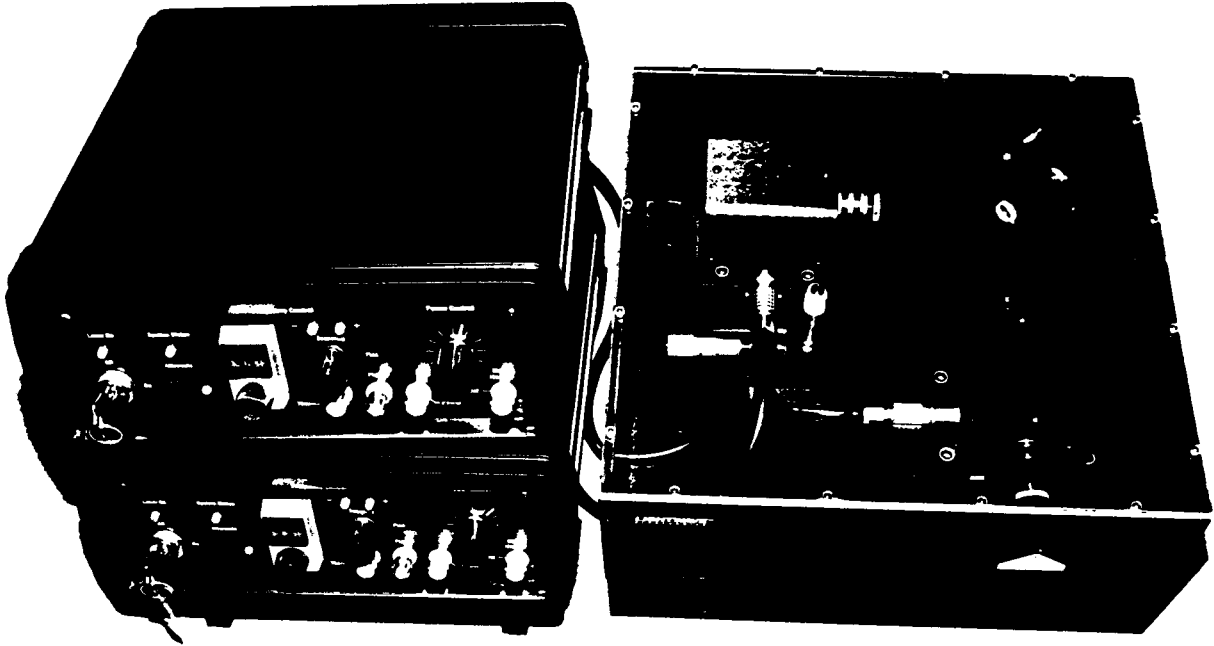


Figure 23. High power laser unit delivered to NASA JPL. The total output power reached 340 mW.

V. REMD (Resonant External Modulation and Doubling)

1. Mechanical Analogy

Resonant external modulation and doubling can be illustrated with the help of an analogy. In Figure 24, a small continuously-operating motor turns a flywheel. The flywheel is designed for very low mechanical loss, so a large kinetic energy can be stored. A second wheel can be either engaged with the flywheel, or disengaged. It is clear that if the second wheel is usually disengaged, then upon engagement large peak powers, greatly exceeding the continuous power of the motor, can be transferred to the second wheel, and utilized. The continuously-running motor is utilized efficiently, since its power is steadily being transferred to the low-loss flywheel. Large powers may be extracted from the flywheel at random intervals with precise timing control, and there is no need for a large motor capable of generating the large power directly.

In the optical system we call a Resonant External Modulator and Doubler (REMD) we use a cw single-frequency laser (analogous to the motor,) a large resonant cavity external to the laser (analogous to the flywheel,) and a second resonator which is both nonlinear and electro-optically tunable (analogous to the second wheel.) The large cavity is held in resonance with the laser, so that the circulating power is over 100 times greater than the laser output. Usually the second resonator is out of resonance with the first, so there is low power circulating in it, and no conversion to the second harmonic. When a pulse is desired, the second resonator is electro-optically tuned into resonance with the first cavity. and large power builds up in the second resonator. This large power results in some of the power being converted to green. This power is not held in the cavity, but is transmitted. The green pulses may have a peak power well above the power of the 1.06- μm cw laser.

2. Possible Configurations

Two configurations for a REMD system were considered. A linear and a ring configuration are shown in Figure 25. The linear configuration is easier to align, but an optical isolator is necessary to avoid destabilizations from feedback. The ring configuration avoids the feedback problem, but involves more optics and alignment time. The laser must be mode matched into the large cavity, which must be mode matched to the small cavity. For this experiment, a ring configuration was chosen. Instead of a small second cavity composed of discrete optical components, a monolithic ring resonator was used. This cavity is a solid piece of magnesium-doped lithium niobate, fabricated with two total internal reflections. The front curved surface is

