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Solid-State Lasers for Coherent Communication and Remote Sensing

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May 1, 1989 through December 31, 1991

Robert L. Byer
Principal Investigator

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ABSTRACT

Semiconductor-diode-laser-pumped solid-state lasers have properties that are superior to other lasers for the applications of coherent communication and remote sensing. These properties include efficiency, reliability, stability, and capability to be scaled to higher powers. We have demonstrated that an optical phase-locked loop can be used to lock the frequency of two diode-pumped 1.06-μm Nd:YAG lasers to levels required for coherent communication. Monolithic nonplanar ring oscillators constructed from solid pieces of the laser material provide better than 10-kHz frequency stability over 0.1-sec intervals. We have used active feedback stabilization of the cavity length of these lasers to demonstrate 0.3-Hz frequency stabilization relative to a reference cavity. We have performed experiments and analysis to show that optical parametric oscillators (OPO's) reproduce the frequency stability of the pump laser in outputs that can be tuned to arbitrary wavelengths. Another measurement performed in this program has demonstrated the sub-shot-noise character of correlations of the fluctuations in the twin output of OPO's. Measurements of nonlinear optical coefficients by phase-matched second harmonic generation supported in part by this grant are helping to resolve inconsistency in these important parameters.

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Robert C. Eckardt — Senior Research Associate

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Alan Nilsson — Ph.D., August 1989

Charles D. Nabors — Ph.D., December, 1989

Murray K. Reed — Ph.D., June 1990

Timothy Day — Ph.D., September 1990

Robert C. Eckardt — Ph.D., June 1991

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Darwin Serkland — Graduate Student

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Principal Investigator

I. Introduction

This program has supported a number of studies in laser development and nonlinear optical frequency conversion that have application in coherent communication and remote sensing. These topics include: the analysis of mode structure in nonplanar oscillators; optical parametric oscillator coherence; demonstration of optical squeezing in the twin outputs of a parametric oscillator, mode-locked injection seeding of a high-power laser; laser stabilization to sub-Hertz levels; demonstration of optical phase-locked loops; analysis of doubly resonant optical parametric oscillator tuning and stability; and measurement of nonlinear optical coefficients. There are also investigations that have begun as part of this program that will be concluded elsewhere.

This research progress is presented in a number of ways in this final technical report. The most important technically is the list of publications in the archival literature given in section V. These publications contain the detailed descriptions of this research. Reprints of two topics that have not been reported in the earlier progress reports, squeezing in the twin outputs of a parametric oscillator and mode-locked injection seeding, are included as appendices to this final report. The list of presentations given in section VI gives a sense of the pace of the progress. The presentations are a more rapid form of communication, and the invited presentations also indicate interest in these topics. The research progress is summarized in section III and its significance is discussed in section IV. A particularly satisfying measure of the success of a program is the progress of the students.

The list of personnel associated with this grant shows that six students who were supported by this program completed their Ph.D. program in the last three years. The theses of the students whose dissertation research was supported in part by this grant are listed in section II.

II. List of theses supported in part by NASA Grant NAGW-1760

1. Alan C. Nilsson, "Eigenpolarization theory and experimental linewidth study of monolithic nonplanar ring oscillators," Ph.D. dissertation, Applied Physics Department, Stanford University, (Aug. 1989); Ginzton Laboratory Report No. 4552 (Stanford University, Stanford, CA, Aug. 1989).

2. Charles David Nabors, "Coherence and two-color squeezing in doubly resonant optical parametric oscillators," Ph.D. dissertation, Applied Physics Department Stanford University, (Dec. 1989); Ginzton Laboratory Report No. 4619 (Stanford University, Stanford, CA, Dec. 1989).

3. Murray Keith Reed, "Nd:glass slab laser development and application for x-ray lithography," Ph.D. dissertation, Applied Physics Department Stanford University, (June 1990); Ginzton Laboratory Report No. 4695 (Stanford University, Stanford, CA, June 1990).

4. Timothy Day, "Frequency stabilized solid state lasers for coherent optical communication," Ph.D. dissertation, Electrical Engineering Department, Stanford University, (Sept. 1990); Ginzton Laboratory Report No. 4740 (Stanford University, Stanford, CA, Sept. 1990).

5. Robert Charles Eckardt, "Continuous tuning and frequency stabilization of double resonant optical parametric oscillators," Ph.D. dissertation, Applied Physics Department, Stanford University, (June 1991); Ginzton Laboratory Report No. 4832 (Stanford University, Stanford, CA, June 1991).

III. Summary of research results

A. The NonPlanar Ring Oscillator

Solid-state lasers with the NonPlanar Ring Oscillator (NPRO) configuration [1,2,3] generate stable single-axial-mode output important for coherent communications and remote sensing. The highly coherent output of these lasers can be used to pump efficient nonlinear optical frequency conversion permitting the laser output to be shifted to arbitrarily selected wavelengths. Semiconductor-diode-laser pumping of the NPRO's [2,4] provides advantages of efficiency and reduced heat loading. In addition, the low amplitude fluctuations of the diode-laser pump source provide improved frequency stability. The exceptional frequency stability of the diode-pumped NPRO's compared to dye lasers, gas lasers, or semiconductor lasers provides unique advantages for active frequency stabilization.

A schematic illustration of a NPRO is shown in Fig. 1. Spatial hole burning in the population inversion is avoided by unidirectional oscillation in a ring cavity. The monolithic cavity non-planar path includes three total internal reflections and a fourth reflection at non-normal incidence from a multilayer-dielectric-coated curved output coupler. The nonplanar total internal reflections provide reciprocal polarization rotation, and non-reciprocal rotation is produced by Faraday rotation when the laser material is placed in a magnetic field, and non-normal reflection from the multilayer dielectric coating is polarization dependent. The result is four nearly degenerate modes, two for the different eigenpolarizations in each direction of oscillation. One of the four modes will have minimum loss.[3] Relatively small loss differences result in single-mode unidirectional laser oscillation. Designs have been produced that maximize loss difference to increase the resistance to optical feedback, an effect that can reduce frequency stability.[5]

The beatnote linewidth of two monolithic Nd:YAG (neodymium-doped yttrium aluminum garnet) lasers or two Nd:GGG (neodymium-doped gadolinium gallium garnet) lasers has been observed to be between 3 kHz and 10 kHz for short periods of time, typically 100 ms.[4,6,7] *Over longer periods of time the frequency drifts through greater*

1. T. J. Kane and R. L. Byer, Opt. Lett. 10, 65 (1985).
2. W. R. Trutna Jr., D. K. Donald and M. Nazarathy, Opt. Lett. 12, 248 (1987).
3. A. C. Nilsson, E. K. Gustafson and R. L. Byer, IEEE J. Quantum Electron. 25, 767 (1989).
4. T. J. Kane, A. C. Nilsson and R. L. Byer, Opt. Lett. 12, 175 (1987).
5. A. C. Nilsson, T. J. Kane and R. L. Byer, Proc. SPIE 912, 13 (1988).
6. B.-K. Zhou, T. J. Kane, G. J. Dixon and R. L. Byer, Opt. Lett. 10, 62 (1985).
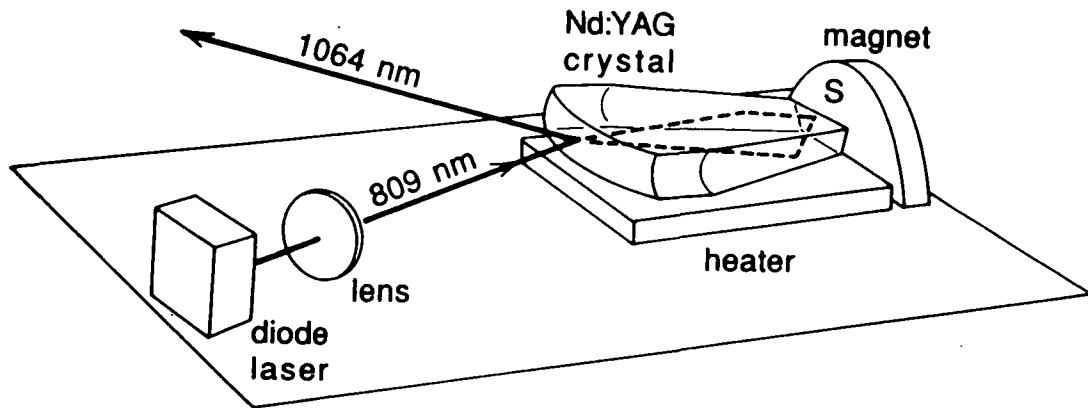
Figure 1. Semiconductor-diode-laser-pumped NonPlanar Ring Oscillator (NPRO).

excursions due to the temperature tuning rate which is -3.1 GHz/°C for monolithic Nd:YAG oscillators. Temperature fluctuations in the millidegree range produce a frequency wander of several MHz. Short term stability of a few kHz and MHz stability over periods of minutes, however, is adequate for a number of coherent communication and remote sensing applications, as well as a number of nonlinear optical frequency conversion demonstrations. Furthermore, long term experiments can be carried out when the laser is slaved to the nonlinear cavity by active frequency control. The temperature sensitivity can be used for tuning, but the response is slow, typically 1 sec. Piezoelectric crystals bonded directly to non-optical surfaces of the monolithic lasers provide limited tuning range but much faster response extending to frequencies of hundreds of kHz.[8,9] A split servo with feedback to both the temperature and the piezoelectric crystal can have both narrow jitter linewidth and long term frequency control.

Pulsed pumping of monolithic lasers usually results in a frequency chirp during laser output caused by heating. Continuously pumped lasers reach a steady-state condition with constant temperature. There are several ways that the frequency-stable output of continuously pumped lasers can be used used to obtain frequency-stabilized pulsed lasers. One way is by applying a small amount of modulation to the pump radiation at the

7. W. K. Williams, A. Dandridge, A. D. Kersey, J. F. Weller, A. M. Yurek and A. B. Tveten, Electron. Lett. 25, 774 (1989).
8. A. Owyoung and P. Esherick, Opt. Lett. 12, 999 (1987).
9. T. J. Kane and E. A. P. Cheng, Opt. Lett. 13, 970 (1988).

relaxation oscillation frequency to produce spiking in the laser output. Also cw laser output can be time gated and amplified. And the continuous wave output can be used to injection seed high-power pulsed lasers.

