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HIGH ENERGY EFFICIENT SOLID STATE LASER SOURCES

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ABSTRACT

We continue our investigations of diode-laser-pumped solid-state laser oscillators and non-linear processes using them as sources. A new generation of non-planar oscillators has been fabricated, and we anticipate pushing passive linewidths to the kilohertz regime. A number of new diode-pumped laser transitions have been demonstrated in the rod configuration. Second-harmonic conversion efficiencies as high as 15% are routinely obtained in a servo-locked external resonant doubling crystal at 15 mW cw input power levels at 1064 nm.

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I. Introduction.

The objective of this program is to perform basic research and to develop technology for solid state lasers for remote sensing and communication applications. Our recent efforts have been concentrated on the refinement of the high-stability diode-pumped nonplanar ring laser design. We have also extended our research on new materials for high efficiency second harmonic generation using the diode-pumped ring laser as a source. We have explored new wavelengths for diode laser pumped operation and have successfully operated cw Nd:YAG at 946 nm and Tm:Ho:YAG at the eyesafe wavelength 2.01 μm.

The consistent theme of the program has been the use of semiconductor diode lasers for high efficiency and high frequency stability applications. Diode pumping is efficient in the sense that pump radiation is focussed entirely in the mode volume and has its energy entirely in the absorption band of the lasing ions, leading to low thresholds and outstanding slope- and wallplug efficiencies. It is also efficient in the sense that the solid state laser (or non-linear process) has far greater coherence than the pumping laser, leading to orders of magnitude improvement in spectral brightness.

Our current progress is to a large extent limited only by the availability of ever more powerful diodes. However, the pace of diode laser mass production techniques is such that we can look forward in a mere five years to 1 W single-stripe devices that can be purchased with petty cash. As these high power devices become available, the all-solid-state technology that we have been developing under this program will replace flashlamp-pumped lasers entirely.

II. Research Progress.

In the past six months the experimental work of the group has been focussed in three main areas. These are development of next-generation non-planar ring lasers in Nd:YAG and Nd:glass for frequency-stable applications, exploration and development of diode pumped miniature rod lasers in different materials and wavelengths, and resonant harmonic doubling to the green of our existing Nd:YAG lasers. We have also done modeling and design work on diode array pumped slab Nd:glass lasers.

The current generation of non-planar ring oscillators has been characterized for frequency stability by performing a frequency mixing experiment with two identical devices [a]. The lasers were offset-locked at 17 MHz in a heterodyne experiment and frequency fluctuations of less than ±40 kHz were observed for periods of 8 minutes. A major analysis and design optimization program has been completed and Nd:YAG and Nd:glass lasers have been fabricated and will soon be available for evaluation. The initial goal is to repeat the experiment described in [a] using all-new servo electronics and a vacuum isolation system to achieve an order of magnitude improvement. The vacuum system has been assembled in a refurbished lab, and the new temperature control/offset locking system electronics have been designed and will soon be prototyped.

Theoretical work has been done to model the effects of temperature, power fluctuations, magnetic field and stress on the frequency stability of the non-planar ring lasers. We have analyzed the astigmatic transverse modes of these devices, and a computer program for calculating the generalized astigmatic paraxial mode of any optical cavity has been developed. Additionaly, we have explored the feasibility of monolithic unidirectional ring lasers in anisotropic crystal hosts such as YLF, BEL, FAP, and $MgO:LiNbO_3$.

Our recent work has led to cw diode laser pumped cw operation of Nd:YAG at 0.946 μm [b] [c], and in the Tm:Ho:YAG system at the important 2 μm wavelength [d] [e]. These systems operated at room temperature and have been modeled and studied spectroscopy to understand optimum doping levels and output couplings. The Tm:Ho:YAG system is of interest because it oscillates in an eye-safe region of the spectrum and has the potential for greater than unity pump-laser quantum efficiency.

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[a] T.J. Kane, A.C. Nilsson and R.L. Byer, "Frequency Stability and Offset Locking of a Laser-Diode-Pumped Nd:YAG Monolithic Nonplanar Ring Oscillator," Opt. Lett. **12**, 175-177 (March 1987).
[b] T.Y. Fan and Robert L. Byer, "Modeling and cw operation of a quasi three level 946-nm Nd:YAG laser," to be published, IEEE J. Quantum Electron.
[c] T.Y. Fan and Robert L. Byer, "Diode Laser Pumped 946-nm Nd:YAG Laser at 300 K," paper FL3, Conference on Lasers and Electro-Optics, Baltimore, April 27 - May 1, 1987.
[d] T.Y. Fan, G. Huber, R.L. Byer, and P. Mitzscherlich "Continuous-wave operation at 2.1 μm of a diode-pumped, Tm-sensitized $Ho:Y_3Al_5O_{12}$ laser at 300 K," submitted to Optics Letters.
[e] T.Y Fan, G. Huber, R.L. Byer and P. Mitzscherlich, "Continuous Wave Diode Laser Pumped 2-μm Ho:YAG Laser at Room Temperature," paper FL1, Conference on Lasers and Electro-Optics, Baltimore, April 27 - May 1, 1987.

