Beat-note jitter suppression in a dual-frequency laser using optical feedback

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An efficient locking technique based on optical feedback is demonstrated to suppress jitter on the rf beat note between the two modes of a dual-frequency Yb:Er glass laser. The method consists of a self-injection process in which one selected mode serves as a master oscillator to lock and stabilize the second mode via a frequency-shifted optical feedback. The beat note adjusted near 170 MHz was stabilized with an accuracy of 250 mHz using an optical feedback loop with a double pass through an acousto-optic modulator. The beating note can be tuned over 300 kHz by controlling the reference oscillator. The extensions and limitations of the technique are discussed. © 2007 Optical Society of America

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The beat note between the two orthogonally polarized eigenstates[1] simultaneously emitted by dual-frequency lasers has been demonstrated as an efficient tool for THz radiation generation by photomixing in low-temperature-grown GaAs crystal,[2] lidar–radar detection,[3] self-mixing,[4] or heterodyne interferometry. In a dual-frequency laser, the round-trip gain and losses must be kept perfectly isotropic with respect to polarization to obtain similar thresholds on both modes, allowing them to oscillate simultaneously. Moreover, it ensures similar emission efficiency on the two orthogonal modes, leading to a maximum of contrast on the beating signal. The frequency difference between the two modes can be adjusted via optical birefringent elements into the cavity [a pair of quarter-wave (QW) plates[1,5] or electro-optic modulator[6,7]]. As most of the applications require an extremely stable beating signal, dual-frequency lasers must be actively stabilized to suppress the remaining jitter between the two optical frequencies, which is attributed to the external perturbations (thermal drift, index variation in the amplifying medium). The major drawback with active stabilization is that it requires multi-electronic phase-locked loops acting simultaneously on the different parameters of the laser oscillator[8] (such as temperature, pump power, or cavity length).

It is well known that spatial or spectral/temporal laser properties can be efficiently controlled via an optical feedback. Spectral narrowing or external mode locking have been already demonstrated using an external cavity. In this Letter, we investigate an original approach to stabilize the beat note of a dual-frequency laser via an optical self-injection process. The basic principle consists of selecting one of the two linear modes with a polarization filter, then frequency shifting the optical wave using an external optical modulator, and finally using it to reinject on the other mode. This self-injection stabilization process is demonstrated on the 1.53 μm dual-frequency phosphate glass laser shown schematically in Fig. 1. The gain medium is a 710 μm thick thin plate of QX-glass codoped with 20% Yb^{3+} and 0.8% Er^{3+} purchased from Kigre. It is longitudinally pumped using a fiber-pigtailed InGaAs laser diode (100 μm core diameter, $P_{\max}=1.5$ W at $\lambda_p=980$ nm). The hemispherical cavity is 10 cm long with one mirror ($R=99.98\%$ at 1535 nm and $T>90\%$ at 980 nm) directly coated on one side of the amplifying disc, whereas the output coupler is an external mirror with 100 mm radius of curvature and a transmission coefficient of $T=2\%$ at 1535 nm. The output mirror is mounted on a translation stage for fine adjustment of the cavity length. A 200 μm thick silica etalon coated on both sides ($R=30\%$ at 1535 nm) forces the two polarization eigenstates to oscillate on the same longitudinal order mode. Two QW plates are inserted to adjust the beat note between the two orthogonal modes. All the optical components (QX-glass plate, etalon, QW plates, and the output coupler) are mounted on robust optical mounts fixed on a common rail to ensure a good mechanical stability. Potentially, such a dual-frequency laser has a beat note continuously tunable between 0 and $c/4L=750$ MHz. In the present case, as already reported elsewhere,[4] the beating frequency $\Delta\nu_{\mathrm{BF}}$ was tuned from 0 to 200 MHz via an angular adjustment ρ of the QW plates varying between 0° and 13°.