High-power Q-switched lasers have been a traditional source of high power optical radiation. The short buildup times and high gain of the Q-switched lasers usually result in highly multimode output. If the oscillation of one mode is injection seeded with a few mW of cw radiation, oscillation on that laser mode can buildup and deplete the population inversion before other laser modes have a chance to grow to significant levels. Several commercial lasers are available that offer injection-seeded operation with nearly time-bandwidth-limited output of typically 10-nsec duration.

B. Pulsed optical parametric oscillators

1. Background

The potential of optical parametric oscillators (OPO's) for converting laser output to tunable radiation at arbitrarily selected frequencies was recognized with the first OPO demonstration.[10] The early parametric oscillators were doubly resonant. Doubly resonant oscillators (DRO's) have an advantage of low pumping threshold for oscillation, but DRO's also have complex tuning properties and stable DRO operation is difficult. These problems were demonstrated in early experiments and analysis[11] and became more apparent with the first demonstration of continuously pumped OPO's.[12,13] Further investigation demonstrated the stringent cavity tolerances required for stable DRO operation.[14] Theoretical analysis shows that when these tolerances are satisfied, the DRO will provide many useful and unique properties for generating tunable radiation with coherence that nearly reproduces the pump coherence.

Singly resonant optical parametric oscillators (SRO's) have less complicated tuning properties than DRO's, and SRO's are free of some of the constraints that make stable operation of DRO's difficult. Pump thresholds, however, are higher for SRO's, and it has been difficult demonstrating cw operation in these oscillators. The double resonance

10. J. A. Giordmaine and R. C. Miller, Phys. Rev. Lett. 14, 973 (1965).
11. J. A. Giordmaine and R. C. Miller, in Physics of Quantum Electronics, P. L. Kelly, B. Lax and P. E. Tannenwald, eds. (McGraw, New York, 1965), pp. 31-42.
12. R. G. Smith, J. E. Geusic, H. J. Levinstein, J. J. Rubin, S. Singh and L. G. Van Uitert, Appl. Phys. Lett. 12, 308 (1968).
13. R. L. Byer, M. K. Oshman, J. F. Young and S. E. Harris, Appl. Phys. Lett. 13, 109 (1968).
14. R. G. Smith, IEEE J. Quantum Electron. QE-9, 530 (1973).

condition also provides frequency selectivity that easily results in single-mode-pair oscillation. This frequency selection is not available with single resonance unless frequency selecting components are added to the SRO.

SRO's have been forced to operate single-mode on the resonated signal wave even with highly multimode pumping.[15] The combined frequency selection of phase matching, a dispersing grating, and an intracavity etalon were necessary to achieve single-mode oscillation with these conditions. The multi-axial-mode pump resulted in a multimode output at the nonresonated idler field. When this type of frequency control is used with a pulsed SRO pumped with an injection-seeded Q-switched laser with single-mode output, the result is single-mode output at both the signal and idler wavelengths.[16] With the addition of piezoelectric control of the cavity length and computer control of all the adjustable parameters, spectrographic measurements with 300-MHz resolution were possible.[17] These SRO's used angle tuned $LiNbO_3$ pumped at 1.06 µm.

2. SRO pumped by a Q-switched laser

The single-mode pump alone is not sufficient to produce single-mode-pair oscillation in a simple SRO with no frequency selection except that of phase matching. This was observed in a BaB_2O_4 SRO pumped with the 354-nm third harmonic of the output of an injection seeded Q-switched Nd:YAG laser.[18] The single frequency pump did reduce OPO output energy fluctuation to 10% from 30% which was observed with multimode pumping when injection seeding of the Q-switched laser was blocked. The plane-parallel-cavity SRO with 1.2-cm-long BaB_2O_4 crystal and 3-cm overall length pumped by a 6-nsec pulse would oscillate on typically 8 axial modes at the signal wave. The broad tuning range of the BaB_2O_4 OPO extending from 412 nm to 2.55 µm included both the 1.064-µm fundamental and 532-nm second harmonic of the laser, which were available for injection seeding the SRO. With injection seeding at 532 nm or 1.064 µm, the buildup time of the SRO oscillation was substantially decreased, and single-mode-pair oscillated was achieved. Measurements of the SRO threshold yielded values that were less than predicted from calculations based on reported values of the nonlinear coefficient of BaB_2O_4. This observation lead to a series of measurements that resulted in a reassessment of the scale for optical nonlinear coefficients. Injection seeding is an effective means of obtaining single-

15. S. J. Brosnan and R. L. Byer, IEEE J. Quantum Electron. QE-15, 415 (1979).
16. T. K. Minton, S. A. Reid, H. L. Kim and J. D. McDonald, Opt. Commun. 69, 289 (1989).
17. T. K. Minton, H. L. Kim, S. A. Reid and J. D. McDonald, J. Chem. Phys. 89, 6550 (1988).
18. Y. X. Fan, R. C. Eckardt, R. L. Byer, J. Nolting and R. Wallenstein, Appl. Phys. Lett. 53, 2014 (1988).

mode operation of and SRO.[19][20][21] A stable cw DRO would be an excellent radiation source for this application.

3. Long-pulse-pumped SRO's

Greater frequency selection is possible with longer buildup times of parametric oscillation. Pump pulses of 500-nsec duration were derived from a diode-pumped NPRO by gating the cw output followed by multipass amplification in a flashlamp pumped laser amplifier.[22] A monolithic SRO was pumped by the second harmonic generated by the oscillator-amplifier laser system. Pumping with the 532-nm harmonic allowed noncritical phase matching in the 5%MgO:LiNbO$_3$ crystal. The purpose of this experiment was to investigate spectral narrowing and to reduce OPO threshold to a level approaching that which could be achieved directly by diode-pumped lasers.

The monolithic SRO tuned from 834 to 958 nm and 1.47 to 1.2 μm when temperature was adjusted between 190° and 125°C.[23] Damage limitation of the MgO:LiNbO$_3$ SHG crystal required that the 5-kW output of the laser amplifier be no longer than 500 ns. Under these conditions 800 W of 532-nm harmonic was generated. The ring-cavity configuration of the SRO allowed high efficiency; up to 60% pump depletion was observed after threshold was reached. About 20% of the time single-mode operation of the SRO was observed. More often, however, simultaneous oscillation on three axial modes was observed, and occasionally as many as 8 modes oscillated simultaneously. Thus long-buildup time alone was not sufficient to guarantee single-mode oscillation.

4. Pulse-pumped doubly resonant optical parametric oscillation.

A further reduction in OPO threshold is obtained with the doubly resonant oscillator (DRO) configuration in which the OPO is resonant at both the signal and idler wavelengths. The added constraint of double resonance in addition to phase matching and conservation of energy, however, makes stable operation of the DRO difficult.[14] The frequency stability of the NPRO and the mechanical stability of monolithic DRO construction are useful in overcoming this difficulty. A doubly resonant monolithic DRO was constructed from MgO:LiNbO$_3$ with broad-band dielectric mirrors highly reflecting near 1.06 μm coated on the crystal.[24] A ring geometry was formed by using reflections from two 10-mm radius-of

19. J. E. Bjorkholm and H. G. Danielmeyer, Appl. Phys. Lett. 15, 171 (1969).
20. V. L. Boichenko, M. M. Novikov and A. I. Kholodnykh, Sov. J. Quantum Electron. 17, 392 (1987).
21. J. G. Haub, M. J. Johnson, B. J. Orr and R. Wallenstein, Appl. Phys. Lett. 58, 1718 (1991).
22. T. J. Kane, W. J. Kozlovsky and R. L. Byer, Opt. Lett. 11, 216 (1986).
23. W. J. Kozlovsky, E. K. Gustafson, R. C. Eckardt and R. L. Byer Opt. Lett. 13, '102 (1988).
24. W. J. Kozlovsky, C. D. Nabors, R. C. Eckardt and R. L. Byer, Opt. Lett. 14, 66 (1989).

curvature surfaces on the ends of the noncritically phase-matched, 1.25-cm-long crystal and a polished flat on one side for total internal reflection (Fig. 2). The DRO was pumped at 532 nm by second-harmonic pulses generated from the relaxation oscillations of a Nd:YAG NPRO. Pulsed operation was required because the DRO threshold was marginally higher than could be produced by the NPRO and harmonic generator when operated cw.

A 10% modulation of the diode-laser current at 325 kHz drove the Nd:YAG NPRO into relaxation oscillations. The 1.06-μm fundamental pulses had 260-mW peak power and were efficiently converted into 400-ns, 230-mW, 532-nm pulses by externally resonant second-harmonic generation. The buildup of parametric oscillation occupied most of the pump pulse duration. Overall DRO efficiency was only 7% due to the long buildup time. After threshold was reached 60% pump depletion occurred. The DRO tuned between 1.02 and 1.12 μm by adjustment of both temperature and electric field. The most remarkable aspect of the DRO operation was that single-mode-pair oscillation was achieved on almost every pulse. The only exception was when the DRO was tuned between cluster centers and either simultaneous or alternating output on widely spaced modes approximately 4 nm apart were observed. The monolithic DRO with a pulsed single-mode pump will oscillate on a single mode pair due to the constraint of double cavity resonance.
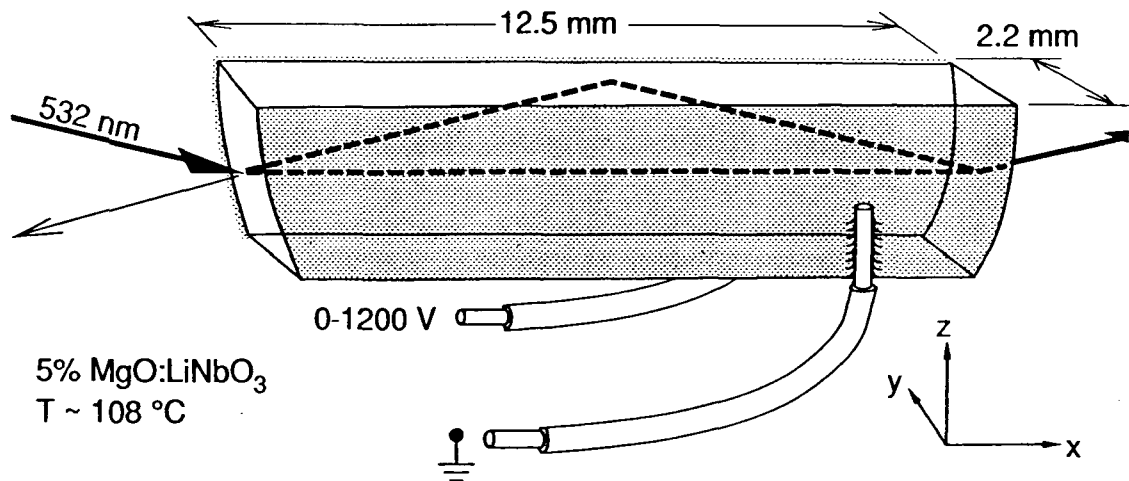
Figure 2. Monolithic DRO geometry used for experimental observations

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C. Nonlinear optical coefficient measurements

The injection-seeded spatially-filtered Q-switched Nd:YAG laser provided a suitable pump for phase-matched second-harmonic measurements of nonlinear optical coefficients. High optical quality in both the pump beam and the nonlinear material is needed for precise control of phase matching which is also a requirement of these measurements. The measurements included careful characterization of phase matching for each observation. In addition it was determined that there were no extraneous spatial, temporal, or spectral components of the pump.

