Frequency stability and offset locking of a laser-diode-pumped Nd:YAG monolithic nonplanar ring oscillator

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The frequency stability of laser-diode-pumped, monolithic Nd:YAG solid-state unidirectional nonplanar ring oscillators was studied by heterodyne measurements. We obtained cw single-axial- and transverse-mode power of 25 mW at 1064 nm at a slope efficiency of 19%. Two independent oscillators were offset locked at 17 MHz with frequency fluctuations of less than ±40 kHz for periods of 8 min.

In a previous Letter we reported the operation of a monolithic, nonplanar ring resonator that was end pumped by an argon-ion laser.[1] The device is a monolithic block of Nd:YAG on which four reflecting facets (one spherical face with dielectric coatings; three flat, total internal reflection faces) are polished to form a nonplanar ring resonator. Because of its monolithic ring construction and built-in optical diode, the oscillator eliminates the effects of spatial hole burning, is insensitive to optical feedback, and operates in a single axial mode. The oscillator's frequency stability makes it an attractive laser source for laser radar,[2] coherent communications, spectroscopy and nonlinear optics,[3] and inertial rotation sensing.[4] We called the device a MISER (Monolithic, Isolated, Single-mode, End-pumped Ring), but a more descriptive acronym is SUNPRO (Solid-state, Unidirectional, Non-Planar Ring Oscillator).

The new SUNPRO is constructed from a single Nd:YAG crystal with dimensions of 12 mm × 9 mm × 3 mm. The small size and resultant reduced mode volume lead to a reduced threshold that makes pumping by a multistripe laser diode possible. The laser-diode-pumped SUNPRO is a compact, efficient source of frequency-stable 1064-nm laser radiation. In this Letter we describe experiments carried out with the laser-diode-pumped SUNPRO's: an experiment in which a laser-diode-pumped monolithic rod[5] was offset locked to a laser-diode-pumped SUNPRO and heterodyne measurements involving two independent, laser-diode-pumped SUNPRO's.

Figure 1(a) shows a schematic of the laser-diode-pumped SUNPRO. The SUNPRO was pumped by a 10-element, phased array of GaAlAs laser diodes, Spectra Diodes Laboratories (SDL) Model 2420-C,[6] that emitted 200 mW of 810-nm radiation in a two-lobed far-field pattern. The temperature of the laser diode was controlled with a thermoelectric cooler to tune the emission wavelength to the strong Nd:YAG absorption band at 809 nm. The output of the SDL 2420-C was collimated and focused onto the spherical face of the Nd:YAG block as shown in Fig. 1(a).

The SUNPRO operates in a TEM_{00} spatial mode with dimensions fixed by the 50-mm radius of curvature of the dielectric-coated surface and the 28.54-mm path length of the ring. Output is taken through the curved surface, which is coated for normal-incidence reflectivity of 99.1% at 1064 nm. The measured threshold was 16.9 mW, and the slope efficiency was 19.6%. The SUNPRO, which incorporates an optical diode[7,8] into its resonator by virtue of its nonplanar light path and the applied magnetic field, oscillates unidirectionally in a single axial mode.

Figure 1(b) shows a schematic of the experimental setup used for the offset-locking experiments. A laser-diode-pumped monolithic rod laser was offset locked to a laser-diode-pumped SUNPRO. The output beams of the two laser-diode-pumped Nd:YAG lasers were focused into two single-mode optical fi-

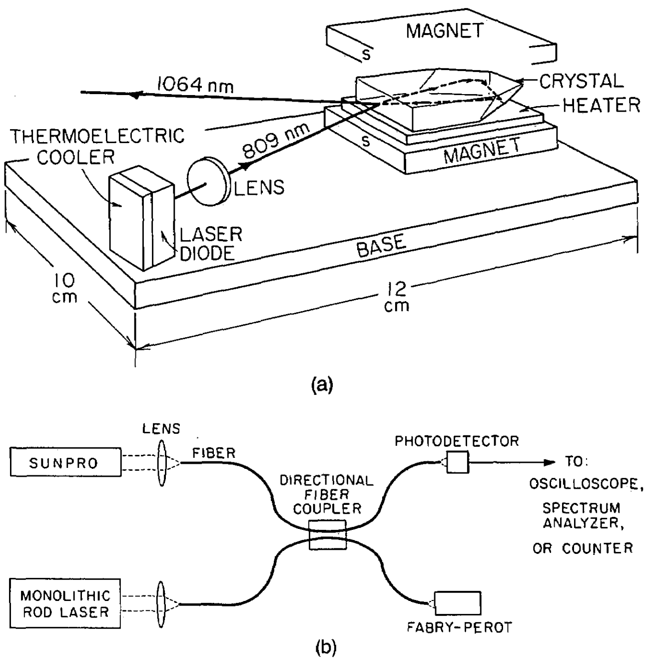

Fig. 1. (a) Schematic of laser-diode-pumped SUNPRO. (b) Experimental setup for heterodyne measurements and offset locking.