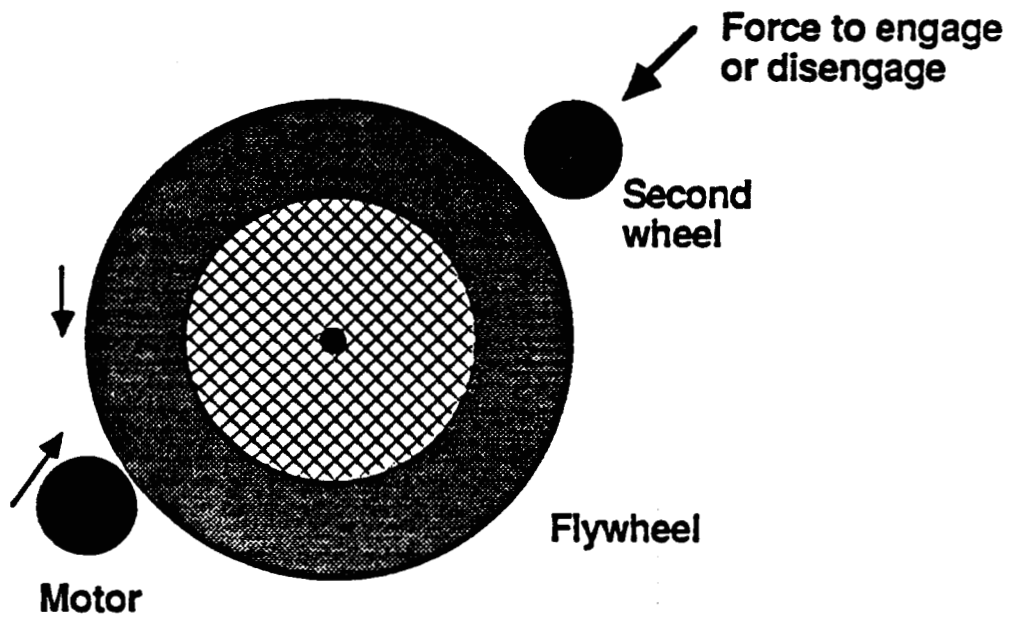


Fig. 24. Mechanical analog of resonant external modulator / doubler. Motor continuously powers flywheel. Large peak power can be extracted when movable wheel is occasionally engaged with flywheel.