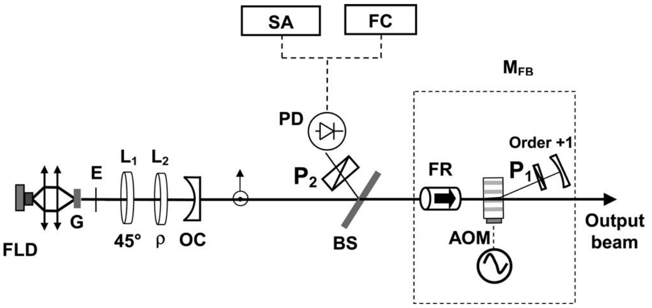


Fig. 1. Experimental setup for frequency-shifted self-injection technique. G, Yb:Er glass plate; L_1 and L_2, quarter-wave plates; P_1 and P_2, linear polarizers; E, intracavity etalon; OC, output coupler; BS, beam splitter, FR, Faraday rotator; AOM, acousto-optic modulator; PD, photodiode; SA, spectrum analyzer; FC, frequency counters. FLD, fiber pigtailed laser diode; M_{FB}, optical feedback module; ρ, angular adjustment.

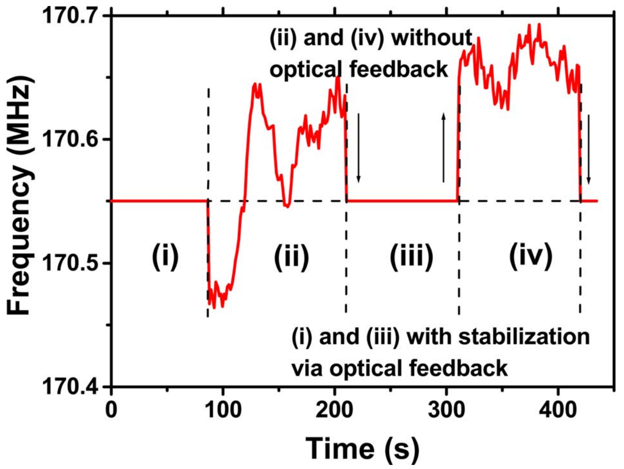


Fig. 2. (Color online) Temporal fluctuations of the beat-note frequency in the free regime [sequences (ii) and (iv)] and stabilized with the optical feedback [sequences (i) and (iii)].

To check the stability of $\Delta\nu_{\mathrm{BF}}$, we have recorded the beat note versus time. Slowly varying fluctuations of the frequency difference between the two orthogonal modes can be observed as shown in Fig. 2 for a frequency difference adjusted around 170 MHz.

To stabilize the frequency gap $\Delta\nu_{\mathrm{BF}}$, an optical feedback loop is added (dashed box in Fig. 1). The external cavity is simply added on the output beam and contains a polarization control module [with a Faraday rotator (FR) and a linear polarizer (P_1)] and an acousto-optic modulator (AOM). The polarization module selects one mode and projects its electric vector on the other mode via the nonreciprocal FR. The AOM is a Bragg cell with an acoustic resonance around 80 MHz. A double pass through the Bragg cell ensures a total frequency shift on the diffracted beam around 160 MHz. To precisely control the frequency shift, the Bragg cell is power supplied using an amplified high-frequency signal synthesizer. The zero-order beam of the Bragg cell is used as the output beam.

The two orthogonally polarized modes are partially reflected on a beam splitter ($R=4\%$) and optically mixed using a linear polarizer (P_2). The beat note is detected using a fast InGaAs photodiode and characterized either on a rf spectrum analyzer or a frequency counter.

