HIGH ENERGY EFFICIENT SOLID STATE LASER SOURCES

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ABSTRACT

Recent progress in the development of highly efficient coherent optical sources is reviewed. This work has focussed on nonlinear frequency conversion of the highly coherent output of the Non-Planar Ring laser Oscillators developed earlier in the program, and includes high efficiency second harmonic generation and the operation of optical parametric oscillators for wavelength diversity and tunability.

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I. Introduction

This final report for NASA Grant NAG 1-182 will describe the progress we have made in the development of highly efficient coherent sources since the last formal report. The thrust of our work in the High Energy Efficient Laser Sources program has moved over the years from high energy laser systems for LIDAR applications to the development of highly efficient diode-laser-pumped solid-state lasers and non-linear optics using these lower power cw sources. This program which began in June 1981 has continued to address specific NASA requirements for laser sources. We describe our recent progress in high efficiency, wavelength diverse coherent sources, including second harmonic generation experiments, a variety of optical parametric oscillator systems, and further laser development.

The specific topics which we have chosen to investigate form a coordinated research program directed to satisfy aspects of laser source requirements for remote sensing applications. Our early research in this program in the area of flashlamp pumped slab lasers has become a basis for the development of high average power diode-laser-array-pumped slabs. Diode pumping offers the potential of high average power operation with good efficiency and long term reliability. Semiconductor-diode-laser pumping of solid-state lasers has been demonstrated in this program to provide the frequency stability and coherence required for Doppler LIDAR wind velocity measurements. Our present investigation of nonlinear frequency conversion can provide the frequency agility required for differential absorption LIDAR measurements of atmospheric water vapor content, pressure, temperature and pollutant concentrations. There are also other important applications of these methods to a variety of applications including coherent communication, fundamental physics, precise timing, ranging, and inertial guidance.

Our current nonlinear frequency conversion investigations are being performed at low power levels but are scalable to the required higher levels. Even with 53 milliwatts of cw 1064-nm laser output, we were able to achieve 56% conversion to second harmonic at 532 nm. We are demonstrating similar levels of conversion in tunable optical parametric oscillation. These recent advances have been made possible by improvements in pump laser technology and the quality of nonlinear optical materials. The nonlinear conversion techniques will be scalable to high average power just as the highly coherent miniature diode-pumped lasers were scaled by injection seeding of high power oscillators or by amplification. High average power nonlinear frequency conversion of neodymium laser radiation can be competitive with titanium-doped-sapphire and Alexandrite lasers, and with further development the nonlinear frequency conversion techniques could offer significant advantages.

II. Review of Recent Progress

A. Harmonic conversion

Our result of November 1987 of 56% conversion efficiency of a 53 mW cw single-axial mode diode-pumped Nd:YAG laser was reported at SPIE's O-E Lase conference[1], the Conference on Lasers and Electro-Optics (CLEO '88) [2] and in the IEEE Journal of Quantum Electronics[3]. The generation of 30 mW of frequency stable cw light at 532 nm has attracted a great deal of attention, and two companies have announced development

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[1] C.D. Nabors, W.J. Kozlovsky, and R.L. Byer, "Efficient second harmonic generation of a diode-pumped cw Nd:YAG laser using and externally resonant cavity," paper 898-18, SPIE O-E Lase '88, Los Angeles, January 11-12, 1988; also published in Proc. SPIE **898**, *Miniature Optics and Lasers* pp. 105-109 (June, 1988).

[2] W.J. Kozlovsky, C.D. Nabors, and R.L. Byer, "52% Efficient Second Harmonic Generation of a cw Diode-Pumped Laser Using a Monolithic External Ring Cavity," paper FE1, 1988 Conference on Lasers and Electro-Optics, Anaheim California, April 1988.

[3] W.J. Kozlovsky, C.D. Nabors, and R.L. Byer, "Efficient second harmonic generation of a diode-laser-pumped cw Nd:YAG laser using monolithic MgO:LiNbO$_3$ external resonant cavities," *IEEE J. Quantum Elec.* **24**, 913 (1988).

efforts to productize our technique. Since then, we have worked to use the MgO:LiNbO$_3$ monolithic resonant frequency doublers to produce higher powers for OPO pumping. We succeeded in operating and servo-locking the resonant doubler while the laser source was driven into deep spiking (see below) to produce peak powers in the green of as much as 500 mW. In this mode, the resonant doubler was also observed to exhibit parametric oscillation at ± 1 nm from the 1064-nm laser light. This phenomenon is still under investigation. We have also begun investigating the use of stoichiometric LiNbO$_3$ prepared by vapor transport equilibration[4] as a material for monolithic harmonic generators and optical parametric oscillators.