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bers, combined by a directional fiber coupler,[9] and mixed on an InGaAs photodetector. The beat signal from the photodetector was then sent to a frequency counter, oscilloscope, or spectrum analyzer.

The frequency difference between the two lasers was varied by changing the temperature of the monolithic rod while holding the temperature of the SUNPRO constant. A monolithic resonator of Nd:YAG changes its resonant frequency by −3.1 GHz/°C at room temperature. We used circuitry to count the frequency of the beat signal, compare it with a desired frequency difference, and generate an error signal that was then fed back to the temperature controller of the monolithic rod laser.[10] By this technique we were able to offset lock the SUNPRO and the monolithic rod laser.

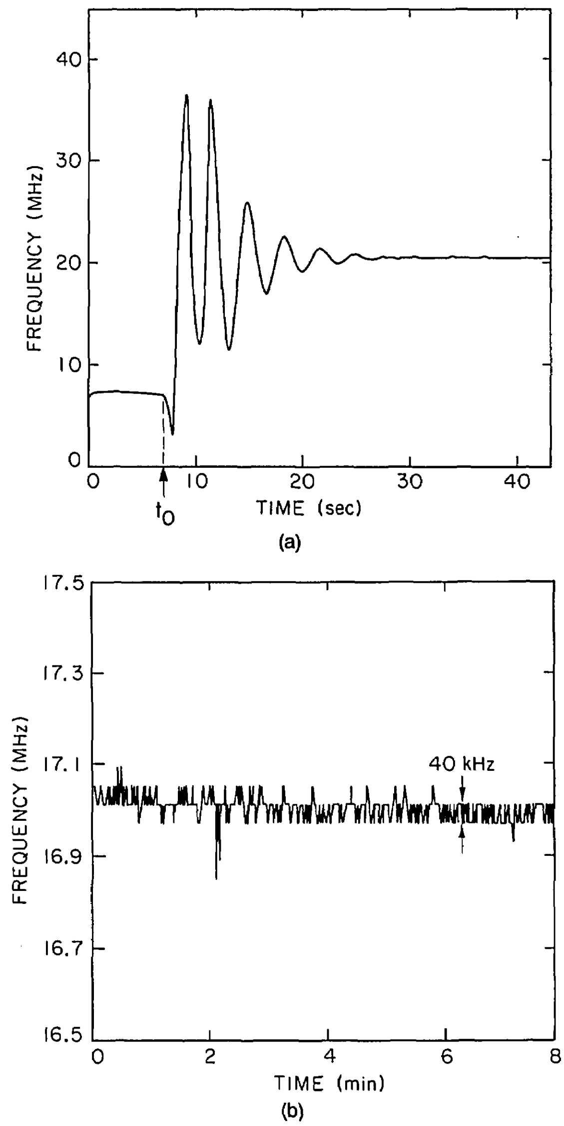


Fig. 2. (a) Offset-frequency-locking transient of laser-diode-pumped monolithic rod and SUNPRO. Locking circuit turned on at t_0. (b) Stable heterodyne signal between offset-locked oscillators as measured by frequency-counting circuit. Frequency resolution of the counting circuit is ±40 kHz.

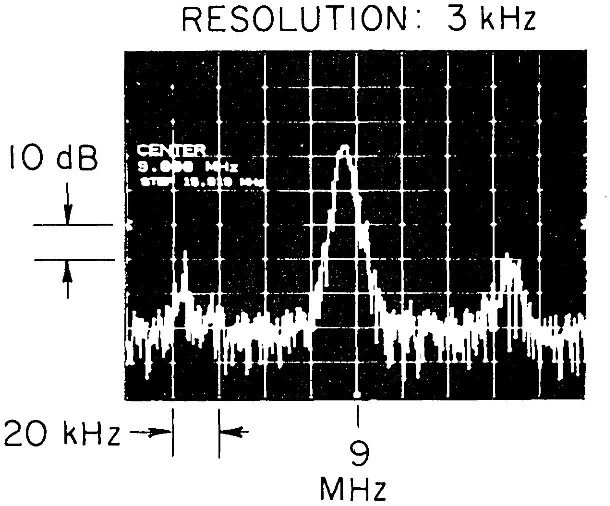
Figure 2(a) shows the capture transient and the subsequent locked performance of the SUNPRO and miniature monolithic rod laser at an offset frequency of 21 MHz. Figure 2(b) shows the frequency difference between the two lasers offset locked at 17 MHz and controlled to within ±40 kHz for 8 min. The data shown in Figure 2(b) were obtained by counting the zero crossings of the beat signal during a fixed time interval of 25 μsec, yielding a mean frequency data point that was relayed to computer storage. The counting circuit was reset and the process repeated. The total number of data points and the time interval between data points were variable. The fixed counting interval of 25 μsec and the counting accuracy of ±1 count limited the frequency resolution of any data point to ±40 kHz.