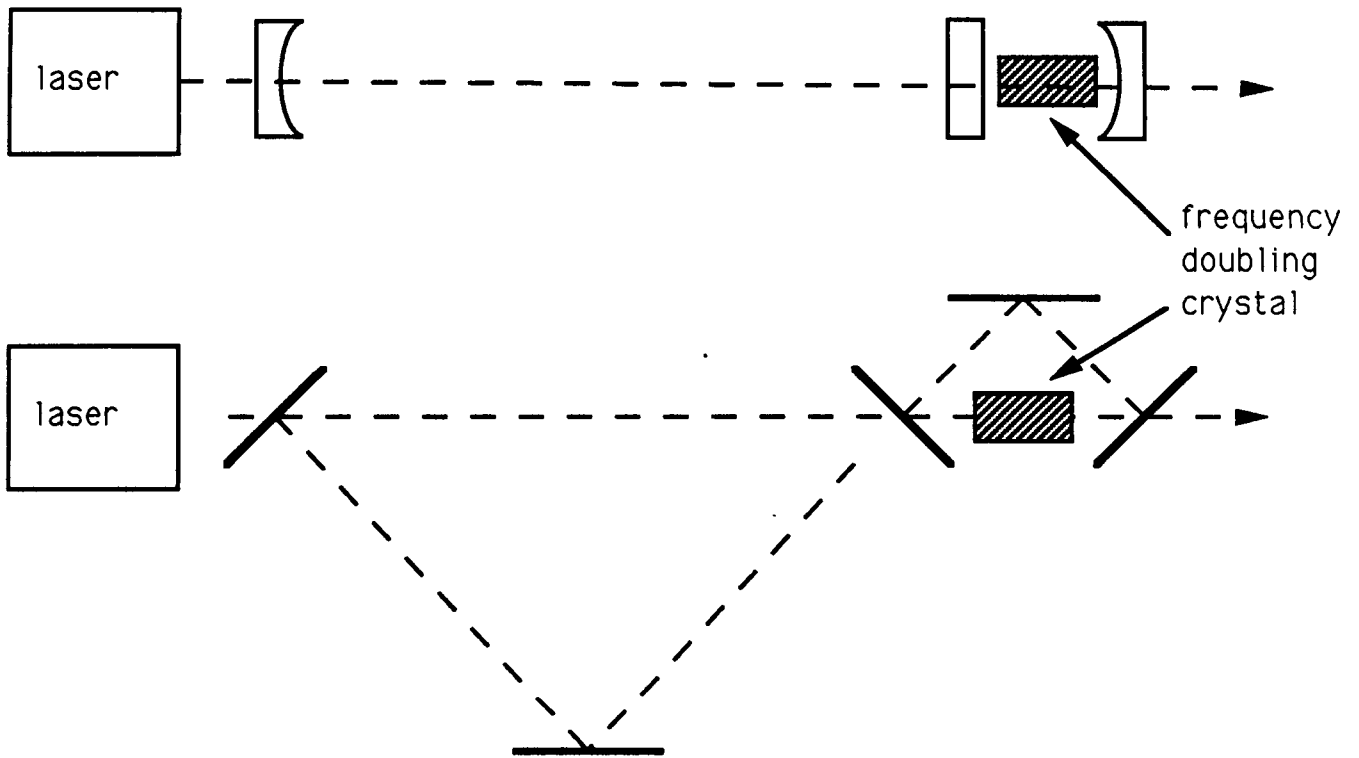


Figure 25 depicts two possible configurations for resonant external modulation and doubling. The first layout has two linear, standing wave cavities. The first cavity consists of the curved mirror next to the laser and the flat mirror on the left of the frequency doubling crystal. The second cavity contains the nonlinear material and is bounded on the right by a curved mirror which is highly reflective for 1.06μ light and transmissive for 532 nm light.

The lower configuration consists of two traveling wave ring cavities. The large empty cavity "stores" energy, which is then "dumped" quickly to the smaller ring cavity when brought into resonance.

polished and coated to be 98% reflective at 1.06 μm . The top and bottom surfaces of this crystal are gold plated to allow electrodes to be attached to it, as shown in Figure 26. The crystal was held in between copper plates with leads soldered on. Electric fields can now be applied across the crystal, to induce changes in the refractive index via the electro-optic effect. This changes the effective length of the crystal. The laser frequency is tuned to resonate in the large cavity, so large circulating powers build up. The small cavity stays off resonance during this time, so its internal fields are small. When a pulse is desired, the small cavity is quickly switched into resonance with the right voltage. The large circulating power in the large cavity is now suddenly made available (dumped) to the small cavity, and an intense green pulse is emitted.

3. Experimental Set-up

As diagrammed in Figure 27, a 50 mW laser is mode matched with a 7.5 cm focal length, AR coated lens, into a large cavity, consisting of a 98% reflecting flat mirror, the coated, curved surface of the doubling crystal, and an HR mirror with a 40 cm focal length. The round-trip length of the cavity is about 79 cm. The doubling crystal's front surface has a radius of curvature of 26 mm and a round-trip path length of 25 mm.

Instead of designing the electronics to lock the laser frequency to the large cavity, a simpler approach was taken. The HR 40 cm mirror was mounted on a piezo-electric stack, which was scanned slowly at 60 Hz to bring the cavity in and out of resonance with the laser. The doubling crystal was quickly switched with a function generator to scan the small cavity through resonance at a fast rate compared to the large cavity. Pulse trains of green light were detected, corresponding to peak powers of 50 mW of 532 nm light. The envelope of the pulses is the 60 Hz cycle of the large cavity resonance with the laser frequency. The lithium niobate ring resonator (the small cavity) was tuned at about 300 kHz over a 30 Volt range, giving 2% of a free spectral range of tuning, or 7.2° of modulation, if a full free spectral range is 360° .

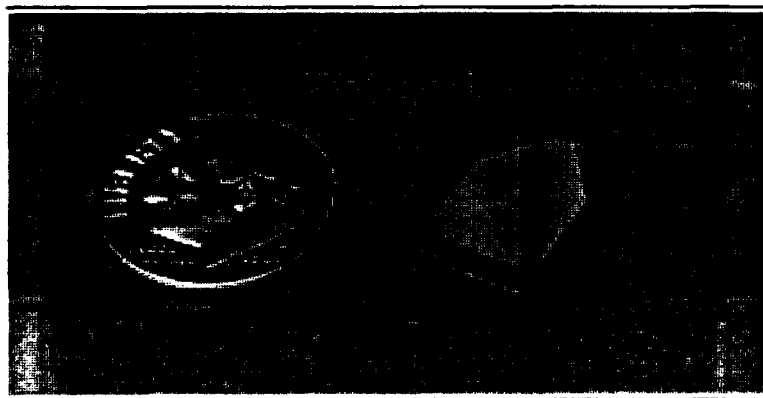


Figure 26. The monolithic, lithium niobate ring resonator used as the second cavity in the resonant external modulation and doubling technique.