B. Singly resonant optical parametric oscillator in MgO:LiNbO$_3$

A monolithic MgO:LiNbO$_3$ singly resonant optical parametric oscillator was operated in both the standing wave and ring geometries[5,6,7]. The OPO was pumped by the second harmonic of the amplified single-mode diode-laser-pumped Nd:YAG laser, operating at a 3-Hz repetition rate. Pump depletions of greater than 60% were observed when pumping four times above the 35-watt threshold, with a corresponding energy conversion efficiency of 35%. The pump power was 120 watts at 532 nm in a 500-nsec pulse.

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[4] Y. S. Luh, M. M. Fejer, R. L. Byer and R. S. Feigelson , "Stoichiometric LiNbO$_3$ single-crystal fibers for nonlinear optical applications," Journal of Crystal Growth **85**, pp. 264-269 (1987).

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[6] W. J. Kozlovsky, E. K. Gustafson, R. C. Eckardt and R. L Byer, "An efficient monolithic MgO:LiNbO$_3$ singly resonant optical parametric oscillator," to be published, Optics Letters.

[7] W. J. Kozlovsky, C. D. Nabors, R. C. Eckardt and R. L Byer, "Monolithic MgO:LiNbO$_3$ doubly resonant optical parametric oscillator pumped by a frequency-doubled diode-laser-pumped Nd:YAG laser," to be published, Optics Letters.

The OPO output at the resonant signal tuned with temperature from 834 nm to 958 nm while the corresponding idler tuned from 1.47 to 1.2 μm. The spectral output varied from pulse to pulse, with single frequency operation observed on approximately 20% of the pulses. The remaining pulses contained as many as eight axial modes of a total spectral width of less than 0.7 cm^{-1}, with a center frequency that was stable to ±0.2 cm^{-1}. The multimode behavior can be attributed to crystal temperature fluctuations and microscopic mode competition effects during the build-up period of the oscillator. A similar crystal with 2% net output coupling is expected to run single axial mode and have a threshold for singly resonant cw operation of 3 watts.

C. Doubly resonant optical parametric oscillator in $MgO:LiNbO_3$

A doubly resonant monolithic optical parametric oscillator was demonstrated. It was the first OPO ever to be pumped with a diode-pumped solid-state laser as its source. The frequency doubled output of a non-planar ring laser driven into spiking was mode matched into a monolithic cavity much like those used in the harmonic generation experiments. The higher powers were needed as our original OPO design was misfabricated in the thin-film coating process, producing an OPO threshold of 40 mW cw rather than the design point of 5 mW. This OPO operated near degeneracy and was temperature tunable from 1.01 to 1.13 μm. Overall energy conversion of the pump light at 532 nm was 7%. This work has been accepted for publication[8].

The OPO could be tuned by applying an electric field across the crystal, which changed the ordinary index of refraction via the electro-optic effect and the effective cavity length via the electro-optic and piezo-electric effects. Near degeneracy the OPO tuned 5 nm

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[8] W. J. Kozlovsky, C. D. Nabors, R. C. Eckardt and R. L Byer, "Monolithic $MgO:LiNbO_3$ doubly resonant optical parametric oscillator pumped by a frequency-doubled diode-laser-pumped Nd:YAG laser," to be published, Optics Letters.

with approximately 800 volts applied. Away from degeneracy, the OPO operated in a single axial mode, but tended to drift from mode to mode as the crystal temperature varied, and no active control was used. In October, a new crystal was obtained with improved coatings that oscillated under true cw pumping conditions with a threshold of approximately 10 mW. This OPO is still under investigation.

A complete theory of the tuning and mode control properties of monolithic doubly resonant OPOs is under development, and has been presented at the recent Optical Society of America meeting[9]. This system is also an excellent candidate for the production of squeezed states of light, and an effort is being made to observe these states that exhibit noise levels below that of the Standard Quantum Limit, or the shot noise.