The results of careful nonlinear optical coefficient measurements[25] are reproduced in Table I. The investigation, which at first was motivated by the BaB_2O_4 SRO results, grew to include a total of six materials. This was necessary because the earlier BaB_2O_4 measurements were relative to KDP, and a controversy existed over the value of the nonlinear coefficient of that material. The measurements described here were performed in a two-beam setup which permitted both relative measurements between two crystals and absolute measurements with harmonic power measured in one beam and fundamental power measured in the other. The reproducibility of these measurements was ±4% which should also be the relative accuracy. The absolute accuracy is estimated to be better than ±10%.

The KDP coefficient listed in Table I agrees within experimental error with other phase-matched harmonic measurements.[26] The coefficients tabulated here yield a ratio $d_{22}(BaB_2O_4)/d_{36}(KDP)$ of 5.8 at variance with the ratio of 4.1 reported earlier.27 The absolute value for the BaB_2O_4 coefficient, however, more closely agrees with the SRO threshold observations. A more significant variance is with earlier parametric fluorescence measurement of $LiIO_3$ for which the nonlinear coefficient was 1.73 times the value reported here. Relative measurements between KDP and $LiIO_3$, however, are in agreement with earlier results. The difference between the previously reported nonlinear coefficient of KTP and that reported here is even larger: $d_{eff} = 7.3$ pm/V reported earlier compared to 3.18 pm/V reported here.

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25. R. C. Eckardt, H. Masuda, Y. X. Fan and R. L. Byer, IEEE J. Quantum Electron. 26, 922 (1990).
26. D. Eimerl, Ferroelectrics 72, 95 (1987).
27. D. Eimerl, L. Davis, S. Velsko, E. K. Gram and A. Zalkin, J. Appl. Phys. 62, 1968 (1987).

TABLE I.
NONLINEAR OPTICAL COEFFICIENTS

Crystal	Nonlinear optical coefficient[a] (10^{-12} m/V)
KDP	$d_{36} = 0.38$
KD*P	$d_{36} = 0.37$
LiIO$_3$	$d_{31} = -4.1$
5%MgO:LiNbO$_3$	$d_{31} = -4.7$
BaB$_2$O$_4$	$d_{eff} = 1.94$ $|d_{22}| = 2.2$[b]
KTP	$d_{eff} = 3.2$ $|d_{15}| = 1.9$[c] $|d_{24}| = 3.5$

(a) Nonlinear coefficients are given for 1064- to 532-nm second-harmonic generation.

(b) Assumes that $|d_{31}| \ll |d_{22}|$ for BaB$_2$O$_4$.[27]

(c) Using $|d_{24}| / |d_{15}| = 1.8$ [28] and assuming d_{24} and d_{15} have the same sign.

A consensus, however, is developing from application of these values and further measurements. Recent measurements of OPO threshold in KTP [28,29] and lithium iodate [30] have shown agreement with our measurements. Recent phase-matched second-harmonic measurements of BaB2O4 [31] and KTP [32] also agree with our measurements within a few percent. The highly coherent laser output that is becoming routinely available from diode-pumped solid-state lasers allows greater precision in the determination of nonlinear optical coefficients. Hopefully the developing consensus will resolve the confusion that has developed over the absolute value of these coefficients.

28. K. Kato, IEEE J. Quantum Electron. 27, 1137 (1991).

29. L. R. Marshall, J. Kasinski, A. D. Hays and R. Burnham, Opt. Lett. 16, 681 (1991).

30. P. F. Curley and A. I. Ferguson, Opt. Commun. 80, 365 (1991).

31. S. P. Velsko, M. Webb, L. Davis and C. Haung, IEEE J. Quantum Electron. 27, 2182 (1991).

32. R. DeSalvo, D. J. Hagan, M. Sheik-Bahae, G. Stegeman, E. W. Van Stryland and H. Vanherzeele, Opt. Lett. 17, 28 (1992).

D. cw OPO's

The diode-laser-pumped solid-state NPRO has proved to be an excellent source of stable, cw, single-axial-mode radiation for many applications including resonant cavity nonlinear frequency conversion. In an initial demonstration of cw harmonic conversion, Kozlovsky generated 29.6 mW of 532-nm radiation from 56-mW of 1.064-μm pump radiation in a $MgO:LiNbO_3$ monolithic-external-resonant-cavity second harmonic generator.[33] The fundamental radiation was the output of a Nd:YAG NPRO pumped by a 500-mW diode-laser array. More recently we have generated 6.5 watts of cw 532-nm radiation using lithium triborate (LiB_3O_5 or LBO) in a discrete-component external-resonant-cavity harmonic generator pumped by 18 W of 1.064-μm radiation.[34] The source of pump radiation was an arc-lamp-pumped cw Nd:YAG laser injection locked by a 40-mW diode-pumped laser.[35] It is expected the semiconductor-diode-laser-pumped Nd:YAG laser will replace the arc-lamp-pumped laser in the near future.

Our cw OPO experiments have used the second harmonic radiation described above for pumping. The availability of 532-nm pump radiation and noncritical phase matching with a reasonable temperature tuning range in $MgO:LiNbO_3$ was important for these experiments. Temperature-tuned noncritically phase-matched monolithic resonators provided mechanical stability and low loss for these DRO studies. A drawing of a ring-path monolithic OPO is shown in Fig. 2. Pulsed radiation of 400-ns duration and cw 532-nm radiation produced by the monolithic resonant cavity harmonic generator was used to pump the DRO's.[24,36] The DRO performance was remarkable. The threshold for the cw device was only 11 mW. Single-mode-pair output was observed routinely in the cw DRO's. As much as 80% pump depletion was observed at two times above threshold. The output coupling of the OPO was not optimized for maximum output. Nevertheless, the slope efficiency shown in Fig. 3 was 64% and surprisingly linear. The free-running cw DRO without servo control would oscillate for periods of one minute on a single mode pair. At degeneracy the DRO would stably produce the subharmonic of the pump for periods of 20 minutes.

33. W. J. Kozlovsky, C. D. Nabors and R. L. Byer, IEEE J. Quantum Electron. 24, 913 (1988).
34. S. T. Yang, C. C. Pohalski, E. K. Gustafson, R. L. Byer, R. S. Feigelson, R. J. Raymakers and R. K. Route, Opt. Lett. 16, 1493 (1991).
35. C. D. Nabors, A. D. Farinas, T. Day, S. T. Yang, E. K. Gustafson and R. L. Byer, Opt. Lett. 14, 1189 (1989).
36. C. D. Nabors, R. C. Eckardt, W. J. Kozlovsky and R. L. Byer, Opt. Lett. 14, 1134 (1989).
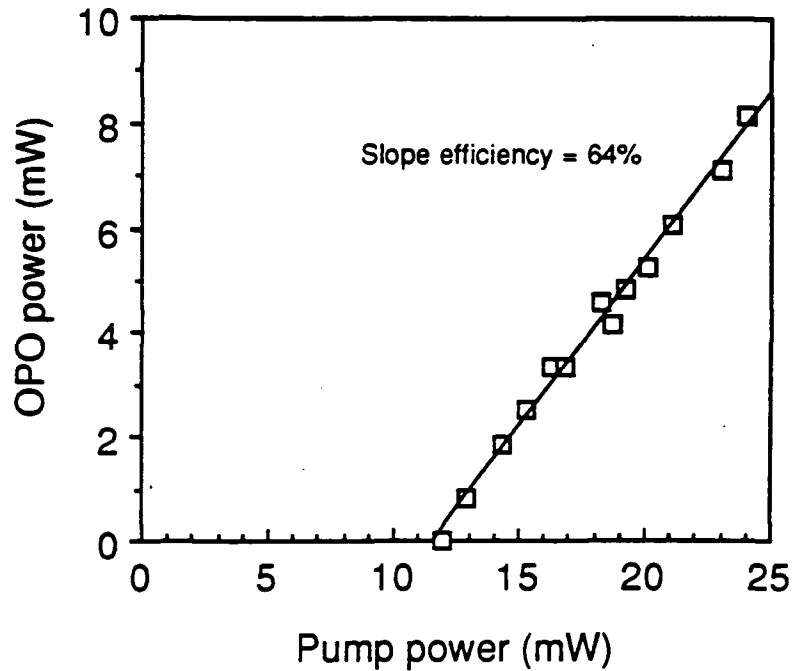
Figure 3. Output power as a function of pump power for a cw monolithic MgO:LiNbO₃ DRO. The DRO was pumped at 532 nm and the output was near degeneracy at 1.064 μm.

The coherence properties of the cw DRO are also remarkable.[37] It was observed during the periods of stable operation between mode hops that the coherence of the outputs of the DRO reproduced the coherence of the pump radiation. When operated on a mode pair adjacent to degeneracy, the signal and the idler difference frequency was stable to better than 1 kHz, the limit of resolution of the measurement. The difference frequency of the signal and the idler is an indication of the additional frequency noise that the DRO adds to that present on the pump radiation. At degeneracy, the output of the DRO was a phase-locked subharmonic of the pump radiation. This was shown by interference of the DRO output and the laser radiation used to generate the second harmonic that was in turn used to pump the DRO.

