input and output signals demonstrating division by 3 and multiplication by 2. Multiplication by rational fractions (a combination of multiplication and division) has also been demonstrated by overlap of different input signal and self-pulsing frequency harmonics.[4]

In addition to the simple mathematical division and multiplication functions, other applications include optical multiplexors/demultiplexors, optical frequency synthesizers, and optical clock distribution. Synchronized division has direct application to time division multiplexed optical communications systems where it is necessary to extract a frame clock at fractions of the data rate.[2] An optical frequency synthesizer could be based on frequency multiplication of the output of a modelocked long external cavity laser.

Using our method, a computerized system could control the self-pulsing laser bias and select a precise output frequency. Optical clock distribution has already been demonstrated using diode lasers,[5] but where different parts of a system require different clock frequencies, these can now all be generated using a single distributed master clock with our technique.[4] To our knowledge these results represent the first such mathematical functions to be performed optically on data signals by semiconductor lasers, and we expect a number of important applications to follow, along with more investigations on the mechanisms responsible within the laser devices.

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Frequency-Stabilized Diode-Laser-Pumped Solid State Lasers: Optical Clocks of the Future

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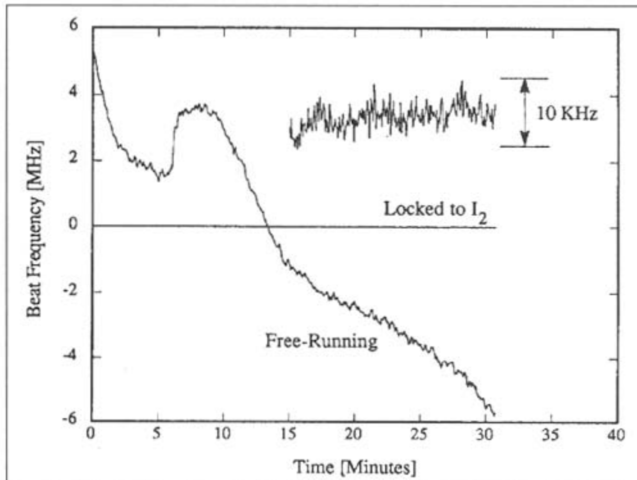
Monolithic diode-laser pumped solid state lasers[1] are compact, reliable, and inherently-stable optical oscillators, providing nearly diffraction-limited beams with linewidths narrower than 10 kHz. While this linewidth is much narrower than that of most other lasers, the quantum-limited value is less than 1 Hz for an output power of 1 mW. However, the dependence of the cavity length and refractive index on the environment (temperature, acoustic vibrations, etc.), causes the lasing frequency to drift at a rate of several

MHz per minute. External frequency stabilization can therefore improve the oscillator performance.

Relative stabilization of two diode-pumped Nd:YAG lasers to the same Fabry-Perot cavity at the sub-Hertz level has been recently reported.[2] The stable reference Fabry-Perot cavity can suppress the high frequency fluctuations of the laser, thus enabling very sensitive interferometric measurements, *e.g.*, gravitational wave detection. However, locking to an external cavity does not guarantee an improved long term absolute stability, since the resonant frequency of the cavity itself may drift. For some applications, stabilization to an absolute standard is required.

We chose the absorption lines of molecular iodine[3] at the second harmonic of Nd:YAG, near 532 nm, as the absolute reference. The laser frequency is externally resonantly-doubled with high efficiency using a compact, 8 mm long $MgO:LiNbO_3$ monolithic nonlinear crystal, with dielectrically coated surfaces. The 532 nm output of the doubler is the source for FM Doppler-free saturation spectroscopy[4] of $^{127}I_2$. Once the laser frequency coincides with a Doppler-free transition of iodine, the dispersion signal of this line is fed back through a servo amplifier to the piezo-electric frequency actuator of the laser, thus locking the laser frequency to the hyperfine transition[5].

Two independent systems have been built, with each laser locked to its own 10 cm long iodine cell. The heterodyne beatnote between the lasers is measured at 1064 nm



Typical variation of beatnote frequency as a function of time. Each frequency measurement takes 4 seconds. Inset shows an expanded view of the beat frequency between the Iodine-stabilized lasers over 15 minutes.[5]

using a photodetector followed by a frequency counter. The figure shows the typical variation of the beatnote frequency when free-running and when under lock. The best stability—two sample deviation of 650 Hz—is maintained for measurement time from 24-80 seconds. The laser oscillates at a frequency of 281.63 THz, hence the fractional stability is $2.3 * 10^{-12}$. A clock with this stability would be wrong by less than a second in 10,000 years.

A favorable feature for some metrological applications, *e.g.*, precision length measurements, is that two stabilized frequencies (the fundamental and second harmonic) are available. Furthermore, the available power levels of diode-pumped solid state lasers are sufficient to efficiently generate, through nonlinear frequency conversions, a series of stabilized frequencies from the UV to the near IR. Frequency synthesis by pumping a doubly-resonant parametric oscillator is possible, since the sum of the signal and idler frequencies must equal the stabilized pump frequency. As diode-pumped solid state laser technology becomes space qualified, several interesting measurements with frequency stabilized lasers, *e.g.*, high resolution gravity field mapping and microarcsecond astronomy, can be realized. As once predicted,[1] these monolithic oscillators may one day play a similar role in optical devices to that of the quartz crystal oscillator in electronics.

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