The SUNPRO showed better resistance than the monolithic rod laser to instabilities caused by reflections from the faces of the optical fibers. To attain a stable heterodyne signal, the output of the monolithic rod laser was attenuated by 30 dB before it was focused into the fiber, whereas the SUNPRO required no attenuation. The SUNPRO has four nondegenerate eigenmodes (two eigenpolarizations for each of two directions of propagation around the ring), and unidirectional oscillation occurs for the eigenmode with the largest eigenvalue modulus.[11] Output radiation retroreflected back into the SUNPRO travels opposite the oscillating mode and is offset in frequency from the eigenfrequencies of the possible retropropagating modes. These two effects reduce the influence of optical feedback on the SUNPRO relative to the influence on a standing-wave oscillator.

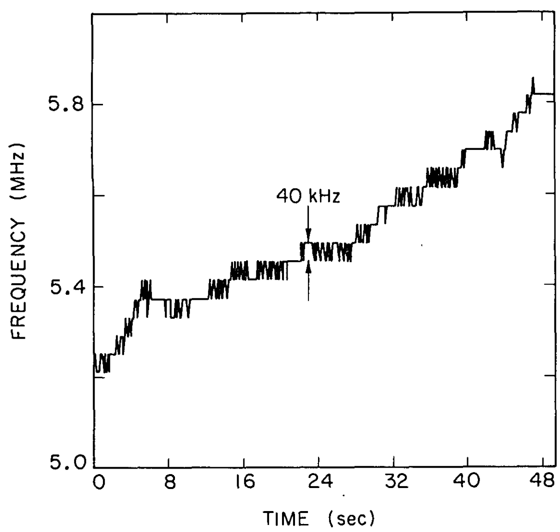
The offset-locking experiment demonstrated the extreme frequency stability of laser-diode-pumped monolithic laser sources but did not differentiate between the frequency fluctuation contributions of the two different oscillators. To address this question, we constructed a second SUNPRO and performed a heterodyne experiment using the two SUNPRO's. The setup shown in Figure 1(b) was used with the monolithic rod laser replaced by the second SUNPRO. Because of the larger thermal time constant of the SUNPRO, we did not offset lock the devices but instead explored the beat frequency between two free-running oscillators.

A rf spectrum-analyzer trace of the heterodyne signal from the two SUNPRO's is shown in Fig. 3(a). This scan shows a central peak near 9 MHz and relaxation oscillation sidebands at ±70 kHz from the central peak. The relaxation oscillation sidebands are 35 dB down from the amplitude of the central beat frequency. The key feature of the scan is the spectrum-analyzer-limited 3-kHz full width at the −3-dB points of the beat note. We conclude that each of the free-running SUNPRO's has a linewidth of less than 3 kHz over the 100-msec spectrum analyzer sweep time. Frequency jitter and drift in the beat signal precluded meaningful measurements for the sweep times required to give resolution better than 3 kHz.

Using the frequency-counting circuit to analyze the long-term behavior of the heterodyne signal gave the data shown in Fig. 3(b). Since the SUNPRO's were



(a)



(b)

Fig. 3. (a) Spectrum-analyzer trace of heterodyne signal between two free-running SUNPRO's, showing a central peak at the 9-MHz offset frequency and relaxation oscillation sidebands. Full width at the −3-dB points of the central peak is 3 kHz, limited by the resolution bandwidth of the spectrum analyzer. (b) Heterodyne signal between free-running SUNPRO's, measured by the frequency-counting circuit. Note the uncompensated drift rate of 12 kHz/sec.

not locked, there was a large uncompensated thermal drift of 12 kHz/sec. Apart from the drift, however, the individual data points show behavior similar to that observed with the offset-locked oscillators. Careful thermal design will permit offset locking of SUNPRO's in the future.

The multistripe laser-diode arrays used as pumps in these experiments are not optimal for producing frequency-stable operation in SUNPRO's. Fluctuations in the output power and the spatial mode of the phased array cause frequency fluctuations in the output of a SUNPRO. For example, an increase of 100 μW of heat input for 100 μsec produces a temperature increase of 4 μK in the 10^{-3}-cm^3 mode volume of the SUNPRO. Multiplying by Nd:YAG's thermal tuning coefficient of −3.1 GHz/K gives a frequency shift of 12.4 kHz. This simple calculation shows the extreme sensitivity of Nd:YAG to thermally induced frequency shifts and thus underscores the importance of stable pumping. In future experiments we plan to reduce the Nd:YAG SUNPRO dimensions, thereby reducing the threshold pumping power to permit operation with single-stripe, single-mode laser diodes.

In summary, we have demonstrated that the diode-pumped SUNPRO offers high single-mode output power in a compact device with excellent frequency stability. We have amplified the output of a SUNPRO by 60 dB, making available high-power, narrow-linewidth radiation.[12] This narrow-linewidth, high-power source has already performed successfully in a coherent laser radar experiment[13] and will prove similarly useful as a pump source for nonlinear-optics experiments. That the SUNPRO can be laser-diode pumped also makes it attractive for spaceborne experiments in which compactness, low power consumption, and reliability are essential. We are currently investigating the fundamental linewidth limitations of the SUNPRO.

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