Our measurements of DRO performance and coherence provided the basis for a theoretical analysis of the frequency-tuning and -control properties of these devices.[38] The analysis showed how three tuning parameters are required for controlling two cavity resonances and phase matching in the DRO. It was possible to model the observed tuning

37. C. D. Nabors, S. T. Yang, T. Day and R. L. Byer, J. Opt. Soc. Am. B 7, 815 (1990).
38. R. C. Eckardt, C. D. Nabors, W. J. Kozlovsky and R. L. Byer, J. Opt. Soc. Am. B 8, 646 (1991).

properties of monolithic $MgO:LiNbO_3$ DRO's using temperature dependent dispersion, thermal expansion, electro-optic, and piezoelectric properties of the material. The analysis is applicable to both monolithic and discrete component cavities. The tuning analysis can be used to calculate the tolerances for stable DRO operation. These tolerances are stringent, for example $0.001°C$ temperature stability and $5×10^{-10}$ m cavity length stability are typical requirements. More stringent tolerances than these, however, are achieved in laser frequency stabilization. Lasers are now available that provide the required frequency stability for resonant cavity nonlinear frequency conversion techniques. It is an interesting and important challenge to reproduce the available laser frequency stability in the output of a nonlinear frequency conversion device.

E. Injection locking.

The use of a low power frequency-stabilized oscillator to stabilize the output of a higher power oscillator is an established technique. When injecting the low-power master laser output into the higher power slave laser, it is necessary to isolate the master from optical feedback, provide spatial mode matching, and to lock the resonances of the master and slave lasers. High-power, diode-pumped lasers are in the developmental stage, but injection locking has been demonstrated on a hybrid system with a diode-pump laser used to lock the output of an arc-lamp-pumped, high-power laser.[34] Ring geometry was used in the high-power laser to reduced optical feedback and avoided spatial hole burning effects. Locking of the cavities was achieved by the FM-sideband technique, which provided an error signal used to drive mirrors mounted on piezoelectric translators and control the cavity length of the slave oscillator. It was possible to maintain injection locking for a slave-to-master power ratio of 400:1 with a 13-W, single-frequency output. Analysis of phase noise showed the total additional rms phase noise of the slave over that present on the master oscillator was less than 0.3 radians. The measurement was limited by low-frequency laboratory acoustics. As the cost of semiconductor diode lasers decreases with advances in production, diode-pumped, high-power, solid-state lasers will become common.[39] A diode-pumped slave laser is expected to be much less noisy due to the more stable pumping provided by diode lasers, higher efficiency and therefore less heating, and the elimination of turbulent coolant flow. Such all-solid-state lasers are good candidates to scale the output of frequency stabilized lasers to higher powers.

39. R. L. Byer, Science 239, 742 (1988).

F. Nd:YAG Laser Frequency Stabilization

1. Mathematical overview

It is often not possible to compare the laser to a more stable standard, and it becomes necessary to compare two lasers with approximately the same level of frequency stability. If the two lasers are completely independent, the bandwidth of the difference frequency generated when the two laser outputs interfere at a photodetector, the heterodyne signal, sets an upper limit on the individual laser bandwidths. If the two lasers are not completely independent in such a comparison, it is possible that there will be some common mode rejection, that is some frequency noise will be identical in the two lasers and not be evident in the heterodyne signal. Other measurements such as those derived from the signals used to stabilize a laser provide information on the lower bound of noise. Measurements by several different techniques reduce uncertainties.

The spectral bandwidth is the frequency width that would be observed using a scanning interferometer with sufficiently narrow transmission band. The heterodyne signal of the laser output and a much more stable reference displaced from the laser output by a small frequency difference translates the laser spectral distribution to a region in which it can be measured by radio-frequency spectral analysis. Mathematically the bandwidth Δf_{FWHM} is the full width at half maximum of the power spectrum,

$$W(f) = \frac{1}{2} E^*(f) E(f),$$ (1)

where $E(f)$ is defined by the Fourier transform

$$E(f) = \lim_{T \to \infty} \frac{1}{\sqrt{T}} \int_{-T/2}^{T/2} E(t) e^{i2\pi ft} dt.$$ (2)

The normalization of Eq. (2) is useful for ergodic processes. An ergotic process is one for which the time average is equal to the ensemble average. With this normalization, the power spectrum of an ergodic process will approach a constant distribution as the sample time T increases.

The time dependent electric field of a phase modulated output can be expressed as

$$E(t) = E_o \exp\{-i [2\pi f_o t + \phi(t)]\},$$ (3)

where $\phi(t)$ is a time dependent phase and f_o is a fixed frequency. A phase noise can be represented by $\phi(t)$. The instantaneous frequency shift is given by

$$\Delta f(t) = \dot{\phi}(t) / 2\pi .\tag{4}$$

A complex spectral amplitude of frequency noise is obtained from the Fourier transform

$$S(f) = \frac{1}{\sqrt{T}} \int_{-T/2}^{T/2} \frac{\dot{\phi}(t)}{2\pi} e^{i2\pi f t} \, dt ,\tag{5}$$

where T is the duration of the sample. The linear spectral density of frequency noise is obtained by averaging the absolute value of the spectral amplitude over many samples

$$S_f(f) = \left\{ \langle S^*(f) \, S(f) \rangle \right\}^{1/2}.\tag{6}$$

The units of $S_f(f)$ are $Hz/\sqrt{Hz}$. One method of measuring $S(f)$ is radio-frequency Fourier spectral analysis of a frequency discriminant signal, for example a voltage proportional to the instantaneous frequency shift of the laser output.

The Schawlow-Townes limit describes the noise due only to the random addition of spontaneous emission to the laser oscillation. The bandwidth of frequency noise in this limit is

$$\Delta f_{FWHM} = 2 \pi \Delta v_c^2 h \, v_1 / P ,\tag{7}$$

where Δv_c is the width of the laser cavity resonance, h is Planck's constant, v_1 is the frequency of the laser oscillation, and P is the output power of the laser. The linear spectral density of frequency noise in the Schawlow-Townes limit is constant in frequency and given by

$$S_{f,0} = \Delta v_c \sqrt{2 \, h \, v_1 / P} .\tag{8}$$

The condition $(S_{f,0})^2 \ll B$ where B is the bandwidth of the noise applies, and it is appropriate to use the relationship [40]

$$\Delta f_{FWHM} = \pi S_{f,0}^2.\tag{9}$$

Another measure of frequency stability is the two sample variance

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40. D. S. Elliott, R. Roy and S. J. Smith, Phys. Rev. A 26, 12 (1982).

$$\sigma^2(\tau) \; = \; \frac{1}{2\,(M-1)} \sum_{i=1}^{M-1} (y_{i+1} - y_i)^2. \tag{10}$$

Here y_i is the $i^{\,\text{th}}$ frequency measurement of M successive measurements each of duration τ. A division of the two sample variance by the frequency of the oscillation yields the Allen variance.[41] In practice the two-sample variance can be measured using the heterodyne signal obtained from two lasers slightly offset in frequency. A time and interval counter can be used to measure zero crossings of the heterodyne signal in successive time intervals. One data set can be manipulated mathematically to yield the variance as a function of the time interval between measurements τ.

2. Laser stabilization loop

The control loop for laser stabilization can be modeled as four elements: the laser oscillator which is perturbed by a noise process $S_{f,\text{laser}}$, a discriminator that monitors the frequency fluctuations with a voltage responsivity D_v in units of V/Hz, a servo that amplifies the error signal with a gain G, and an actuator that converts the amplified error signal to changes in laser frequency with the coefficient K in units of Hz/V. Any stage may limit stabilization, but the discriminator is particularly susceptible to noise in the optical signal and technical noise such as length fluctuations of the reference cavity.

Diode-pumped, solid-state, monolithic lasers usually operate at the Schawlow-Townes limit of frequency stability above 50 kHz, and exhibit a noise roughly proportional to $1/f$ below that frequency. A piezoelectric crystal can be bonded to the monolithic laser oscillator to serve as the frequency actuator. A typical response coefficient for this type of actuator is $K = 1$ MHz/V with a ±20-MHz dynamic range and bandwidths flat to 200 kHz. Slower control of laser frequency with much larger range is achieved by temperature tuning. The servo has large gain at low frequencies, typically 120 dB, to control the large $1/f$ noise and unity gain in the 50- to 100-kHz region. The discriminator technique that will be described here is called Pound-Drever [42] locking, which involves the phase-sensitive detection of frequency-modulated light reflected from a reference cavity. Ideally the linear spectral density of frequency noise $S_{f,\text{cl}}$ under closed-loop conditions would be reduced from the free running value for the laser by

41. D. W. Allen, IEEE Trans. Ultrson. UFFC-34, 647 (1987).

42. R. W. P. Drever, J. L. Hall, F. V. Kowalski, J. Hough, G. M. Ford, A. J. Munley and H. Ward, Appl. Phys. B. 31, 97 (1983).

$$S_{f,cl} = \frac{S_{f,laser}}{|1 + K\,G\,D_v|}, \tag{11}$$

where K is the actuator response coefficient, S is the servo gain, and D_v is the discriminator voltage responsivity. If stabilization is limited by noise in the frequency discriminant, the minimum linear spectral noise density will be

$$S_{f,cl,min} = \frac{S_{f,disc}}{D_v}. \tag{12}$$

3. Frequency discriminant

Resonant cavities can be used for a stabilization reference both in transmission and reflection. The frequency modulation technique using reflection proposed by Drever, *et. al.* [41] has several advantages over locking to the side of a cavity transmission band. A frequency modulation is applied to the laser output before it is incident on the reference cavity. The modulation frequency is typically 10 MHz or greater. The FM sidebands are separated from the carrier by the modulation frequency which is greater than the optical bandwidth of the reference cavity. If the carrier is centered on the resonance it will be at a minimum of reflection, and if the carrier is slightly detuned from resonance, the amplitude of its reflection will grow, and it will be shifted in phase by an amount dependent on the detuning. The FM sidebands, however, will be well separated from the cavity resonance and therefore be nearly totally reflected with no phase change. The reflected light has a resulting amplitude modulation which is dependent in magnitude and sign on the degree of detuning of the carrier. The modulation frequency of the AM signal is the same as that of the FM.