We have also enjoyed a great deal of success recently in our efforts to resonantly double the 1.064 μm radiation from our YAG oscillators to the green [f] . In this experiment [see figure] single mode cw 1064 nm radiation from a non-planar ring laser is coupled to an externally resonant cavity formed by a nonlinear crystal with highly reflecting mirrors deposited on its ends. The circulating intensity in this structure is much higher than the incident power, which leads to high conversion efficiency for nonlinear processes. We have obtained 15% conversion efficiency to the green with only 15 mW input at 1.064 μm, which is a record. To achieve these results a special oven with 0.01°C temperature stability was constructed that also allowed a voltage of 1000 V to be applied to the crystal. This voltage was used to tune the resonant frequency of the doubler to that of the incident light by use of the electro-optic effect. We have also used this technique to lock the harmonic generator resonator frequency to the laser so that cw green light may be obtained for arbitrarily long periods.

This technique has several advantages over the intracavity method more commonly used for frequency conversion of low power devices [g] [h]. The most important are the stable output power and true single-frequency output obtainable with our technique. We have theoretically characterized this system and have designed a travelling-wave version of the doubler which will produce green light which propagates only in the forward direction, in contrast to the current standing wave system which produces light going in both directions. This should result in a factor of four improvement in output power in the green.

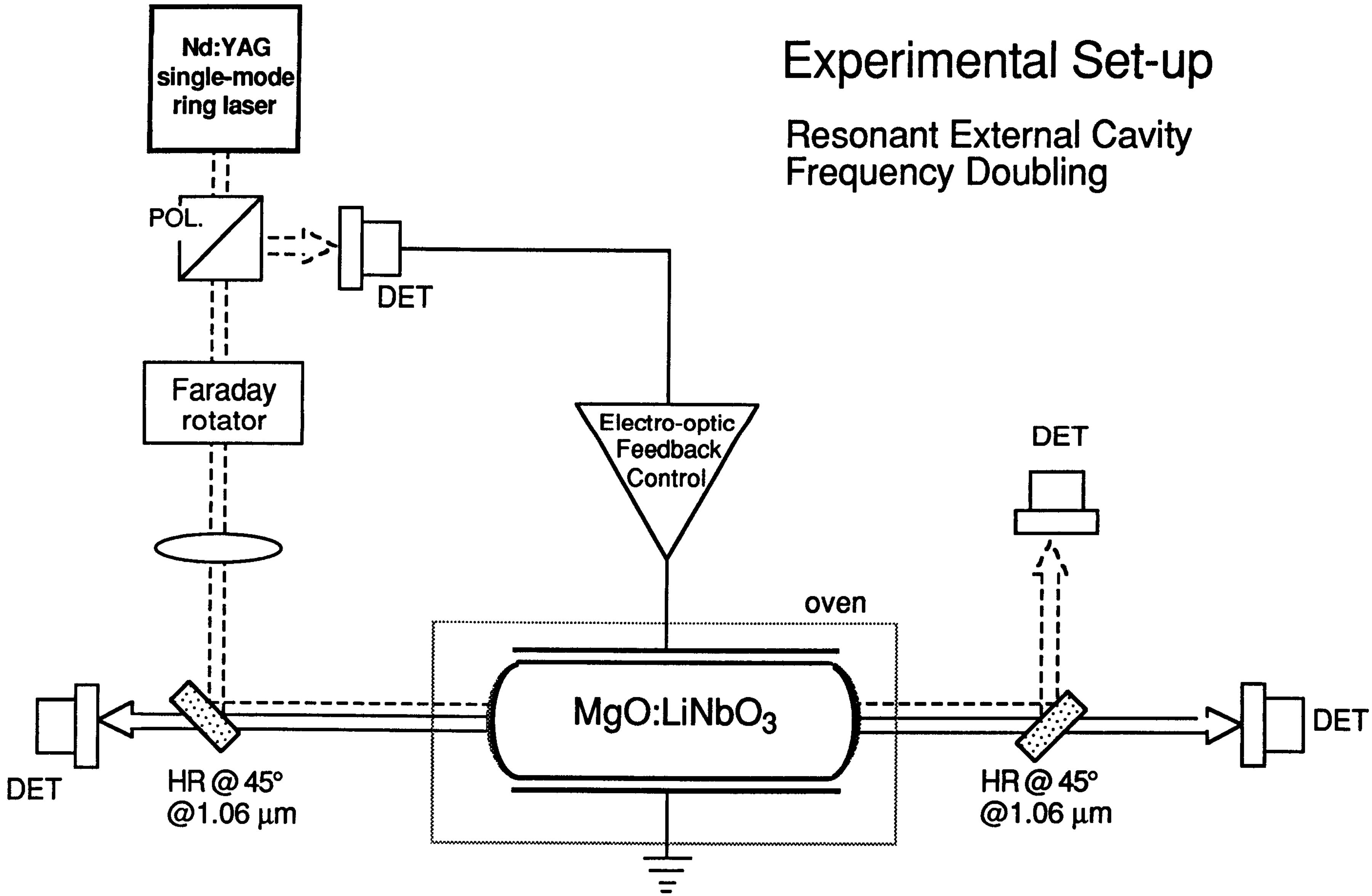
III. Planned Future Research.