D. Non-planar diode-pumped ring lasers

Theoretical development of non-planar ring oscillators (NPROs) is largely complete, and has been presented at the SPIE's O-E Lase conference and submitted to the IEEE Journal of Quantum Electronics [10,11]. Emphasis has been placed on laser designs with improved isolation to feedback, low threshold, narrow linewidth, and frequency tuning with applied magnetic field.

Support for experimental work has largely been taken over by Stanford University/NASA SUNLITE program (grant NAG 1-839). Currently, the linewidths of

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[9] R. C. Eckardt,C. D. Nabors, W. J. Kozlovsky and R. L. Byer, "Simultaneous Electro-optical and temperature tuning of a doubly resonant optical parametric oscillator," paper TuN4, Annual Meeting of the Optical Society of America, Santa Clara, California, Nov., 1988.

[10] A. C. Nilsson, T.J. Kane, and R. L. Byer, "Monolithic nonplanar ring oscillators: resistance to optical feedback", paper 912-03, Optoelectronics and Laser Applications in Science and Engineering (O-E/LASE'88), Los Angeles, California, January, 1988; also published in Proc. SPIE 912, *Pulsed Single-Frequency Lasers: Technology and Applications*, pp. 13-18 (June, 1988).

[11] A. Nilsson, E. Gustafson, and R. L. Byer, "Eigenpolarization theory of monolithic nonplanar ring oscillators," submitted to IEEE J. Quantum Electron.

two Nd:GGG ring lasers are being measured by frequency locking to an external reference cavity and spectrum analyzing the heterodyne beatnote between them. This work has yielded a linewidth measurement for the improved oscillators of approximately 300 Hz.

E. Driven relaxation oscillation spiking and noise suppression in diode-pumped ring lasers

Relaxation oscillation noise in diode pumped solid state lasers is a serious problem for many applications such as coherent communications and LIDAR. Relaxation oscillations can be exploited, however, by deliberately modulating the diode laser pump at the relaxation oscillation frequency to produce spikes in the output power whose peak power can be greater than 20 times the cw power at the same average pump power. In the doubly resonant OPO experiment described above, higher intensities were needed to bring the OPO above threshold, so a 10% modulation was applied to the diode pump to induce spiking.

To eliminate relaxation oscillation noise for cw operation, active electronic feedback of the solid-state laser power to the diode laser current was employed to achieve a 25 dB suppression of the noise peak at 375 kHz. This result is of considerable practical importance, and work continues to improve the noise suppression over a broad band. Additionally, a number of effects such as bistability and chaos have been observed for the system and are under investigation.

F. Widely tunable optical parametric oscillator in barium borate

A visible BaB_2O_4 optical parametric oscillator pumped by a single-axial-mode 355-nm source has been demonstrated[12]. This was a collaborative experiment with workers from the University of Hannover. The laser pump souce was a Spectra-Physics DCR-3D

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[12] Y. X. Fan, R. C. Eckardt, R. L. Byer, J. Nolting and R. Wallenstein, "A visible BaB2O4 optical parametric oscillator pumped at 355 nm by a single-axial-mode pulsed source," to be published, Applied Physics Letters.

Q-switched unstable resonator Nd:YAG system. The laser was injection seeded for single-axial-mode operation, and the output light spatially filtered before generating the third harmonic, yielding a quasi-Gaussian transverse mode profile. Good coherence and spatial mode quality of the pump is needed for narrow band, stable OPO operation.

An average output power of 140 mW with a signal wave conversion efficiency of 13% an an idler conversion efficiency of 11% for a total conversion efficiency of 24% has been achieved. The observed threshold energy of 2-5 mJ is a factor of 2-3 lower than the value calculated, indicating that previous measurements of the nonlinear coefficient may be low. The oscillator has been continuously tuned from 412 nm to 2.55 μm, limited by the infrared transmission range of the crystal. Through injection seeding we obtained single-axial-mode OPO operation with a corresponding OPO linewidth of less than 3 GHz.

III. Conclusion

This program has been very fruitful, sponsoring in whole or in part the theses of numerous graduate students and leading to a number of publications and 4 patents, including the Monolithic Isolated Single-mode End-pumped Ring laser oscillator (MISER), the angularly multiplexed Nd:YAG laser amplifier, diode-laser pumped Nd:Glass lasers, and highly efficient second harmonic generation in monolithic resonators.