In the simplest analysis an FM signal can be approximated by a carrier and two sidebands

$$\sin\{\omega_o t + \alpha + \beta\sin(\omega_m t + \gamma)\}$$
$$\approx \sin(\omega_o t + \alpha) + \frac{\beta}{2}\sin[(\omega_o+\omega_m)t+\alpha+\beta] + \sin[(\omega_o-\omega_m)t+\alpha-\beta+\pi]\ . \tag{13}$$

Note that the sum of the phases of the two sidebands differs by π from twice the phase of the carrier. A similar expansion illustrates that the sum of the phases of AM sidebands is exactly twice the phase of the carrier. More accurately the FM signal is represented by a series with Bessel function coefficients

$$\exp\{i\,(\omega_0 t + \beta \sin \omega_m t\,)\} =$$

$$\left[J_0(\beta) + \sum_{k=1}^{\infty} J_k(\beta)\{e^{i\,k\,\omega_m t} + (-1)^k e^{-i\,k\,\omega_m t}\}\right]e^{i\,\omega_0 t}. \qquad (14)$$

The complex reflection coefficient of the resonator is

$$R\,(\Delta f) = \frac{r_1 - r_2\,e^{i\,\theta\,(\Delta f)}}{1 - r_1 r_2\,e^{i\,\theta\,(\Delta f)}}, \qquad (15)$$

where r_1 and r_2 are the field reflection coefficients of the first and second mirrors respectively and the cavity round trip phase shift is given by $\theta(\Delta f) = 2\pi\,\Delta f\,/\,\Delta f_{FSR}$ where Δf_{FSR} is the free spectral range of the reference cavity. Eq. (15) assumes there are no losses in the cavity. If $r_1 = r_2 = r$, and Δf is small compared to Δf_{FSR}, then

$$R\,(\Delta f) \approx \frac{-i\,\theta\,(\Delta f)}{1-r^2} \approx \frac{-i\,2\,\mathcal{F}\Delta f}{\Delta f_{FSR}}, \qquad (16)$$

where $\mathcal{F}$ is the finesse of the resonator. If the reflectivity given by (16) is assigned to the carrier of (13) and the two side bands are assigned unity reflectivity, the total reflected intensity is obtained by taking the square of the absolute value of the amplitude. Only the term that is intensity modulated at angular frequency ω_m is kept, and this result is normalized by dividing by the average value of the incident intensity to yield the normalized error signal

$$V_{NOR} = \frac{I_r(\omega_m)}{I_i} = -\,(4\beta\,F\,\Delta f\,/\,\Delta f_{FSR}\,)\sin \omega_m t\,. \qquad (17)$$

This result is in agreement with a more detailed derivation [43] that treats a single Fourier component of frequency noise rather than a fixed frequency offset and uses Eqs. (14) and (15) in the expansion. The detailed derivation uses an incident field that is modulated at two frequencies

$$E = E_i \exp\left\{i\,(\omega_0 t + \alpha \sin \omega_N t + \beta \sin \omega_m t\,)\right\}, \qquad (18)$$

with the conditions that $\omega_0 >> \omega_m >> \omega_N$ and $\alpha << 1$. The normalized signal is

43. T. Day, "Frequency Stabilized Solid State Lasers for Coherent Optical Communications," Ph.D. thesis (Stanford University, 1990); Ginzton Laboratory Report No. 4740 (Stanford University, Stanford, California, 1990).

$$V_{NOR} = \frac{8\mathcal{F}}{\Delta f_{FSR}} J_o(\beta) J_1(\beta) \sqrt{\frac{\text{sinc}^2(x_N/G)}{1 + G^2 \sin^2(x_N/G)}} \ \alpha f_N \cos(\omega_N t + \phi) \sin \omega_m t \quad ,(19)$$

where $x_N = \dfrac{2f_N}{\Delta f_{FSR}}$, $G = 2\mathcal{F}/\pi$, and $\tan \phi = -G \tan(x_N/G)$. The added detail of Eq. (19) gives information about the frequency response of the frequency discriminant. Bandwidth, frequency dependent phase shift, and optimum value for the depth of modulation $\beta = 1.08$ are specified by this equation.

The FM stabilization technique offers several advantages over the transmission method of stabilization. The error signal for the FM technique is at a frequency well above the frequency of excess noise amplitude fluctuations of the laser over the shot noise limit, thus preventing these amplitude fluctuations from being interpreted as frequency noise. Also the FM technique does not have loop delays due to resonance buildup time, and it has a slightly greater sensitivity to frequency change than the transmission method.

4. Laser frequency noise

It is important to characterize the spectral density of frequency noise of the laser for the purpose of determining design parameters of the control loop. The frequency discriminant is useful for this measurement. Calibration of the frequency discriminant was performed by directing the laser output through an acousto-optic modulator in addition to the electro-optical modulator that was used to introduce the 10-MHz FM sidebands. The frequency of the acousto-optic modulator was in turn modulated with a low frequency sinusoidal input. The fixed frequency offset of the deflected beam had no consequence, but the varying component served as a calibrated frequency noise signal. The total modulation of the laser output was as described in Eq. (18). The measurement of laser spectral noise density was performed under closed loop conditions, and the laser noise was deconvolved with knowledge of the characteristics of the loop components. This measurement was performed using a 40-mW commercial Nd:YAG NPRO. The results[43] are shown in Fig. 4. Similar results have been obtained with various techniques such as Fourier analysis of time-domain measurements, fiber delay measurements,[44] and cavity transmission measurements.[45]

44. W. K. Williams, A. Dandridge, A. D. Kersey, J. F. Weller, A. M. Yurek and A. B. Tveten, Electron. Lett. 25, p. 774, (1989).
45. P. Fritschel, A. Jeffries and T. J. Kane, Opt. Lett. 14, 993 (1989).

The spectral noise density of the Nd:YAG NPRO has a strong $1/f$ dependence decreasing to a constant value at approximately 50 kHz. The white noise above 50 kHz is approximately four times the calculated Schawlow-Townes limit of 0.05 $Hz/\sqrt{Hz}$. The observed noise density at 1 kHz is 20 $Hz/\sqrt{Hz}$. Corresponding values at this frequency are typically 10^3 $Hz/\sqrt{Hz}$ for dye lasers and nearly 10^4 $Hz/\sqrt{Hz}$ for Argon ion lasers. The noise of the NPRO appears largely due to fluctuations in the output of the diode pump laser used for pumping. This is substantiated by numerical modeling which shows that white noise in the diode-laser output would transfer to the spectral noise density with
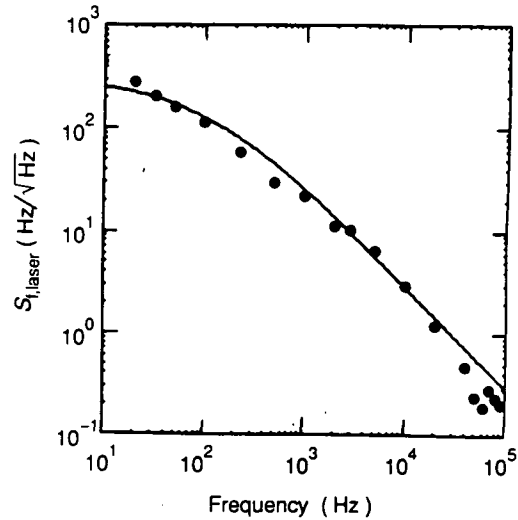

Figure 4. Measured NPRO linear spectreal density of freq uency noise (data points) compared to the modeled frequency (solid line) dependence for a NPRO with pumped by a source with a white-noise component.

the same frequency dependence observed. If the diode laser noise were reduced to the shot noise limit, the numerical calculation indicates that the spectral noise density of the NPRO would decrease to 20 $Hz/\sqrt{Hz}$ at DC. The low noise and potential for further noise reduction make the NPRO an excellent laser for frequency stabilization.

5. Frequency stabilization of the NPRO

The FM-stabilization or Pound-Drever technique was used to stabilize two identical NPRO lasers. The lasers were locked to adjacent fringes of a Fabry-Perot cavity with a finesse of $\mathcal{F}$ = 22,000 and a free spectral range of Δf_{FSR} = 6.327 GHz. The frequency separation resulting from the use of adjacent fringes allowed independent stabilization of the two lasers relative to the same reference cavity. In this measurement[46,47] the two lasers were constructed from Nd:GGG which has a higher Verdet constant than Nd: YAG. The higher Verdet constant provided greater loss difference of the lasers modes and therefore higher resistance to optical feedback.

The experimental setup for the stabilization of the two lasers is shown in Fig. 5. The FM frequencies imposed by the two electro-optical modulators EO1 and EO2 were 10.9

46. T. Day, A. C. Nilsson, M. M. Fejer, A. D. Farinas, E. K. Gustafson, C. D. Nabors and R. L. Byer, Electron. Lett. 25, 810 (1989).

47. T. Day, E. K. Gustafson and R. L. Byer, Opt. Lett. 15, 221 (1990).

and 20.3 MHz respectively. The two laser beams were combined at the beamsplitter (BS). One of the beams from the beamsplitter was incident on a fast photodiode (D1) used to observe the beating of the laser outputs at 6.327 GHz. This signal was mixed down to 20 kHz with a precision RF oscillator and analyzed with an audio spectrum analyzer. The second combined beam from the beamsplitter was transmitted through a polarizing beamsplitter (PBS), a quarter wave plate ($\lambda/4$), and a mode-matching lens (L1), then reflected from the reference cavity back through the lens and waveplate to the polarizing beam splitter where it was reflected to a second photodiode (D2). The signal from the photodiode was mixed with the 10.9- and 20.3-MHz signals from oscillators f_1 and f_2. The signals from the mixers were sent through respective low pass filters and amplified in the servos, and finally applied to the actuators piezoelectric crystals on the lasers. The actuator response was $K = 450$ kHz/V with a bandwidth of 500 kHz and a 20-MHz dynamic range. The servos had 125-dB gain at DC and unity gain at 100 kHz. The discriminant response was 0.4 V/MHz.