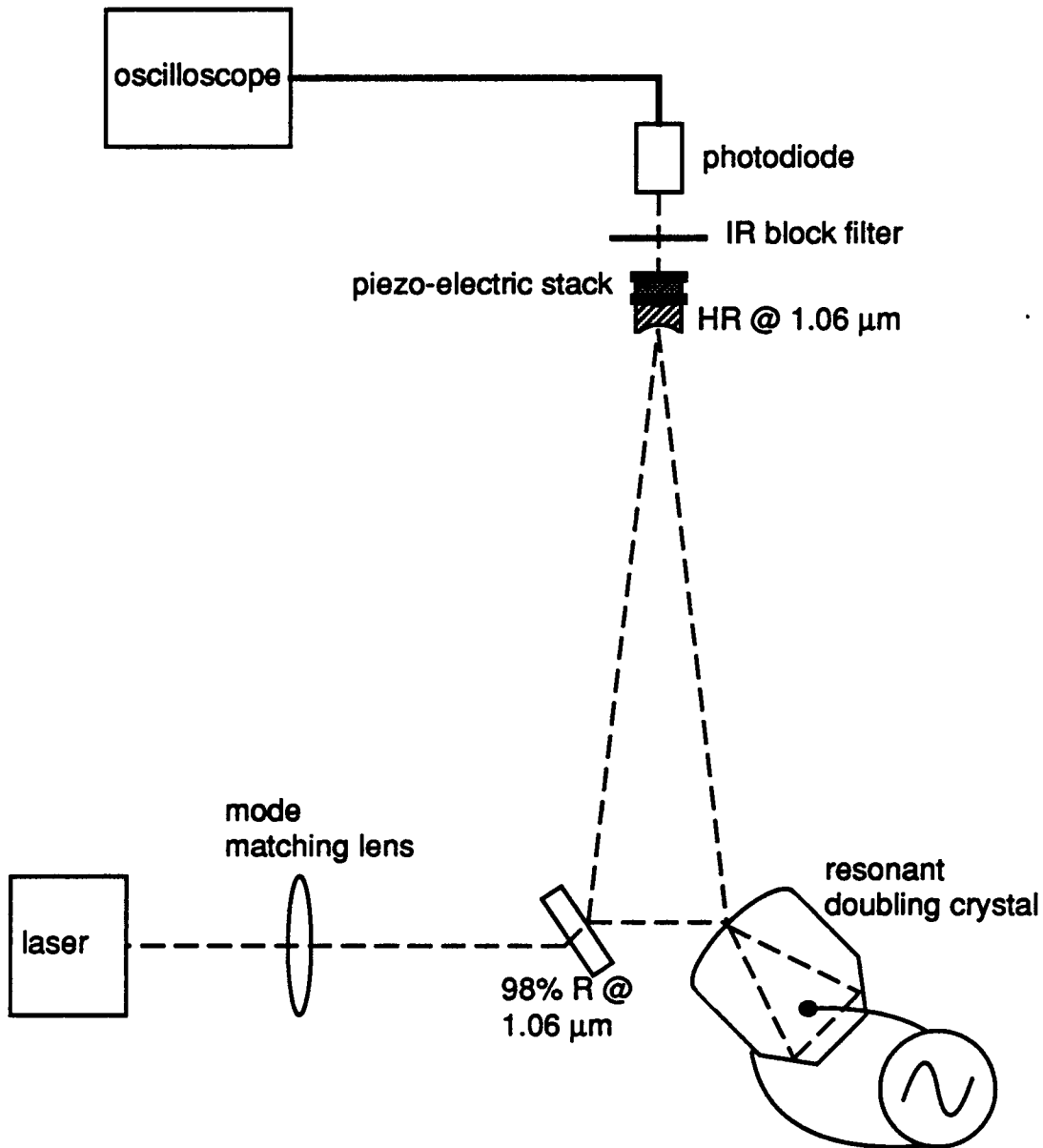


Figure 27 shows the experimental set-up for resonant external modulation and doubling. A 40 mW MISER laser is mode matched into a large cavity consisting of a 98% reflecting flat mirror, a 40 cm focal length high-reflecting mirror, and the front curved surface of a magnesium-doped lithium niobate resonant doubling crystal. This monolithic non-linear crystal is the second resonator, consisting of the front coated surface, and two total internal reflections. It has electrodes attached to the top and bottom surfaces, so its index of refraction (and effectively, its length) can be changed via the electro-optic effect. When the MISER is resonant with the big cavity and not the small one, high circulating powers build up in the large cavity. Then, the small monolithic cavity is quickly switched into resonance with the large cavity. The stored energy is then "dumped" into the non-linear crystal, and a powerful green pulse results.

4. Computer model

A computer program was written which modelled the REMD process. A more complete description of this model is given in Appendix 2. This model is a one-dimensional finite-element model. The program divides the two resonators of the REMD system into a few hundred elements. This division is along the direction of propagation of the beams - the transverse field distribution is assumed to be Gaussian. The amplitude and phase of the light in each element is stored. The program works by keeping track of what happens to light in each element in the few picoseconds which it takes to transit through the element. In most elements, nothing happens - the light is simply translated into the next element. In the electro-optic element, the light is either phase shifted or not, depending on whether or not the second cavity is in or out of phase with the first. In the doubling element, some green light is created, proportional to the square of the infrared power. The infrared power is reduced by an amount which conserves energy. The two points where the most happens are where the beam from the laser enters the first cavity, and where the two cavities meet. At these points the complex amplitudes of the two beams are combined according to the reflectivity of the mirror. Losses are also accounted for at the mirrors.

The parameters which define the particular REMD system being modelled are entered from a menu. This menu is shown in Table 5, along with the definition of each parameter. The values shown are for a hypothetical well-engineered system pumped by a 1-Watt laser.