Continued research is focusing on topics of great interest, concentrating on efficient wavelength-diverse coherent sources, and narrow-bandwidth frequency-stable diode-pumped solid-state lasers. The potential to satisfy NASA transmitter requirements for remote sensing and communications applications has clearly been demonstrated. Much of this research, however, was at a preliminary stage.

Further fundamental research directed to improved performance of resonant second harmonic generation and scaling to higher output powers, development of cw OPOs with controllably tuned output, and noise reduction combined with an investigation of squeezed states of light will follow. This work is essential to continued source development.

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V. Appendices

APPENDIX C

Monolithic MgO:LiNbO$_3$ doubly resonant optical parametric oscillator pumped by a frequency-doubled diode-laser-pumped Nd:YAG laser

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ABSTRACT

We have demonstrated a monolithic MgO:LiNbO$_3$ doubly resonant optical parametric oscillator using an all-solid-state pump. The pump laser was a single-axial-mode monolithic Nd:YAG nonplanar ring oscillator whose diode-laser pump was modulated at 325 kHz to produce relaxation oscillation spikes at 1.06 µm that were frequency doubled in a resonant cavity to 532 nm. Pump depletions for the OPO of greater than 60% were observed when pumping six times above the calculated 40-mW threshold. The OPO output was temperature tuned from 1.01 µm to 1.13 µm, producing single axial mode output over much of the range. By changing the voltage applied across the OPO, the output wavelength was scanned as much as 11 nm in 310 Volts.

Monolithic MgO:$LiNbO_3$ doubly resonant optical parametric oscillator pumped by a frequency-doubled diode-laser-pumped Nd:YAG laser

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Optical parametric oscillators (OPOs) have several potential advantages over tunable lasers in the generation of widely tunable narrowband optical radiation. Laser tuning ranges are generally limited by relatively narrow gain bandwidths and fixed gain centers. The gain center of an OPO is tuned by changing the crystal birefringence with temperature or propagation angle adjustments, yielding a tuning range limited only by the crystal dispersion and transmittance bandwidth. Doubly resonant OPOs, which resonate both signal and idler waves, can have very low pump thresholds but require very good spatially and temporally coherent pumps[1]. Recent advances in frequency-stable, single-mode lasers, coupled with the development of new nonlinear crystals such as MgO:$LiNbO_3$, $AgGaSe_2$, and barium borate have renewed interest in OPOs. In this letter, we report the operation of a monolithic ring-cavity MgO:$LiNbO_3$ doubly resonant OPO pumped by the second harmonic of a frequency-stable, diode-laser-pumped Nd:YAG laser.

The stringent pump laser requirements for pumping doubly resonant OPOs are due to the necessity for simultaneous cavity resonances at both the the signal and idler modes, and that the signal and idler frequencies must sum to exactly equal the pump frequency [2]. Pump frequency fluctuations therefore can cause OPO power output fluctuations and frequency instabilities. In addition, a single-transverse-mode pump laser is necessary to couple power efficiently to the signal and idler modes [3,4]. For these reasons, the TEM_{00}, single-axial-mode, frequency-stable output from diode-laser-pumped Nd:YAG monolithic nonplanar ring laser [5] or its second harmonic [6] are ideal for pumping doubly resonant OPOs.

The simultaneous resonance condition for the signal and idler is also very sensitive to cavity length fluctuations, so that the OPO cavity length stability is very important. A monolithic cavity, fabricated by depositing the OPO mirrors directly onto the nonlinear crystal, provides both excellent cavity stability and the lowest possible OPO cavity losses. Figure 1 shows the monolithic $MgO:LiNbO_3$ OPO cavity design used for these experiments. A ring geometry was used since it allows the maximum efficiency for a doubly resonant OPO by preventing back generation of pump radiation from the resonated signal and idler [7] and because it reduces feedback into the pump laser.

$MgO:LiNbO_3$,[8,9] was selected as the OPO nonlinear gain medium because of its noncritical, temperature tuned phasematching range, useful for monolithic devices, and its low losses at 1 µm. Low losses are especially important for a doubly resonant OPO, as the OPO threshold is proportional to the product of the signal and idler losses[10]. To fabricate the monolithic OPO cavity, the ends of a 1.25-cm-long crystal were polished to 10-mm radii of curvature. The off-axis ring resonator was formed by a polishing a flat total-internal-reflection surface to within 0.18 mm of the mirror axis as shown in figure 1. The confocal parameter[11] for the resonator was 0.433 cm, giving the spot size for the signal wave of 27 µm at 1.064 µm. Electrodes were placed on the crystal surfaces perpendicular to the 2.2-mm-width Y-axis to enable electro-optic tuning of the cavity resonances and the crystal birefringence as described below.