The beatnote bandwidth observed with the spectrum analyzer was 2.9 Hz (Fig. 6a). Sampling times of 1.6 sec were used. Two-sample-variance measurements were also performed on the heterodyne signal from the two lasers (Fig. 6b). The two-sample variance decreases with increased sample duration as typical of white noise until a minimum of 4.3 Hz was reached for $\tau = 0.2$ sec. The increase after the minimum is typical of long-term drift. An analysis of the shot-noise limit of the discriminant signal shows that each laser has a theoretical noise bandwidth of 2.2 Hz. All three of these values, 2.9-Hz beatnote, 4.3-Hz minimum two-sample variance, and calculated 2.2-Hz shot-noise-limited laser bandwidth are in reasonable agreement.
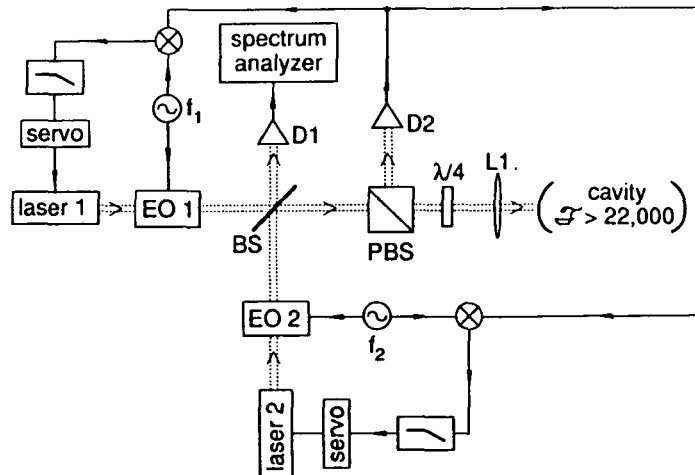

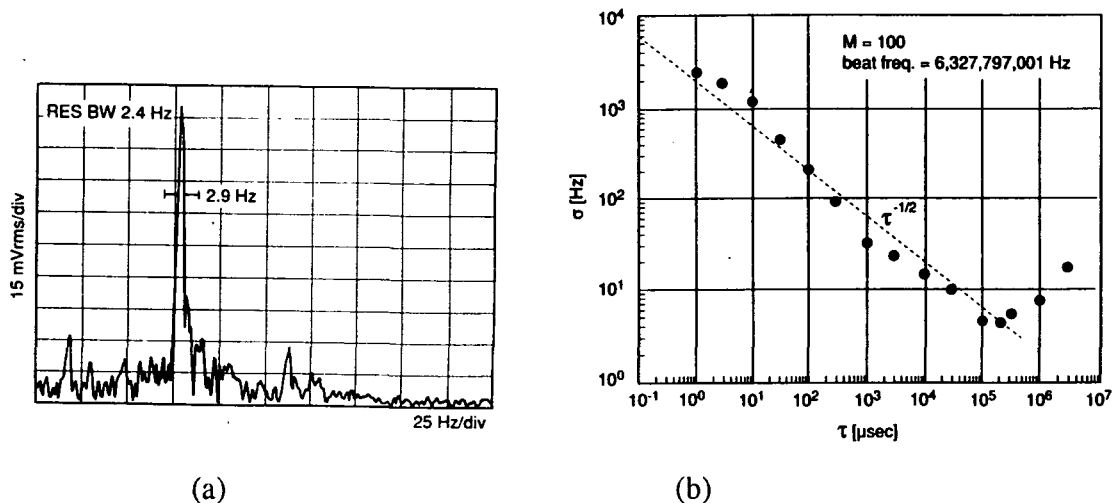Figure 5. Schematic diagram of the dual-laser locking system.

Figure 6. Radio-frequency spectral analysis (a) and two-sample root variance (b)of the heterodyne beatnote between two stabilized NPRO's.

In a subsequent experiment[43,48] the heterodyne beatnote linewidth was reduced to 0.33 Hz. The main factor allowing this was an increase in laser output power. The 2-mW Nd:GGG lasers were replace with 40-mW Nd:YAG NPRO lasers. The increased power and increased sensitivity of the Nd:YAG lasers to feedback made additional isolation necessary. An acousto-optic modulator was used to shift the frequency of the lasers before reflection from the reference cavity. This in combination with the polarizing beam splitter and quarter wave plate provided the required degree of optical isolation. The increased power lowered the theoretical bandwidth due to shot noise to 21 mHz. However, another limit to stabilization had been reached. This limit appears to be mechanical or acoustic noise in the reference cavity. The excess noise of the reference cavity will change the free spectral range as well as the frequency of the resonances.

The work described above is on relative stabilization of the laser frequency. The absolute stabilization is only as good as that of the reference cavity. Work is continuing to isolate the reference interferometer from laboratory noise and to achieve stabilization with narrower reference cavity resonances. The necessity for stabilization of the reference cavity is well known.[49] Absolute stabilization of Nd:YAG lasers is possible by locking to atomic

48. T. Day, E. K. Gustafson and R. L. Byer, "Sub-Hertz frequency stabilization of two diode-laser pumped-Nd:YAG lasers locked to a Fabry-Perot interferometer," submitted to J. of Quantum Electronics.
49. C. Salomon, D. Hils and J. L. Hall, J. Opt. Soc. Am. B 5, 1576 (1988).

or molecular absorptions.[50] He-Ne lasers have been stabilized to 50-mHz levels.[47] Solid-state lasers have many properties important for frequency stable operation and may eventually be stabilized as well or better than He-Ne lasers.

G. Coherent communication

Investigations of coherent communication links using phase-locked receivers have been performed in connection with our frequency stabilized laser efforts. An optical phase-locked-loop architecture suitable for demodulation of a phase modulated carrier was designed and implemented.[51] The receiver can be locked to the transmitter at an arbitrary phase offset, enabling coherent addition, subtraction or quadrature demodulation. The servo-loop bandwidth is suitable for recovering signal at 100 Hz or greater, and 40 dB of signal-to-noise has been achieved for modulation rates of 10.9 MHz. Transmitter powers as low as 20 nW at the detector have been successfully recovered with greater than 10 dB of signal to noise and phase modulation indices of less than 40 mrad can be used to encode the signal. This last result has the potential for enabling very low modulation voltages (<10V with $LiNbO_3$ phase modulators).

By locking the phase of the two lasers at quadrature, any phase modulation imposed on the transmitter can be demodulated by looking at the error signal of the Optical Phase Locked Loop (OPLL). Coherent communication using the homodyne Phase Shift Keying (PSK) is the most sensitive data transmission technique. It is more difficult to use semiconductor lasers to take advantage of the extra sensitivity offered by homodyne PSK due to their inherent large phase uncertainty. Due to inherent low noise, diode-pumped solid-state lasers are ideal for OPLL applications. In our demonstration, a modest band-width servo loop proved sufficient to phase lock the two NPRO lasers with less than 12-mrad rms phase error. Theoretical analysis of minimal phase error in an OPLL also confirms additional advantages of diode-pumped solid-state lasers over semiconductor lasers in homodyne communication links. It is found that since the linewidth of a diode laser is dominated by broad-band quantum noise contributions whereas the diode-pumped solid-state laser linewidth is low-frequency flicker noise dominated, residual phase noise error of the OPLL can be lower for diode-pumped solid-state lasers versus diode lasers with the same linewidth. This conclusion also implies that low-data-rate communication is feasible using diode-pumped solid-state lasers without incurring excessive crosstalk penalty. In our laboratory demonstration system, data rates as low as 20 kHz could be used. This is an

50. A. A. Mak and V. I. Ustyugov, Proc. SPIE 1132, 58 (1989).
51 T. Day, A. D. Farinas and R. L. Byer, IEEE Photonics Tech. Lett. 2, 294 (1990).

important consideration especially for a space based coherent communication link where data rate and laser power requirements can be traded off against each other.

H. Squeezed State Generation

A squeezed state of light is one whose fluctuations of some state variable are less than that of the standard quantum limit, also variously known as the vacuum noise, or the shot-noise level. Due to unique quantum mechanical properties, OPO's have been a prime source for squeezed state generation. As part of our OPO research, we were also interested in investigating the use of OPO's as practical squeezed state generators. Applications of squeezed states include ultra precise interferometric measurements such as what is required for gravitational wave detection. In addition, application of squeezed states for optical communications is also being actively pursued in a number of laboratories.

One possible way to generate squeezed state radiation from an OPO is by taking advantage of the correlation between signal and idler photons generated in the parametric process. Heidmann et. al. in France have carried out an elegant experiment that demonstrates application of signal-idler correlation for sub-shot-noise detection.[52] In this experiment, the signal and idler intensities are separately detected on two nominally identical detectors. Due to signal and idler correlation, the subtracted photo current from the two detectors falls below the shot noise level within the bandwidth of the OPO cavity. In their work, type-II phase matching was used, which allows for separation of signal and idler modes by polarization discrimination.

In our work,[53] sub-shot-noise correlations were generated using type-I phase matching in a monolithic doubly resonant OPO. To separate the signal and idler modes, the OPO was operated away from degeneracy with the wavelength difference between the two waves large enough to permit separation by dispersive prisms. Wavelength of 1012 and 1120 nm were used, and 7-mm beam spatial separation was obtained 1.7 m after transmission through a Pelin-Broca prism. The best result showed 54% noise reduction of the subtracted photo currents compared to the vacuum noise level. The noise reduction was limited by detector efficiency, and absorptiuon loss in the OPO crystal.

As a demonstration of an application for such a two-beam squeezed light, we performed signal detection below the shot-noise limit. An amplitude modulator consisting of a Pockels cell and a polarizer was placed in one of the DRO beams, and a 800-mV peak-

52. A. Heidmann, R. J. Horowics, S. Reynaud, E. Giacobino,k and C. Fabre, Phys. Rev. Lett. 9, 2555 (1987).
53. C. D. Nabors and R. M. Shelby, Phys. Rev. A 42, 556 (1990).

to-peak, 5-MHz modulation voltage was applied to the Pockels cell. With a resolution bandwidth of 30 kHz, the signal was clearly detectable, and yet well below the shot-noise level. This technique has direct application for laser spectroscopy in detecting weak absorption lines and more subtle applications for coherent communication.

I. Continuing research

1. Nonlinear optical frequency conversion
We are continuing to investigate techniques of nonlinear optical frequency conversion. These techniques include resonant cavity harmonic generation and optical parametric oscillation with both discrete and monolithic cavities. Good material quality and knowledge of material parameters are increasingly important in cw applications at increasing power levels. Scattering and absorption losses are important for circulating cw intensities exceeding 10 MW/cm^2. Absorption losses result in crystal heating and distortion, which limit nonlinear frequency conversion efficiency. We are investigating a number of nonlinear optical materials including: various lithium niobate compositions, KTP, barium borate, and lithium triborate for the generation of near infrared, visible, and ultraviolet light applications, and silver gallium selenide and silver gallium sulfide for infrared applications. The nonlinear optical materials are improving, and we now often find the problems are related to surface effects. We are working with optical coating laboratories to resolve problems with surface coatings that appear to limit nonlinear optical frequency conversion performance.