The program begins with the steady-state solution stored in each element. The system is assumed to have been in the "no transmission" mode for a long time. Once the program begins, the power in each element is calculated as a function of time. The output of the program is the power of the green light transmitted from the second cavity, as a function of time.

This program, and a companion program which did a crude information analysis of the transmitted green pulses, were delivered to NASA. More details of these programs are found in Appendix 2.

The computer model was used to estimate the performance of REMD systems which we thought were achievable, and also to model the system we actually built. Figure 28 shows the pulse train transmitted from a system pumped with a 1 Watt pump. The large ratio of peak power transmitted to cw input power is apparent.

TABLE 5

Parameters Defining Resonator:

- 201.0000 A: Length of 1st resonator half-round-trip, mm.
- 12.0000 B: Length of 2nd resonator half-round-trip, mm.
- 99.0000 C: Reflectivity of input mirror, %.
- 80.0000 D: Reflectivity of coupling mirror, %.
- 0.3000 E: Loss in first cavity, %.
- 1.0000 F: Loss in second cavity, %.
- 97.0000 G: Coupling efficiency, % of transmitted light.
- 0.2500 H: Nonlinear coefficient, % / Watt.

Parameters Defining System Inputs:

- 1.0000 I: Input power, Watts.
- 90.0000 J: Modulation phase, degrees.
- 1.0007 K: In-phase time period, nsec.
- 1.5610 L: Length of single time slot, nsec

Parameters Defining Calculation Format:

- 0.3903 M: Period between data outputs, nsec.
- 3.0000 N: Length of elemental light slice, mm.

Files for I/O:

- REMD.IFL O. Access file for data stream
- REMD.OFL P. Output file, transmitted light
- REMD.MFL Q. Name of this master file