The future planned experiments in this program follow naturally from the work described above. In the area of frequency-stable ring lasers we plan to extend the frequency stability and linewidth experiment, and apply the non-planar ring oscillator (NPRO) concept in practice to materials such as Ho:YAG, Nd:GGG, and Nd:MgO:$LiNbO_3$. In particular, Ho:YAG is a promising system for high efficiency lasers because of its extremely long (8 msec) fluoresence lifetime. We also will experimentally study magnetic field and photoelastic stress as methods for tuning the non-planar ring lasers. These fast tuning methods will allow us to lock the optical

[f] W.J. Kozlovsky and R.L. Byer, "External Resonant Cavity Frequency Doubling of a Diode-Pumped Nd:YAG Laser," paper FL5, Conference on Lasers and Electro-Optics, Baltimore, April 27 - May 1, 1987.
[g] Richard G. Smith, "Theory of Intracavity Optical Second-Harmonic Generation," IEEE J. Quantum Electron. **QE-6** 215 (1970).
[h] T. Baer, "Large-amplitude fluctuations due to longitudinal mode coupling in diode-pumped intracavity-doubled Nd:YAG lasers," J. Opt. Sci. Am. B. **3**, 1175 (1986).

Experimental Set-up

Resonant External Cavity Frequency Doubling



frequency of the NPRO to external cavities for frequency doubling and linear tuning, and to atomic or molecular frequency standards for absolute frequency stability.

In the high conversion efficiency second-harmonic generation experiment we will fabricate and test the traveling-wave resonator. We will also use the system to perform sub-Doppler spectroscopy of iodine with a goal of locking the laser to this secondary frequency standard.

IV. PUBLICATIONS AND PRESENTATIONS

A. Publications

1. T. J. Kane, A. C. Nilsson and R. L. Byer, "Frequency Stability and Offset Locking of a Laser-Diode-Pumped Nd:YAG Monolithic Nonplanar Ring Oscillator," Opt. Lett. **12**, pp. 175-177 (March 1987).

2. T.Y. Fan and Robert L. Byer, "Nonradiative Processes and Blue Emission in Nd:LiYF$_4$," in *Tunable Solid-State Lasers II*, A. B. Budgor, L. Esterowitz, and L. G. DeShazer, eds., (Springer-Verlag, Berlin, 1986) pp. 331-335.

3. Thomas J. Kane, W. J. Kozlovsky, Robert L. Byer, and Charles E. Byvik, "Coherent laser radar at 1.06 μm using Nd:YAG lasers," Opt. Lett. **12**, pp. 239-241 (April 1987).

submitted for publication

J. L. Nightingale, W. J. Silva, G. E. Reade, A. Rybicki, W. J. Kozlovsky and R. L. Byer, "Fifty percent conversion efficiency second harmonic generation in magnesium oxide doped lithium niobate," to be published, SPIE Proc. **681**.

T. Y. Fan and Robert L. Byer, "Modeling and cw ooperation of a quasi three level 946-nm Nd:YAG laser," to be published, IEEE J. Quantum Electron.

T. Y. Fan, G. Huber, R. L. Byer, and P. Mitzscherlich, "Continuous-wave operation at 2.1 μm of a diode-pumped, Tm-sensitized Ho:$Y_3Al_5O_{12}$ laser at 300 K," submitted to Optics Letters.

B. Invited presentations

Robert L. Byer, "The Renaissance in Solid-State Lasers," R. V. Pole Memorial Lecture and Plenary Paper MI1, Conference on Lasers and Electro-Optics, Baltimore, April 27 - May 1, 1987.

C. Contributed presentations

1. T. Y. Fan and Robert L. Byer, "Continuous-Wave, Room-Temperature Nd:YAG Laser at 946 nm," paper FK4, 1986 Optical Society of America Annual Meeting, Seattle, 19-24 October, 1986.

2. T. Y. Fan, G. Huber, R. L. Byer and P. Mitzscherlich, "Continuous Wave Diode Laser Pumped 2-μm Ho:YAG Laser at Room Temperature," paper FL1, Conference on Lasers and Electro-Optics, Baltimore, April 27 - May 1, 1987.

3. T. Y. Fan and Robert L. Byer, "Diode Laser Pumped 946-nm Nd:YAG Laser at 300 K," paper FL3, Conference on Lasers and Electro-Optics, Baltimore, April 27 - May 1, 1987.

4. W. J. Kozlovsky and R. L. Byer, "External Resonant Cavity Frequency Doubling of a Diode- Pumped Nd:YAG Laser," paper FL5, Conference on Lasers and Electro-Optics, Baltimore, April 27 - May 1, 1987.