We have extended SHG studies to the UV, generating more than 10 mW of cw 266-nm radiation from 3 W of green fundamental radiation. With improved optics and a good-quality 10-W 532-nm fundamental source, we expect to generate 3 to 5 W of UV output. We are investigating changes in harmonic-generator cavity design, choice of nonlinear optical materials, and improvements of optical components, surface, and coatings required to extend our earlier demonstration of the generation of 6.5 W of 532-nm harmonic by more than an order of magnitude increase in power. Such increases are not a simple matter of scaling and will inevitably involve unexpected problems.

Other current parametric oscillator investigations are using conventional discrete element cavities and monolithic cavities with multilayer dielectric reflecting coatings. We are pursuing several different approaches for achieving cw singly resonant optical parametric oscillation. The most successful approach so far has been a monolithic resonator design in which highly reflecting coatings at 1.32 μm were deposited on two spherical ends of a 5%-MgO:LiNbO$_3$ crystal. The calculated threshold for this oscillator,

assuming 1% round trip losses, is 6 W of 532-nm pump radiation. Damage of the coating and limitations of the 532-nm harmonic generator prevented cw operation, but we were able to achieve oscillation by pulsing the pump source. A cw threshold of 11 W is inferred from the pulsed measurements. We are optimistic that improved coatings and optimized cavity design will decrease the threshold to allow the observation of a true cw SRO operation in the near future. We are also continuing to investigate infrared SRO's pumped by a Q-switched and mode-locked 1.064-μm laser and have plans for further investigation of cw doubly resonant OPO's.

2. *Frequency stabilization*

Frequency stability and amplitude stability are important properties for the applications of the output generated in higher-power diode-laser-pumped solid-state laser systems. We have characterized the injection locking process in the cw arc-lamp-pumped laser by comparing second harmonic generated with an independent lower-power system. Analysis of the beating of the two independent harmonic signals indicates that the linewidth of both signals is less than 10 kHz. With proper alignment the harmonic signal has remarkable good spatial quality, differing from a TEM_{00} Gaussian beam by only 1%. The spectral distribution of the amplitude fluctuations of the injection-locked laser is less than 10^{-6} per $Hz^{1/2}$ at frequencies between 100 Hz and 100 kHz. Slow fluctuations measured in the range of 1 second to a half-hour are on the order of 5%. In these preliminary measurements, no effort was made to control either the frequency or amplitude stability by active feedback stabilization techniques. Preliminary results indicate that the injection locked laser reproduces the frequency stability of the low-power master laser in the laser output and all the way through the second-harmonic generation process.

The stabilization of the NonPlanar Ring Oscillator (NPRO) lasers has continued with the construction of two high-finesse Fabry-Perot cavities. The objective is to further improve the stability of the seed lasers used for injection seeding the high-power Nd:YAG lasers. Since the phase of the slave laser closely tracks the phase of the seed lasers, any improvement in the stability of the seed laser results in a corresponding improvement in the stability of the slave laser. For this purpose a set of six new reference cavities are under construction. All six of the new Fabry-Perot spacers were polished simultaneously in a common jig, making them equal in length (about 17 cm) to better than 0.5 microns. At this point two the reference cavities (5 cm in diameter) have been assembled. These cavities utilize spacers constructed of ULE (Corning's Ultra-Low Expansion glass) for high stability and insensitivity to temperature changes. The mirrors used on these cavities are ultra-low-loss mirrors with a demonstrated finesse of 120,000. These cavities have been

housed in hermetically sealed pressure cans and isolated from room acoustic noise and vibration by means of an O-ring suspension. Current work includes the measurement of the relative frequency stability of two lasers locked to two of these Fabry-Perot reference cavities, and the measurement of the time response of the Pound/Drever frequency discriminator used to lock lasers to cavities.

3. Yb:YAG laser development

We have begun preliminary investigation of Yb:YAG as a laser material for operation at 1.029-μm. We acquired a single Yb:YAG slab, 0.85 mm in thickness, and doped with 6.5% Yb. The upper state lifetime was measured and found to be 1.2 msec. The absorption of this material (Fig. 7) will allow efficient diode pumped operation near 940 nm. The small difference in pump and output wavelengths will substantially reduce heating compared to Nd:YAG. Our first attempt to build a room temperature Yb:YAG laser was unsuccessful due to lack of optics optimized for a Yb:YAG laser and insufficient pumping power. With the available optics, it was necessary to pump the potential laser from the side. The pumping power available from the Ti:Al$_2$O$_3$ laser used for pumping was close to the calculated threshold for optimum conditions. We have investigated possible schemes of building a tunable single-mode 2-W cw output Yb:YAG laser. When the output frequency of this laser is doubled, we expect to produce 1 W of green radiation. The doubled output at 514.5 nm could be a direct replacement for Argon Ion lasers.
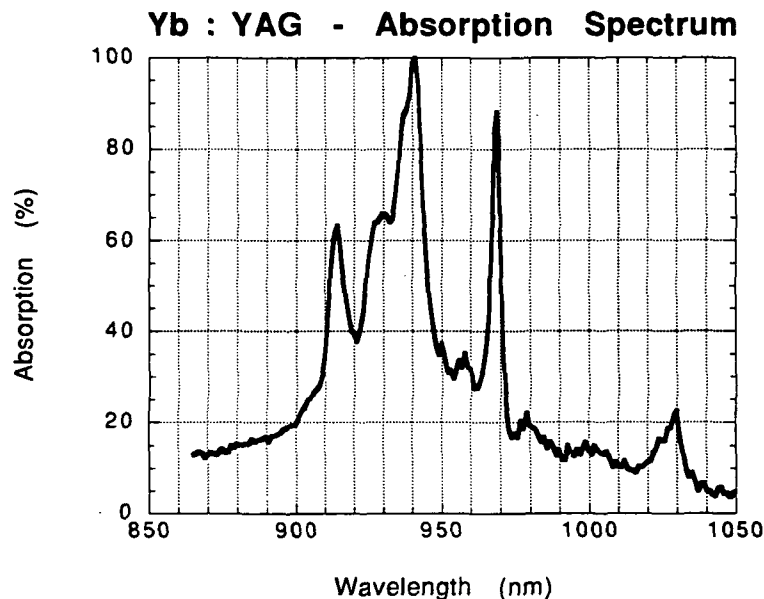

Figure. 7 Absorption spectrum of the pump band Yb:YAG. A 6.5% Yb doped, 0.85-mm-thick sample was used.

IV. Conclusion

The research performed in this program has dealt with a variety of topics important to coherent communication and remote sensing. The topics were in the areas of laser development, laser noise characterization and frequency stabilization, and investigation of the coherence and tuning properties of doubly resonant optical parametric oscillators. An optical phase-locked-loop architecture suitable for demodulation of a phase modulated carrier was designed and implemented with our frequency stabilized laser techniques. Sub-shot-noise signal recovery was demonstrated by modulating one of the output beams of an optical parametric oscillator; this is permitted by the correlation of the fluctuations in the two beams of the parametric oscillator output. The most substantial progress has been of a fundamental nature. These advances include: development of frequency stabilization techniques of diode-pumped solid-sate lasers to achieve 0.3 Hz relative frequency stability; characterization and analysis of the noise of diode-pumped solid-state lasers; demonstration that external resonant cavity harmonic generators and optical parametric oscillators preserve the coherence of the pump radiation; remeasurement of nonlinear optical coefficients to resolve discrepancies of absolute scale; analysis of the tuning and stability of doubly resonant optical parametric oscillators; and injection seeding and locking techniques.

Local oscillators are of central importance both in coherent communications and remote sensing. The program addressed the development of stable-frequency narrowly tunable lasers and widely tunable single frequency optical parametric oscillators. In heterodyne or coherent communication, discrimination of signal in high noise background will increases with stability of transmitter and receiver oscillators. Stable single-frequency operation is also a requirement of the optical sources used to pump the proposed optical parametric oscillators. The parametric oscillators have the capability of preserving the coherence of the pump when it is converted into widely tunable radiation.

The spectral range of a $LiNbO_3$ optical parametric oscillator includes the near infrared wavelengths between 725 - 930 nm that have been proposed for differential absorption LIDAR (DIAL) measurement of atmospheric water vapor content, pressure, and temperature. The tuning range of lithium niobate OPO's can be extended to wavelengths as long a 4 μm making them useful for measurement of concentrations of many atmospheric pollutants. The combination of temperature and electric field tuning of wave length of the doubly resonant OPO outputs should be quite useful in the DIAL applications. Temperature tuning will allow selection of a specific absorption, and electric field tuning can provide rapid electronically controlled shifts between the measured absorption and nearby reference wavelengths. We have demonstrated such frequency control near 1 μm

and expect the same techniques to work at other wavelengths. We have also demonstrated that the pulsed doubly resonant OPO can be made to operate in a single longitudinal cavity mode by proper selection of temperature and applied electric field. The resulting linewidths are narrower than the 0.1-cm^{-1} widths typical of the atmospheric absorptions.

Output powers in the range of 5 - 10 W can be achieved through diode-pumped solid-state laser and nonlinear frequency conversion. The very rapid development of high-power diode lasers promises to extend the operation of optically-pumped solid-state lasers to the range of hundreds of watts output power, and to do so with reliability and economy that was not before possible. High-average-power nonlinear frequency conversion will follow the laser development. Optical parametric amplification will be used to increase the power levels of lower power OPO's. We have begun separate programs to extend diode-pumped solid-state laser operation to the tens of watts level . Nonlinear frequency conversion studies are being scaled to higher power levels and extended in spectral range.

This program has focused on topics of great interest, concentrating on efficient wavelength-diverse coherent sources. Continued development of these laser devices and techniques of broad applicability and interest to the community. The need for continued support, which will allow research to proceed in a logical order, remains urgent. This program has provided many fundamental advances in laser technology and nonlinear optical techniques. The potential to satisfy NASA transmitter requirements for coherent communication applications has been demonstrated. Much of this research, however, is at a preliminary stage, and there is a need for integration of the methods which have been demonstrated separately.

V. Publications supported in part or fully by Grant NAGW-1760

1. M. K. Reed and R. L. Byer, "Mode-locked operation af a Nd:YLF laser and amplification in a Q-switched Nd:glass slab laser," IEEE J. Quantum Electron. **26**, pp. 1399-1404 (1990).

2. C. D. Nabors and R. L. Byer, "Monolithic Optical Parametric Oscillators for Quantum. Optics," *Coherence and Quantum Optics VI*, edited by J. H. Eberly, L. Mandel and E. Wolf (Plenum, New York, 1990), pp. 787-791.

3. C. D. Nabors and R. M. Shelby, "Two-color squeezing and sub-shot-noise signal recovery in doubly resonant optical parametric oscillators," Phys. Rev. **42**, pp. 556-559 (1990).