The mirrors deposited on the OPO cavity had their reflectivity centered at degeneracy, 1.064 µm, so that both signal and idler wavelengths would be resonant. The coatings for the OPO crystal were designed to produce a 5-mW pump threshold based on the anticipated nonlinear gain and cavity losses. The coatings specified consisted of a high reflector at 1.064 μm and high transmittance at 532 nm for one curved end (M1), and a 99.5% reflector at 1.064 μm for the other curved end as the output coupler (M2). The coatings that were actually applied to the crystal consisted of a 99.9% reflector at 1.064 μm with only a 60% transmission at 532 nm for M1 and a 98.8% reflector for the output coupler M2. The measured finesse for the OPO cavity of 360 was in good agreement with these coating reflectivities and bulk and surface losses for the cavity of 0.4%. The calculated OPO threshold for the coatings applied to the crystal was 40 mW.

The Nd:YAG monolithic nonplanar ring laser used for these experiments was pumped with a 500-mW diode laser to produce 65 mW of TEM_{00} output[12]. The laser output was frequency doubled using a resonant external cavity frequency doubler of $MgO:LiNbO_3$ with the same monolithic ring design as the OPO, which provided greater than 50% conversion efficiency to the second harmonic for cw operation[6]. A Faraday rotator isolator was necessary at full cw power to prevent feedback into the laser oscillator from the doubler. This isolator would likely be unnecessary for newer nonplanar ring designs which are more resistant to feedback[13].

The 40 mW calculated threshold for the OPO was higher than the 35 mW cw available from the resonantly doubled laser pump. Higher powers were therefore desired. We produced higher peak powers by applying 10% modulation to the diode-laser pump at the 325-kHz relaxation oscillation frequency of the Nd:YAG oscillator, generating relaxation oscillation pulses of 260-mW peak power from the Nd:YAG laser. These laser pulses were still single-axial-mode and provided the same 65-mW average power as for cw operation. The resonant doubler remained locked onto the laser frequency, producing 230-mW peak power pulses at 532 nm at 35-mW average power. These pulses were used to pump the OPO.

High pump peak powers were desired so that the OPO would be far enough above threshold that parametric oscillation could build-up from noise during the pump pulse. As the OPO begins to oscillate, the pump power is converted to signal and idler power, depleting the pump. Figure 2 shows the OPO output pulse and corresponding depleted pump pulse in comparison to the undepleted 230 mW peak power pump. The 60% pump depletion shown in figure 2 during the OPO pulse indicates the efficiency of the conversion to signal and idler power of the pump. Since the 0.5% scatter and absorption losses of the OPO cavity are small in comparison to the 1.2% OPO output coupler, most (70%) of the depleted pump light is converted to signal and idler waves. The OPO output power averaged 2.5 mW for 35 mW of average pump power. The energy conversion of pump to OPO output was 7%, attributable to the long OPO build-up time resulting in parametric oscillation during only a small fraction of the pump pulse duration. If the pump had been 230 mW of cw power, the 60% pump depletion would have produced a conversion efficiency of 40% to signal and idler power.

Figure 3 shows the observed tuning range of the DR OPO. Oscillation at the signal was observed from 1.064 μm to 1.01 μm, with an idler of 1.064 μm to 1.13 μm. Tuning of the signal and idler wavelength was possible by changing the crystal temperature or the voltage applied across the crystal. This tuning was not continuous, but took place as a series of axial mode hops. Changing the crystal temperature changed the phasematching condition as well as the cavity length. Changing the voltage across the crystal changed the cavity length through the piezo-electric effect and changed the ordinary index of refraction through the electro-optic effect, thereby changing the optical path length and birefringence of the cavity. Figure 3 shows the tuning range of the OPO for voltage scans of 0 to 800 volts at various crystal temperatures. The phasematching curve at constant voltage was generated by taking the published dispersion equations for congruent $LiNbO_3$[14] and altering the extraordinary index coefficient A_1 from 4.5820 to 4.55027 to match the observed 107 °C phasematching temperature for doubling 1064 nm radiation. Detailed calculations for the tuning of the wavelength as a function of applied voltage and temperature of the monolithic cavity are in good agreement to these observed values and are being prepared for a forthcoming publication[15].