To lock the frequency beat note via the optical feedback loop, the rf synthesizer signal is tuned relatively close to the natural beating frequency of the dual-frequency laser. A tolerance of a few hundreds kilohertz is allowed as discussed below. When the frequency-shifted optical beam is correctly reinjected into the oscillating mode of the laser cavity, a stabilization effect on the frequency beat note can be observed. In Fig. 2, we report a recording of the measured beating frequency versus time in a sequence with successive periods of locking [temporal periods (i) and (iii)] and unlocking [temporal periods (ii) and (iv)]. Without stabilization, the fluctuations observed on the beat note are relatively random with fast slope variation as observed during the second period (ii) or slow variations as observed on the fourth period (iv). Typical fluctuation amplitudes of the frequency gap between the two modes $\Delta\nu_{\mathrm{BF}}$ are about a few hundreds of kilohertz up to a few megahertz close to results already reported elsewhere with a similar laser.[8] Such fluctuations do not depend on the adjusted frequency difference and are similar at a lower frequency. It depends only on the mechanical instability of the oscillating cavity and on the thermal drift in the amplifying medium or on the cavity length. Compared with the deviation of the absolute optical frequencies of the two modes (typically a few gigahertz per minute as it could be observed using a Fabry–Perot confocal interferometer), these natural fluctuations of the frequency difference appear limited, as they come from the second-order effects on the cavity length or the index of refraction in the amplifying medium. As soon as the locking is engaged, the beat note appears extremely stable and perfectly equal to twice the reference frequency provided by the external RF generator. The reference frequency has been simultaneously measured to the beat note, and its value multiplied by 2 is also presented as a reference line around 170.55 MHz in Fig. 2 (dashed line). The efficiency of the locking effect can be visualized by the vertical arrows between unlocked and locked periods, illustrating that the laser is directly relocked without any readjustment of the reference signal frequency to overlap the natural beating frequency.

To adjust the frequency difference between the two modes, a series of fast ramps around 85 MHz was then applied to the synthesizer frequency. As one can seen in Fig. 3, the beat note recorded versus time looks like stair steps and exactly follows the command. It allows a tuning range of about ±150 kHz symmetrically on both sides of the natural frequency beat note of the laser. By controlling the power of the RF signal, and thus the diffraction efficiency of the Bragg cell, it has been possible to confirm that the tuning range strongly depends on the amount of light reinjected into the cavity. For the sake of simplicity and robustness, the diffraction efficiency of the AOM was pushed up to 50% per pass, which could explain

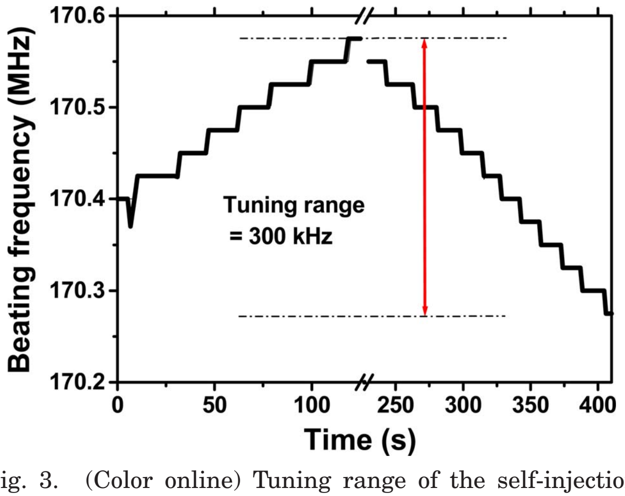
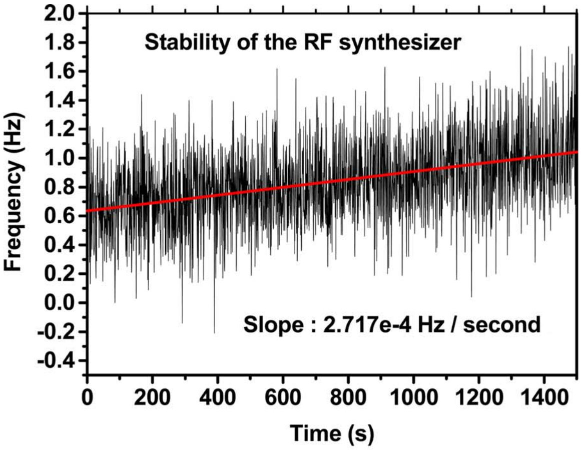