4. C. D. Nabors, S. T. Yang, T. Day and R. L. Byer, "Coherence properties of a doubly-resonant monolithic optical parametric oscillator," J. Opt. Soc. Am. B **7**, pp. 815-820 (1990).

5. M. K.Reed and R. L. Byer, "The output beam quality of a Q-switched Nd:Glass slab laser," IEEE J. Quantum Electron. **26**, pp. 2138-2145 (1990).

6. R. C. Eckardt, C. D. Nabors, W. J. Kozlovsky and R. L. Byer, "Optical parametric oscillator frequency tuning and control," J. Opt. Soc. Am B **8**, pp. 646-667 (1991).

7. R. C. Eckardt, H. Masuda, Y. X. Fan and R. L. Byer, "Absolute and relative nonlinear optical coefficients of KDP, KD*P, BaB_2O_4, $LiIO_3$, $MgO:LiNbO_3$, and KTP measured by phase-matched second harmonic generation," IEEE J. Quantum Electron. **26**, pp. 922-933 (1990).

8. T. Day, E. K. Gustafson and R. L. Byer, "Active frequency stabilization of diode laser pumped, nonplanar ring oscillators," Proc. SPIE **1223**, pp. 181-185 (1990).

9. T. Day, A. D. Farinas and R. L. Byer, "Demonstration of a low bandwidth 1.06 μm optical phase-locked loop for coherent homodyne communication," IEEE Photonics Tech. Lett. **2**, pp. 294-296 (1990).

10. R. L. Byer, "Frequency stable high power lasers in space," *Relativistic Gravitational Experiments in Space*, edited by R. W. Hellings (NASA Headquarters, Washington, D.C, 1989), pp. 166-170.

To be published

1. R. L. Byer, "Advances in nonlinear optical materials and devices," to be published in *Proceedings of the 5th Toyota Conference on Nonlinear Optical Materials, Aichi-ken, Japan, 6-9 October 1991*, S. Miyata, ed. (Elsevier Science, Amsterdam, 1992).

2. T. Day, E. K. Gustafson and R. L. Byer, "Sub-Hertz frequency stabilization of two diode-laser pumped-Nd:YAG lasers locked to a Fabry-Perot interferometer," submitted to J. of Quantum Electronics.

3. R. C. Eckardt, T. Day, E. K. Gustafson and R. L. Byer, "Frequency stable operation of Nd:YAG Lasers," *to be published, Proceedings of the 5th International School on Laser Applications in Atomic, Molecular and Nuclear Physics*, (Vilnius University Press, Vilnius, Lithuania).

VI. Presentations Relating to Work Supported Grant NAGW-1760

INVITED PRESENTATIONS

1. R. L. Byer, "Solid State Lasers for Gravitational Wave Interferometry," given at the 12th International Conference on General Relativity and Gravitation, Univ. of Colorado, Boulder, Colorado, July, 1989.

2. R. L. Byer, "Efficient Nonlinear Conversion of Diode Pumped Lasers," given at The Gordon Conference, New Hampshire, July 1989.

3. R. L. Byer, "Solid State Lasers: The Next Ten Years," OLLRC Topical Workshop, Toronto, Canada, September, 1989.

4. R. L. Byer, "Hertz Linewidth Diode Pumped Solid State Lasers," given as invited paper ELT 3.6 at 1989 LEOS Annual Meeting, Orlando, Florida, October 15-20, 1989.

5. R. L. Byer, "Solid state lasers and nonlinear optics," presented at Quantum Electronics Seminar, Applied Physics Dept., Stanford University, October, 1989.

6. R. L. Byer, "Infrared diode-pumped solid state lasers and efficient frequency conversion techniques," given at 1989 OSA Annual Meeting, Orlando, Florida, October 16-20, 1989.

7. T. Day, E.K. Gustafson, and R.L. Byer, "Active frequency stabilization of monolithic diode-laser-pumped solid state lasers," presented at Lasers 89, New Orleans, Louisiana, December 1989.

8. T. Day, E. K. Gustafson, and R.L. Byer, "Active Frequency Stabilization of Diode-Laser-Pumped Non-Planar Ring Oscillator," presented at SPIE OELase '90, January, 1990.

9. R. L. Byer, "Diode-pumped miniature solid state lasers," given at the Conference on Optronic Techniques in Diagnostic and Therapeutic Medicine, Florence, Italy, March 1990.

10. R. L. Byer, "Narrow linewidth solid state lasers for satellite based wind measurements," Baetjer Seminar, Princeton University, Princeton, NJ, April 16, 1990.

11. R. L. Byer, "Diode pumped solid state lasers for fun and profit," regional OSA Meeting, Tektronix Inc., Portland, OR, May, 1990.

12. R.L. Byer, "Diode-pumped solid state lasers and potential for display applications," Tektronix Seminar, Beaverton, OR, May 11, 1990.

13. R.L. Byer, "Diode pumped solid state lasers," Diode Laser Pumps and Diode Pumped Solid State Lasers, Buchanan Highland Hotel, Drymen, June 19-20, 1990.

14. R. C. Eckardt and R. L. Byer, "Frequency-stable operation of Nd:YAG lasers for OPO pumping," Fifth International School on Laser Applications in Atomic, Molecular and Nuclear Physics, Vilnius, Lithuania, USSR Aug. 21, 1990.

15. R. C. Eckardt and R. L. Byer, "Stable narrow linewidth optical parametric oscillators," invited lecture, Fifth International School on Laser Applications in Atomic, Molecular and Nuclear Physics, Vilnius, Lithuania, USSR Aug. 22, 1990.

16. R. C. Eckardt and R. L. Byer, "Frequency tuning of monolithic, doubly-resonant optical parametric oscillators," Invited lecture, Max Planck Institute, Munich, Federal Republic of Germany, Aug. 30. 1990.

17. R. L. Byer, "Sub-kHz Tunable OPO sources for spectroscopy", U.S. Japan Seminar on Quantum Electronic Manipulation of atoms and fields", Kyoto, Japan, September 3-7, 1990.

18. R. L. Byer, "Linear and Nonlinear Experiments with Diode Pumped Solid State Lasers," Optical Sciences Center, Tucson, AZ, December 6, 1990.

19. R. L. Byer, "Nonlinear Frequency Conversion of Diode Pumped Solid State Lasers," invited seminar, U.S. Army Harry Diamond Laboratory, Adelphi, Maryland, Feb 27, 1991.

20. S. T. Yang, C. C. Pohalski, E. K. Gustafson, and R. L. Byer,"3.5 watt cw nm radiation by resonant external cavity SHG of an 8.5 watt Nd:YAG laser in LBO," invited paper #MF1 at Advanced Solid State Lasers Topical Mtg, Hilton Head, S.C., March 18-20, 1991.

21. R. C. Eckardt, S. T. Yang, C.C. Pohalski, D. Serkland, V. Sirutkaitis, and R.L. Byer, "Tuning and stabilization of doubly resonant OPO's," IEEE LEOS Annual Meeting, San Jose, November 3-8, 1991.

22. R. L. Byer, "Development of solid state lasers - an overview," TENICOLS '91, Session 11, Font-Romeu, France, June 17-21, 1991.

23. A. D. Farinas, E. K. Gustafson, and R.L. Byer, "High Power, Diode Laser Pumped Nd:YAG Lasers," BAPS 36, 7, July/August, 1991.

24. R. L. Byer, "Advances in Nonlinear Materials and Devices," plenary paper P1, Seventh Interdisciplinary Laser Science Conference, Monterey, September 22-26, 1991.

25. R. L. Byer, "Advances in Nonlinear Materials and Devices, "Fifth Toyota Conference, Aichi-ken, Japan, October 6-9, 1991.

CONTRIBUTED PRESENTATIONS

1. E. C. Rea, D. Craven, A. C. Nilsson, R. L. Byer, "Single Frequency, Undirectional, Monolithic Nonplanar Ring Laser in Nd:Glass", paper WH4, Conference on Lasers and ElectroOptics (CLEO), 24-28 April 1989, Baltimore, Maryland.

2. T. Day, A. C. Nilsson, A. D. Farinas, E. K. Gustafson and R. L. Byer, "Active linewidth narrowing of diode laser pumped non-planar ring oscillators," paper WDD27, Conference on Lasers and ElectroOptics (CLEO), 24-28 April 1989, Baltimore, Maryland.

3. C. D. Nabors and R. L. Byer, "Monolithic optical parametric oscillators for quantum optics," paper MAc2, Sixth Rochester Conference on Coherence and Quantum Optics, June 1989.

4. R. L. Byer, "Ultranarrow linewidth solid state oscillators," postdeadline paper, 9th International Conference on Laser Spectroscopy, Bretton Woods, NH, June 1989.

5. C. D. Nabors, A. D. Farinas, T. Day, S. T. Yang, E. K. Gustafson, and R. L. Byer, "Injection locking of a 13-watt Nd:YAG ring laser," poster WL14, OSA Annual Meeting, Orlando, Florida, October 15-20, 1989.

6. R. L. Byer, "An efficient 266 nm solid state ultraviolet laser source," presented at the Engineering Foundation Conference, Santa Barbara, CA, February 26, 1990.

7. C. D. Nabors and R. L. Byer, "High coherence operation and optical frequency division in a monolithic optical parametric oscillator," paper MD2 at OSA topical meeting on Advance Solid-State Lasers, Salt Lake City, March 5-7, 1990.

8. R. C. Eckardt, H. Masuda, Y. X. Fan, and R. L. Byer, "Re-measurement of some nonlinear optical coefficients by phase-matched second harmonic generation," paper CWF-25, Conference on Lasers and Electro-Optics, Anaheim, CA, May, 1990.

9. R. C. Eckardt, S. T. Yang, E. K. Gustafson, and R. L. Byer, "Frequency tuning and control of doubly resonant optical parametric oscillators,"paper MUU3, Optical Society of America Annual Meeting, Boston, Nov. 1990.

10. S. Schiller, N.M. Sampas, and R.L. Byer, "Frequency stabilization of Nd:YAG lasers," Proc. of the 10th Intl. Conf. on Laser Spectroscopy, 1991.

12. R.C. Eckardt and R.L. Byer, "Measurement of nonlinear optical coefficients by phasematched harmonic generation," paper [1561-15], SPIE's International Symposium on Optical Applied Science and Engineering, July 21-26, 1991.