At constant temperature and voltage the OPO operated in a single signal and idler axial mode over much of the tuning range. Operation on two widely separated modes (typically 4 nm apart) was observed for voltages that forced OPO oscillation far off the phasematching peak, allowing more than one simultaneous resonance under the phasematching gain bandwidth. Close to degeneracy, where the OPO gain bandwidth becomes very large, oscillation occurred in many axial modes. The stringent requirements on cavity stability for a doubly resonant OPO were evidenced during single axial mode operation by the mode hopping of the oscillator every few seconds due to oven temperature changes or self-heating from resonated signal and idler power.

Future work in the area of monolithic OPOs will include detailed theoretical study of their tuning properties, continuous tuning of frequency by simultaneous control of voltage and pump frequency, extension to non-degenerate OPOs, and possibly singly resonant OPOs[16]. The potential of these devices for the production of squeezed states of light [17] is also being investigated.

The monolithic ring cavity OPO design resulted in the very low cavity losses and good cavity stability that are important for efficient and stable doubly-resonant OPO operation. Pump laser stability was achieved by using a single-axial-mode diode-laser-pumped monolithic Nd:YAG nonplanar ring laser, which was frequency doubled using a resonant external cavity. The diode-laser pump was modulated at the Nd:YAG laser relaxation oscillation frequency of 325-kHz to produce 230-mW peak power pulses at 532 nm. The OPO generated pump depletions of greater than 60% when pumped at six times the calculated 40 mW cw threshold. The OPO wavelength was temperature tuned from 1.01

μm to 1.13 μm, voltage tuned as much as 11 nm in 310 Volts, and was in a single signal and idler axial mode over much of its tuning range. These experiments have demonstrated the potential for all-solid-state, highly efficient, frequency-stable, and widely tunable OPO's.

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Figure Captions:

Figure 1(a). The doubly resonant optical parametric oscillator (OPO) monolithic $MgO:LiNbO_3$ ring cavity. (b) Experimental setup for the OPO showing the diode-laser-pumped Nd:YAG laser, external cavity resonant doubler, and doubly resonant OPO.

Figure 2. Pump depletion for the OPO and corresponding OPO output at 230 mW peak pump peak power. The solid line represents the undepleted pump pulse shape.

Figure 3. Observed output wavelengths versus temperature for the monolithic $MgO:LiNbO_3$ OPO. Bars represent the electric field tuning range of the output wavelength observed at constant temperature. The solid line is the calculated fit at constant voltage.

