Simple scheme for tunable frequency offset locking of two lasers

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We present a scheme for stabilizing the difference frequency of two independent lasers. The scheme is based on simple electronics and makes use of the frequency-dependent phase shift experienced by a signal when it propagates through a delay line of coaxial cable. The stabilized difference frequency can be tuned over a wide range. Difference frequencies in the radio-frequency domain (100 MHz–10 GHz) can be controlled with long-term stability of better than 1 MHz. © *1999 American Institute of Physics.* [S0034-6748(99)00201-4]

Frequency-offset locking of two lasers has many applications in atomic and molecular physics, e.g., for laser spectroscopy[1] or for laser cooling and trapping.[2] Different techniques have been developed for offset frequencies ranging from a few MHz to several GHz based on, e.g., phase-locked loops[3] or locking to different longitudinal modes of a tunable Fabry–Perot resonator.[4] In this note, we present a simple and robust frequency-offset stabilization with a particularly large capture range and wide tunability. The scheme is based on the frequency-dependent phase shift experienced by the beat note of the two laser frequencies when it propagates through a coaxial cable. Since the time delay introduced by the cable ($\tau \approx 5$ ns for a cable of 1 m length) is independent of the frequency, the phase shift is proportional to the beat frequency, thus providing an appropriate error signal for a servo loop.

In our application, the difference frequency of two extended-cavity diode lasers[5,6] at 670 nm is stabilized close to the hyperfine splitting of the ^{7}Li ground state (803 MHz). The lasers serve as light sources for magneto-optical trapping of lithium.[7] For optimum performance of the trap, the offset frequency has to be tunable over some tens of MHz.

The frequency difference stabilization scheme is depicted in Fig. 1(a). The frequency difference is measured by superimposing a small portion of both laser beams (≈ 150 μW). The light is focused onto an avalanche photodiode (APD) (Hamamatsu 6045) which records the beat note. The photodiode output signal at frequency $\Delta\nu = \nu_1 - \nu_2 \simeq 803$ MHz (level ≈ -30 dBm) is first amplified by 30 dB (Avantek INA-012184) and subsequently mixed (MiniCircuits SRA-2010MH) with the output of a voltage-controlled oscillator (VCO) at $\nu_{VCO} \simeq 850$ MHz (Avantek VTO 9086). The signal at $|\Delta\nu - \nu_{VCO}| \simeq 50$ MHz is split into two equal parts (MiniCircuits PSC-2-1) which are recombined on a phase detector (MiniCircuits SBL 1-1), after one part has been delayed by 1 m of coax cable. The output of the mixer at twice the frequency is blocked by a low pass filter with a cutoff frequency of 10 MHz. The resulting output voltage U of the phase detector varies as $\cos \Phi$ where the phase shift Φ introduced by the cable is given by $\Phi = 2\pi(\Delta\nu - \nu_{VCO})\tau$.

The output signal U of the phase detector as a function of the beat frequency is shown in Fig. 1(b). The beat frequency is scanned over several hundred MHz by varying the frequency of one of the lasers. The envelope of the cosine curve reflects the limited bandwidth of the phase detector. The zero crossings of the signal provide the error signal for locking the difference frequency using a servo loop. A slow servo circuit with integral gain controls a piezo tube, adjusting the length of the external laser cavity (servo bandwidth of ≈ 1 kHz). A second, fast servo loop with proportional gain directly controls the laser diode injection current for suppression of noise in the acoustic frequency domain (servo bandwidth ≈ 1 MHz).

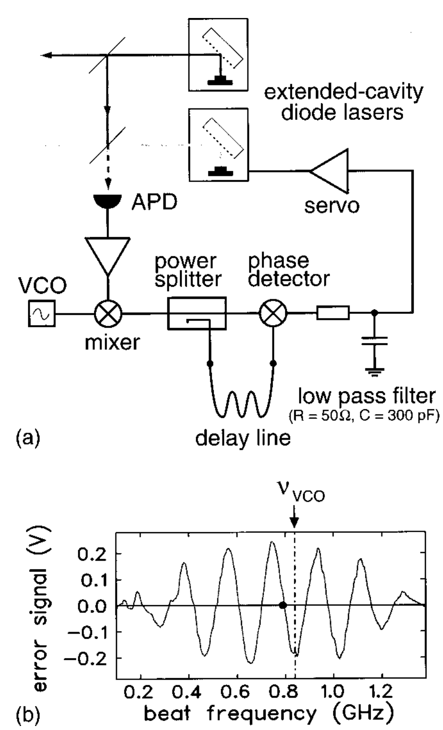

FIG. 1. (a) Scheme of the tunable frequency offset lock. (b) Error signal as a function of beat frequency between the two lasers. The dot indicates one of the locking points of the servo loop, and ν_{VCO} denotes the frequency of the rf oscillator used for frequency shifting the beat signal.

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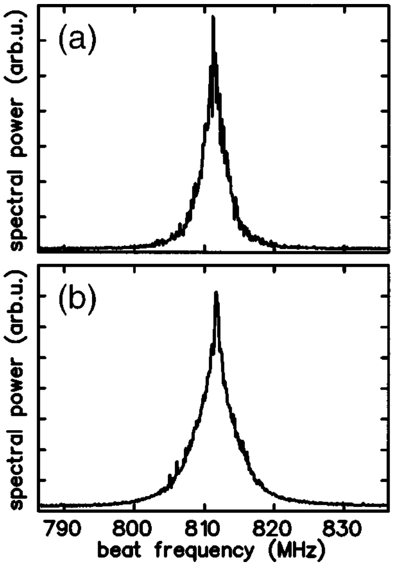

FIG. 2. Power spectra of the beat note (linear scale, resolution bandwidth 100 kHz). (a) Single-shot spectrum with 1 s sweep time. (b) Maximum-hold spectrum measured for 1 h with 5 s sweep time.

The servo circuit allows stable locking to several values of the beat frequency which are spaced by $1/\tau \approx 200$ MHz, corresponding to the zero crossings of the error signal. The locking point can be tuned by simply varying the reference frequency ν_{VCO}. The error signal provides a broad capture range given by $\pm 1/2\tau \approx \pm 100$ MHz. This range is much larger than typical short-term frequency excursions of lasers which prevents the servo loop from hopping between different locking points. The frequency resolution is determined by the slope of the error signal at the locking point. A longer delay line enhances the resolution, but reduces the capture range. Depending on the application, the cable length can therefore be adjusted to either achieve a high frequency resolution or a large capture range.

Day-to-day reproducibility of the difference frequency is better than 2 MHz. Short-term stability of the stabilization scheme is shown in Fig. 2(a) where the beat spectrum is taken as a single shot with a spectrum analyzer at a sweep time of 1s. The full linewidth at half maximum (FWHM) of 4 MHz reflects residual high-frequency fluctuations of the individual diode lasers beyond the bandwidth of the servo loop. To evaluate the long-term stability, the beat spectrum is measured for 1 h in the maximum-hold mode of the spectrum analyzer (sweep time 5 ms). As can be seen from Fig. 2(b), drifts of the center frequency are much lower than 1 MHz.

By choosing a different rf oscillator frequency ν_{VCO} the beat frequency may be stabilized to other frequencies. We employ the same frequency-offset locking technique in an experiment on laser cooling of fast $^9Be^+$ ions in a storage ring.[8] In this application, the difference frequency of two argon-ion lasers at 300 nm is stabilized close to the Be^+ ground state hyperfine splitting of 1.3 GHz. Stable locking over many hours is achieved even under the stringent conditions of a storage ring environment, an essential prerequisite for precision laser experiments on such complex machines.

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