RESONANT MODULATION AND DOUBLING

Example Case REMD.OFL

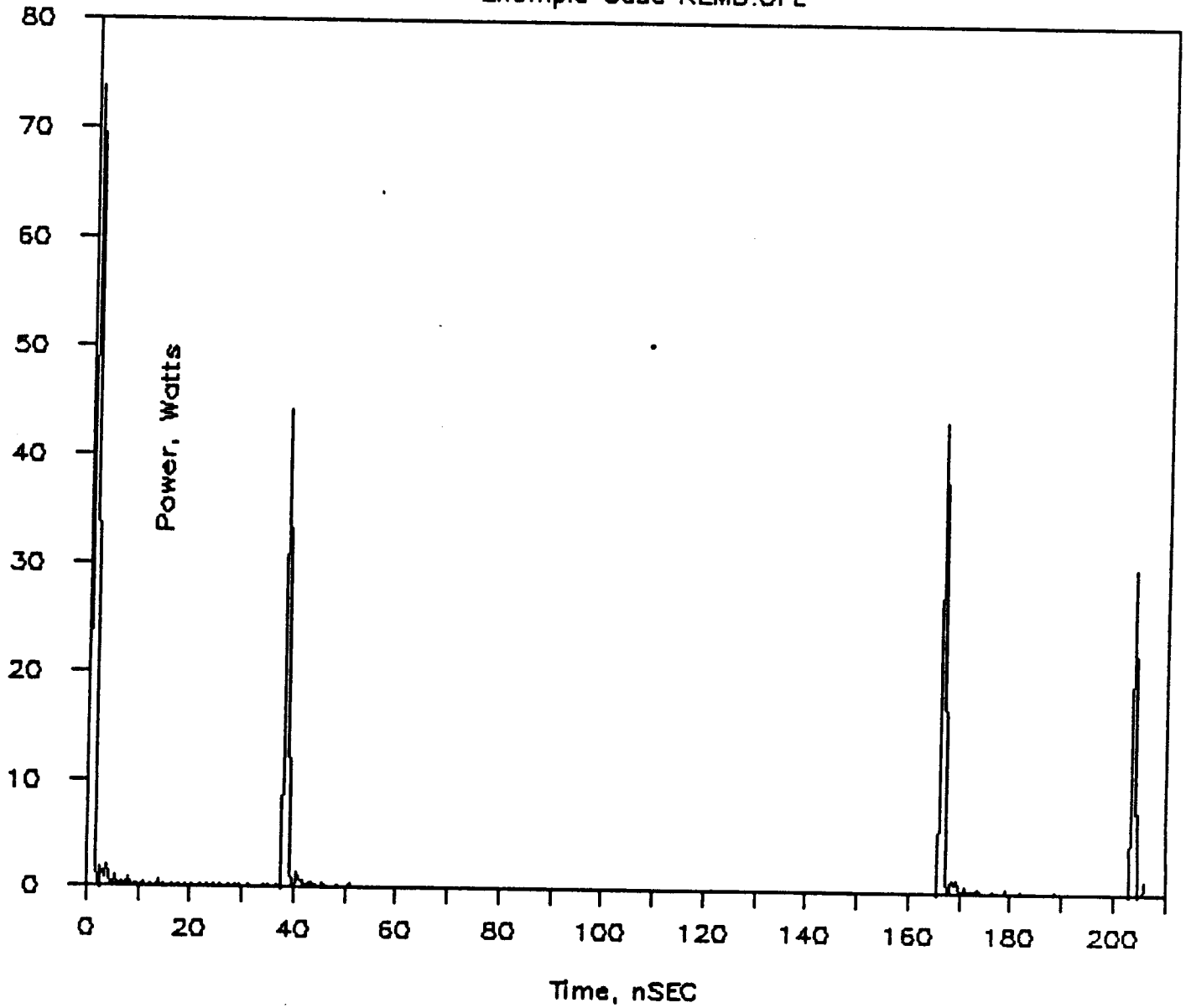


Figure 28. Theoretical pulse train transmitted from a REMD system pumped with a one watt laser.

5. Verification of program results with bench-top results

The system we actually built did not have a 1-Watt pump, and many other aspects of the system were not what could be achieved in an engineered system. We built it mostly to verify the computer model. The experimental results agreed with those predicted by the computer model. Peak green pulses of 50 mW were obtained with this set-up. Oscilloscope traces of a single pulse and the pulse train are shown in Figure 29. The factor limiting the peak power of the green pulses was the rate at which the second, small cavity could be switched into resonance. Higher powers were achieved as the switching time decreased, until the point when the speed was instrument limited. The full width of the green pulse (at the half-maximum point) was measured to be less than 13 nanoseconds. Higher peak power pulses corresponded to thinner pulses. The computer model predicted peak powers of around 45 mW of green light in a 15 nanosecond pulse. The values of the input parameters for this case are shown in Table 6. Some values, such as the reflectivities of the mirrors and the cavity lengths, can be determined in a straightforward manner. Others, however, such as the coupling between the two cavities and the in-phase time period, are not easily measured. Coupling into the large cavity by the laser is not taken into account with this model, and so the initial input power, Parameter I, was reduced to the amount that was estimated to mode-match well into the large resonator. This value was estimated at about 50% of the initial laser power, or 25 mW. The two cavities were not perfectly matched, and so Parameter G was set at 60%. Parameter J, the electro-optic phase shift, was set at 10° . This is equal to the ratio of the voltage applied to the doubling crystal compared to the voltage needed to tune the crystal over a full free spectral range. The model assumes that instantaneous switching into resonance occurred, while the best that could be achieved experimentally was only 120 nanoseconds. All these uncertainties mean that a precise quantitative test of the model was not possible. Nevertheless, we are confident that the model is useful for factor-of-two estimates of system performance.

Figure 30 is a photo of the benchtop experiment used to verify the REMD model.

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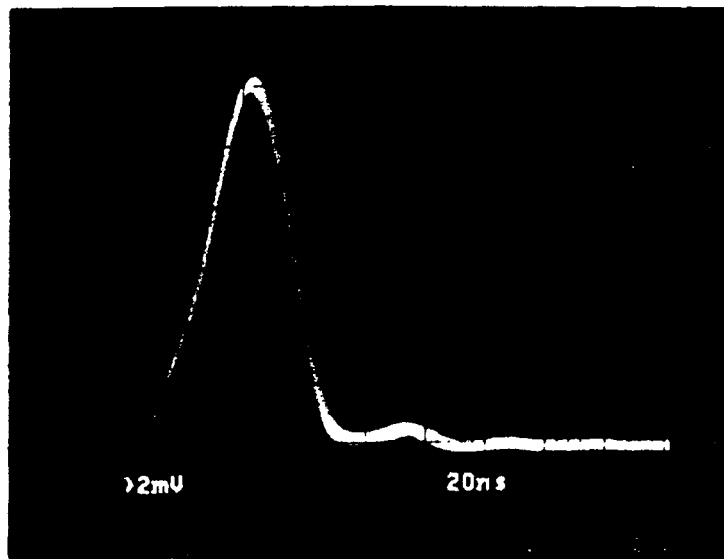
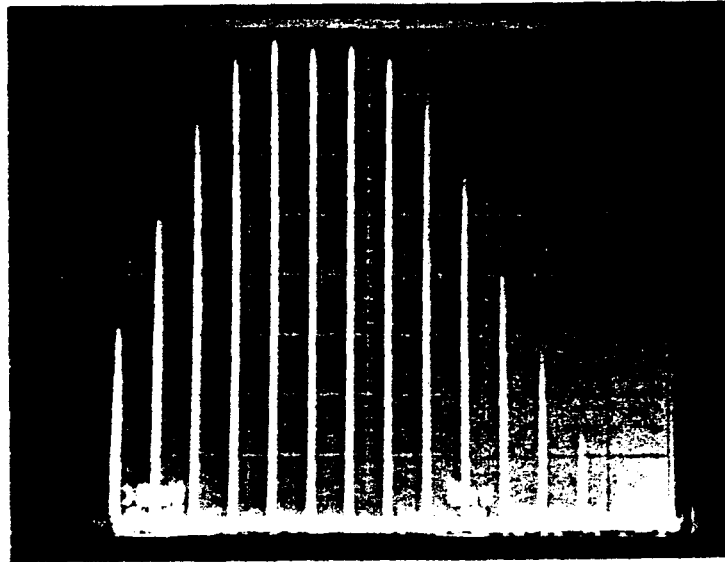


Figure 29. Oscilloscope traces of a pulse train and a single pulse from the experimental REMD system. Peak power at 532 nm reached 50 mW with a FWHM of 30 nsec. This set-up used a 50 mW 1.06 μ m laser as a pump, but only 25 mW was actually coupled into the REMD system.