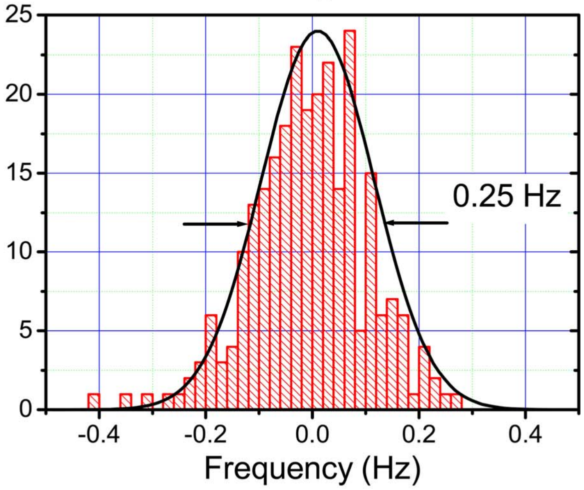
Fig. 3. (Color online) Tuning range of the self-injection process and control of the beat note via the external RF modulator.

the relatively high-frequency range adjustment allowed.

The stability of the locking technique has been tested by recording the beat note versus the synthesizer frequency. As the RF oscillator was not perfectly stabilized, a drift has been observed on the synthesizer frequency. It corresponds to a slow deviation of about 0.27 mHz/s, as illustrated in Fig. 4(a). To estimate the stability and the precision of the optical feedback frequency locking, successive frequency measurements of the beat note and the synthesizer frequency were recorded during 10 min with a sampling rate of 1 Hz. A linear fit was then applied to the measured synthesizer frequency [straight line in Fig 4(a)]. The difference between this reference line and the optical beat note is reported in the histogram-plotted curve of Fig. 4(b). A fitted Gaussian distribution curve allows for estimating the stability of the frequency locking to be less than 0.25 Hz. The precision is overestimated as the two measurements cannot be simultaneously recorded on both channels of the frequency counter. In fact, 0.25 Hz corresponds to the fluctuation observed on the synthesizer frequency for 1 Hz sampling rate, as can be easily observed in Fig. 4(a). A RF synthesizer with higher stability should therefore allow for better stability. The main physical limit on the spectral purity of the beat note is attributed to the relaxation oscillations, which appear as two side bands around the beat-note peak. The phase-locking technique does not allow for reducing these relaxation oscillation peaks, as they are correlated on the two orthogonal modes.[9]



(a)



(b)

Fig. 4. (Color online) (a) Instantaneous fluctuations and long-term deviation of the synthesizer frequency versus time. (b) Histogram of the temporal stability of the beat note between the two orthogonal modes using the locking technique based on the frequency-shifted optical feedback loop.

Compared with the classical scheme usually used in heterodyne interferometric measurement based on a frequency shift through the Bragg cell and a recombination between the nondiffracted beam and the frequency-shifted beam, this injection technique ensures excellent spatial and angular overlap between the two beams with a maximum contrast between them. Moreover, the technique could be extended to higher frequency by using an integrated $LiNbO_3$ electro-optic modulator. Integrated modulators delivering up to 20 GHz frequency modulation are currently commercially available near 1.5 μm. An all-optical fiber feedback loop including such integrated modulator should significantly simplify the alignment and the efficiency of the frequency locking. In the specific case of pulsed Q-switched dual-frequency lasers, it could also solve the problem of coherence loss of the microwave signal between successive pulses.[10] Further extension of the technique to higher frequency beat notes as in the terahertz regime could also be investigated using a nonlinear optical feedback effect in the external cavity. For example, stimulated Raman or Brillouin scattering in a molecular gas cell or in a single crystal could influence a solid-state laser submitted to optical feedback.[11]

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