FIG I

6002-01

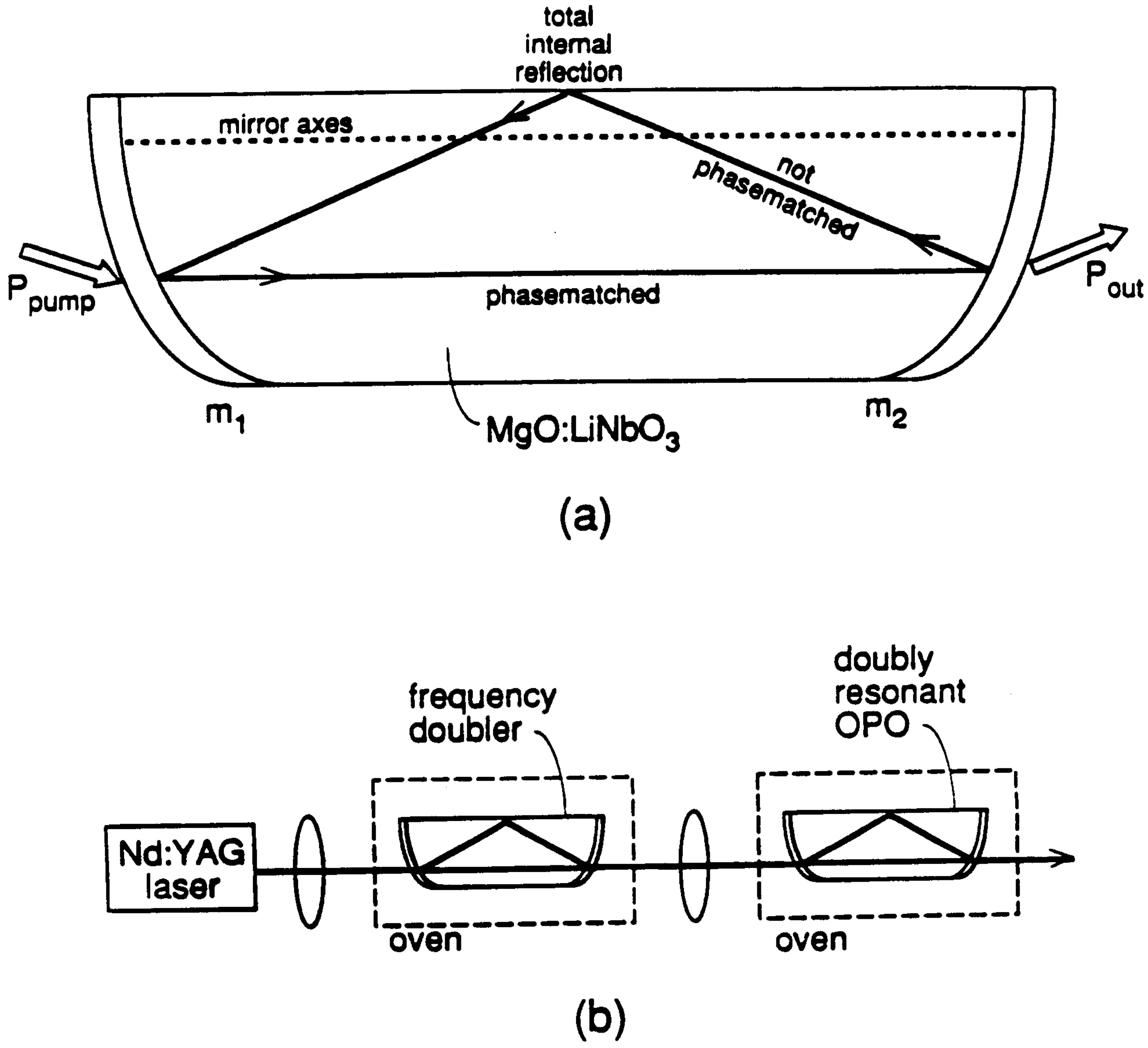
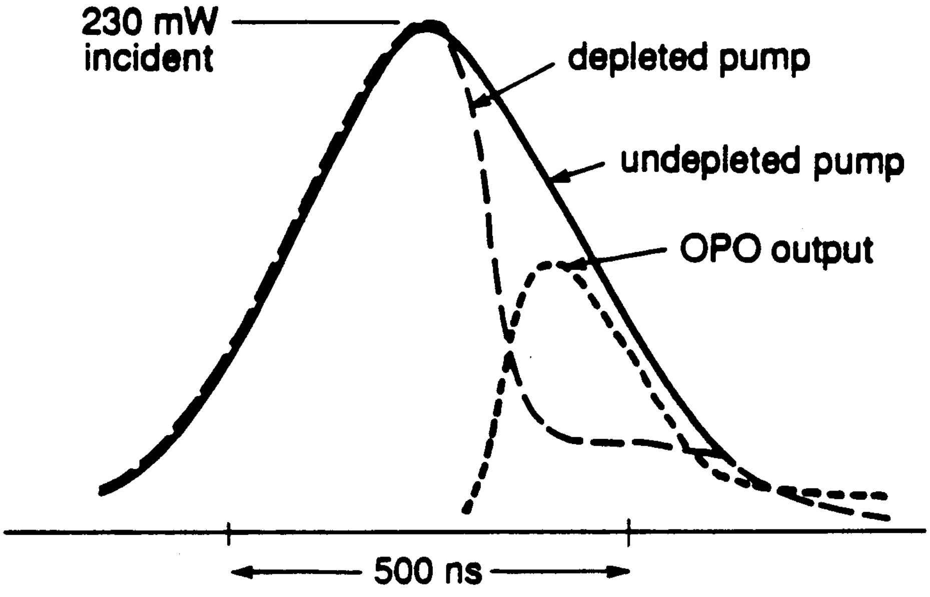
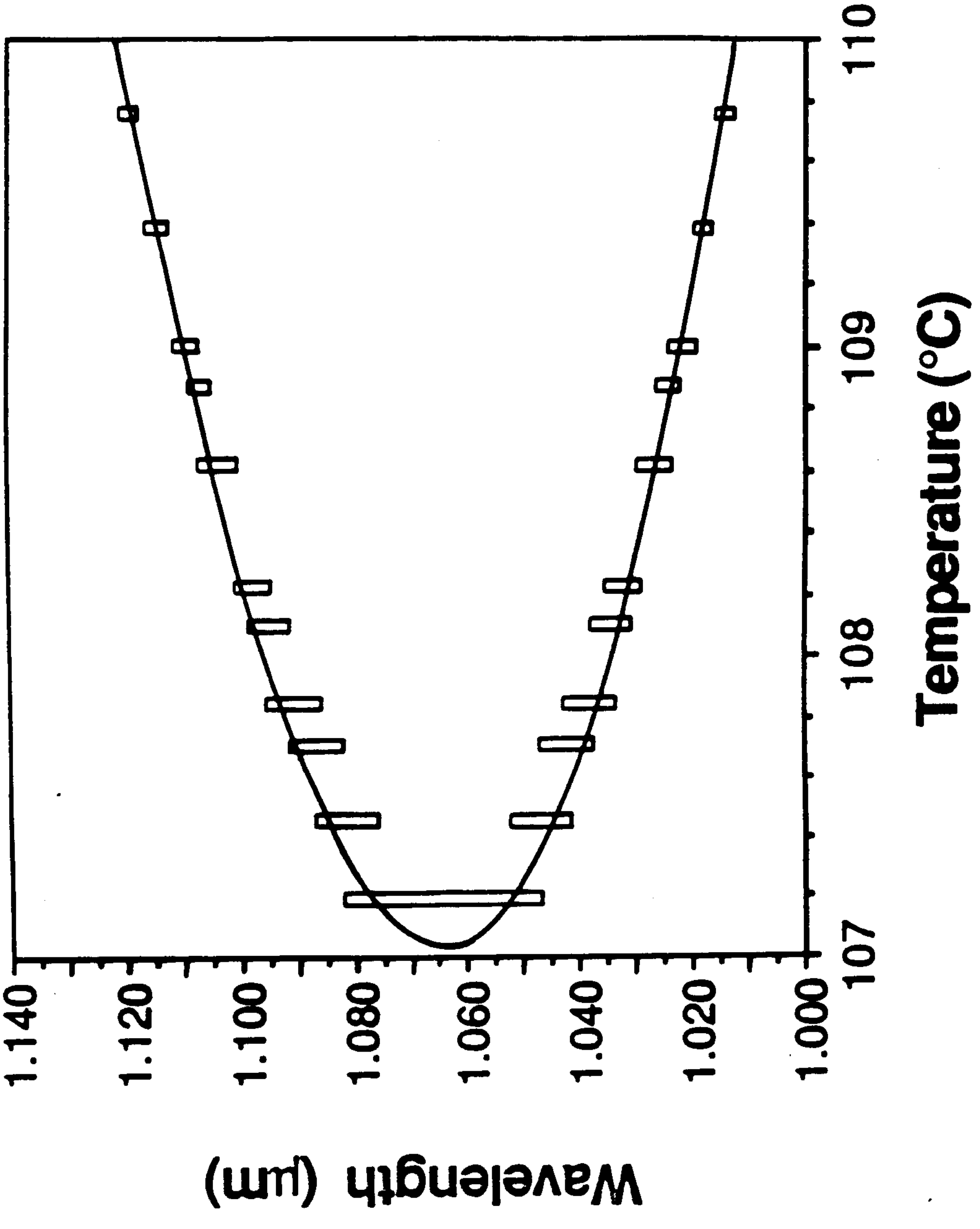

total internal reflection
mirror axes
not phasematched
P_{pump}
phasematched
P_{out}
m_1
m_2
$MgO:LiNbO_3$
(a)
frequency doubler
doubly resonant OPO
Nd:YAG laser
oven
oven
(b)

FIG 2


230 mW
incident
depleted pump
undepleted pump
OPO output
500 ns

6002-2

FIG 3



Wavelength (μm)
1.140
1.120
1.100
1.080
1.060
1.040
1.020
1.000
107
108
109
110
Temperature (°C)