TABLE 6

Parameters Defining Resonator:

380.0000 A: Length of 1st resonator half-round-trip, mm.
25.0000 B: Length of 2nd resonator half-round-trip, mm.
99.0000 C: Reflectivity of input mirror, %.
98.0000 D: Reflectivity of coupling mirror, %.
0.5000 E: Loss in first cavity, %.
3.0000 F: Loss in second cavity, %.
60.0000 G: Coupling efficiency, % of transmitted light.
0.1000 H: Nonlinear coefficient, % / Watt.

Parameters Defining System Inputs:

0.0250 I: Input power, Watts.
10.0000 J: Modulation phase, degrees.
150.0000 K: In-phase time period, nsec.
150.0000 L: Length of single time slot, nsec

Parameters Defining Calculation Format:

0.4003 M: Period between data outputs, nsec.
5.0000 N: Length of elemental light slice, mm.

Files for I/O:

DATA ENTRY BY HAND. O. Access file for data stream
REMD.OFL P. Output file, transmitted light
remd.mfl Q. Name of this master file

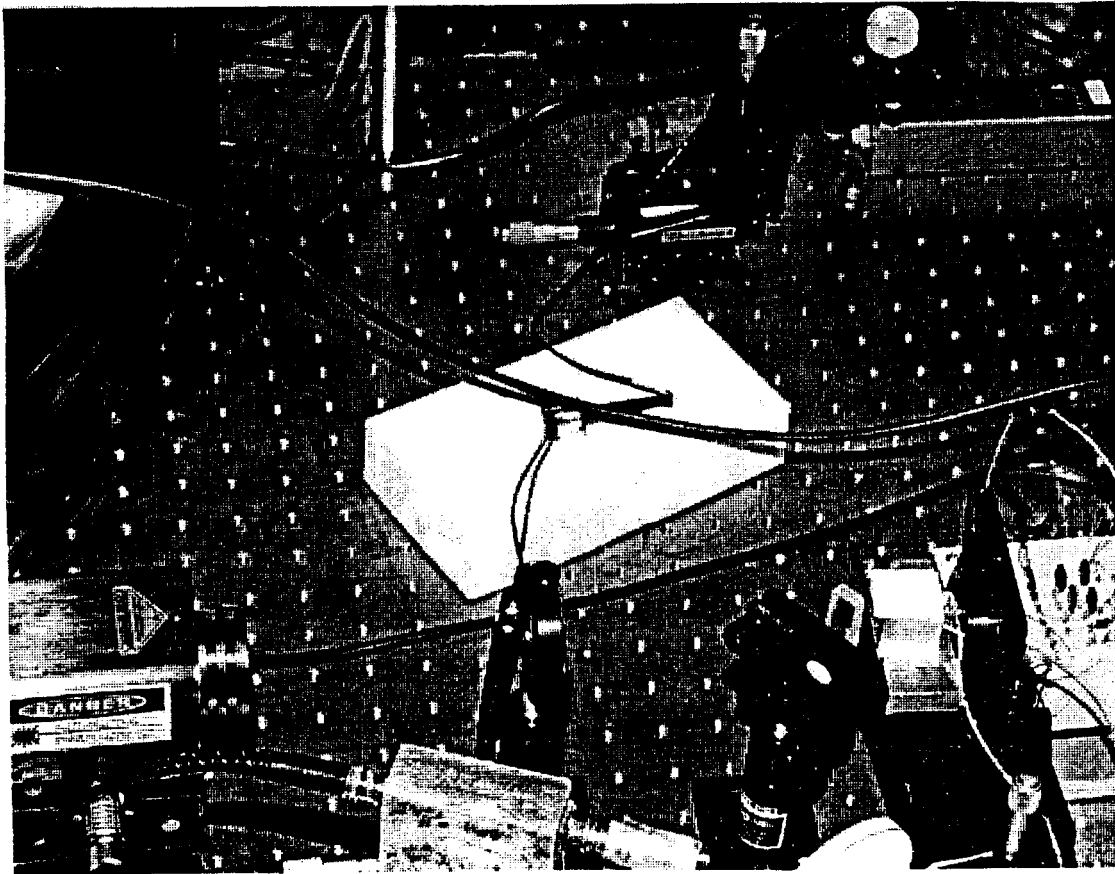


Figure 30. Experimental set-up for resonant external modulation and doubling. A 50 mW laser, seen in the lower left hand corner of the photograph, is mode matched with the lens in the lower center of the photograph, into a large empty cavity. This cavity consists of the 98% reflecting flat mirror (lower right hand corner, at a 45o angle), the front surface of a monolithic doubling crystal (white square immediately to right of the flat mirror), and the 40 cm focal length curved mirror in the upper right hand corner. The monolithic doubling crystal is a solid piece of lithium niobate which serves as the second resonant cavity, where frequency doubling occurs. Voltage is applied to the crystal (via electrodes attached to the gold plating on the top and bottom of the crystal) to change the optical cavity length of the resonator. The 40 cm focal length curved mirror is mounted on a piezo stack so the length of the large cavity can also be modulated.

VI. Relation to Future Work

1. Increasing power output

We demonstrated that a power of 310 mW could be generated, in a diffraction-limited, single-frequency beam, pumped by a single laser diode. This was limited by the appearance of higher-order transverse modes, due to mismatch between the fixed size of the pump beam and the size of the lasing mode, which diminished as pumping increased. There are three ways to reach larger power levels, while maintaining the advantages of the monolithic ring design. The first is to use the "injection chaining" technique developed under this contract. This allows the coherent summation of several lasers, at some cost in complexity. This greater complexity can also lead to a desirable redundancy if the system is well designed. The second way to increase power is to increase the length of the resonator, while maintaining the same pump beam. This will allow diffraction-limited power to increase. According to Eq [7] the increase will be proportional to cavity length. The third way to increase power is to use smaller pump beams with larger power levels. This will be possible if there are improvements in diode technology, or through the use of techniques to combine beams through polarization or spatial multiplexing. With these techniques it should be possible to go beyond 1 Watt. The 10-Watt level will not be possible without more fundamental changes of design.

2. Modulation of output

To transmit information on the laser beam, techniques for either phase modulation, conventional binary amplitude modulation, or pulse-position modulation must be developed. There are conventional techniques for doing the first two with bulk or guided-wave optics. There are problems with these techniques involving either optical damage (for the guided-wave modulators) or high speed modulation of high voltage (for bulk modulators.) We have demonstrated a novel technique for PPM, but it is rather elaborate.

We believe that there are techniques for both phase and amplitude modulation that require neither high voltages or guided waves. These techniques take advantage of the multiplicative effects which occur when a cavity is nearly resonant with a highly coherent laser beam. The phase of a beam reflected from the cavity, or the transmission through the cavity, will change very quickly as a function of the cavity length, which is controlled by a voltage. We hope to prove the feasibility of these techniques shortly.

3. Untended operation

Laser diodes have a structure of mode-hops which is much more complicated than that of the YAG laser they pump. The temperature of the diode laser is adjusted to compensate for the mode hops. The individual making the adjustment must find a temperature where the power of the diode-pumped laser is adequate and the noise of the diode-pumped laser is suitably low. Both these conditions must hold over a range of adjacent temperatures, or the laser will drift to a point of lower power or higher noise. Currently these adjustments are made by technicians at Lightwave. If component values, or the laser diode itself, drift, then these adjustments may have to be repeated.

In an untended system, the parameters of power and noise would have to be monitored by a computer, and adjustments to temperature to counter aging also made by a computer. In principle, a computer could make these adjustments much more consistently than a human. We believe development and testing of a system for untended operation of laser diode-pumped lasers is warranted.

4. Diode lifetime and reliability

In principle, laser diodes can be built to last over 100,000 hours. The diodes that Lightwave uses are expected to last 10,000 hours. Our experience is that many diodes last this long with only a small reduction in power, while others die prematurely. A program aimed at long-lifetime diodes, and also on means to screen diode batches to reduce early death, is important. This type of work is already going on at diode manufacturers laboratories.

VII. Conclusions

The local oscillator laser we built has the power, frequency stability, amplitude stability, and tunability needed for a local oscillator in a coherent communication system. The kilohertz linewidth of these lasers will permit coherent detection techniques to work even at very low bit rates. The demonstration of phase-locking makes possible the detection of phase-modulated light with maximum sensitivity. The high power and shot-noise-limited amplitude stability of the local oscillator will result in heterodyne detection systems with quantum-noise-limited sensitivity.

We built a single-frequency laser with an output power of 310 mW. We also demonstrated a technique of combining the power of multiple lasers in a way that can preserve the diffraction-limited, single-mode character of the individual modules. The pair of modules delivered to NASA

have a combined output of 340 mW. This combining technique, which we call injection chaining, will permit us to reach powers above 1 Watt, while building systems with some redundancy.

We studied a technique, which we call Resonant External Modulation and Doubling (REMD), for converting the cw, infrared output from single-frequency lasers into randomly pulsed, visible output suitable for PPM transmission. A computer model was written and delivered to NASA, and benchtop experiments were used to verify the model. Both model and experiments confirm the potential of this approach. The REMD technique is somewhat complicated, and the experiments carried out were at low power. More work would be necessary to prove that this technique is workable at high efficiency, and to engineer the technique for reliable performance.

VIII. References

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