DIGITAL BEAT FREQUENCY CONTROL
OF AN OFFSET-LOCKED LASER SYSTEM

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ABSTRACT

A digital control system for two coupled laser cavities was developed to generate two lasers beams those frequencies differ by an adjustable beat frequency, which is required for heterodyne interferometer applications. The proposed system is supported by a field programmable gate array and enables a high grade of flexibility. Measurement results demonstrated that the beat frequency could be stabilized with an Allan deviation of 8.6 Hz over an integration time of 1 s. The dynamic behavior of the closed-loop control system was investigated in addition.

Index terms - two-frequency laser source, beat frequency stabilization, thermal control, FPGA-based control

1. INTRODUCTION

Heterodyne interferometry offers a high signal-to-noise ratio and is therefore widely used for high-precision length measurements at national metrology institutes since the first commercial heterodyne system was launched over 40 years ago [1]. The PTB has developed a phase evaluation electronics [2] and interferometer optics with spatially separated input beams [3] to achieve resolving capabilities and nonlinearities down to 10 pm without using error correction methods, such as the Heydemann correction [4]. Within a funded project the PTB and SIOS company have cooperated for almost two years to work on further developments of this heterodyne laser interferometer concept. A significant contribution was the development of an alternative two-frequency laser source. It is able to replace the expensive Nd:YAG solid state laser and two acousto-optical modulators used to generate the beat frequency, that had been operated previously in our laboratory setup. Furthermore, the entire signal processing required high adjustment effort for the commissioning and maintenance of the beat frequency generation. Hence, an offset-locked He-Ne laser system had been developed by the SIOS company supported by the Ilmenau University of Technology to provide a competitive laser source for heterodyne interferometer applications [5]. Measurements using this uncalibrated laser system can be traced back to the SI-unit meter with a relative uncertainty of $1.5 \cdot 10^{-6}$ recommended by the CIPM [6]. Moreover, widely-used optical components for this wavelength can be used to design interferometer setups. The existing control system for the dual laser system applied an analog phase locked loop (PLL) technique. However, a digital system is capable to provide obvious advantages over its analog counterpart. It can be adapted by software easily and offers the ability to change the functionality of the system. The optimum adjustments of control parameters can be tuned and restored at runtime. In addition, results obtained in the field of frequency stabilization of lasers lately showed that high frequency stabilities and reproducibilities were achievable by the introduction of novel digital control methods [7, 8].

In this article, a digital control method using a field programmable gate array (FPGA) is presented. Introductory, a brief description of the frequency stabilization technique is provided. Then the system design and electronics used for the frequency stabilization and performance evaluation are described. Finally, the experimental results of the proposed laser stabilization are discussed.

2. OFFSET FREQUENCY STABILIZATION OF TWO INTERNAL-MIRROR HE-NE LASERS

An unstabilized laser is subject to many perturbations to its frequency, such as thermal variations, pressure changes, mechanical vibrations and magnetic fields. The laser frequency stability of an internal-mirror He-Ne laser is mainly influenced by thermal variations of the spacer material between the cavity endplates carrying the mirrors [9]. Different heating methods have been used to regulate the laser tube length, e.g. heater coils [7], thermo foils [10], water-flow [11] or light radiation [12]. However, a preheating of the tube is required to ensure an efficient cooling mode to be able to change effectively the laser cavity length in both directions.

Most commercial He-Ne lasers employ the two-mode frequency stabilization technique [13] to control thermally the laser frequency of a single laser. In this method the difference of the optical powers in two orthogonally polarized modes are determined and the difference is controlled to be zero. The laser frequency stability of such systems is in the range of about $4 \cdot 10^{-9}$ over an observation time of 1 h [14]. However, the frequency difference between both axial modes of common He-Ne laser tubes is higher than a few 100 MHz. Such a high beat frequency is rarely used in heterodyne displacement interferometry because it leads to difficulties in the signal acquisition and / or -processing. Typically, beat frequencies down from of a few 10 kHz [15] to 20 MHz [16] are generated by using acousto-optical modulators (AOM) or in the range of 1.5 to 7.2 MHz using a magnetic field applied to the laser tube (Zeeman laser, [17]). But a Zeeman laser providing one beam containing both laser frequencies is not suitable to feed our interferometer design, which uses spatially separated input beams to minimize periodic nonlinearities.
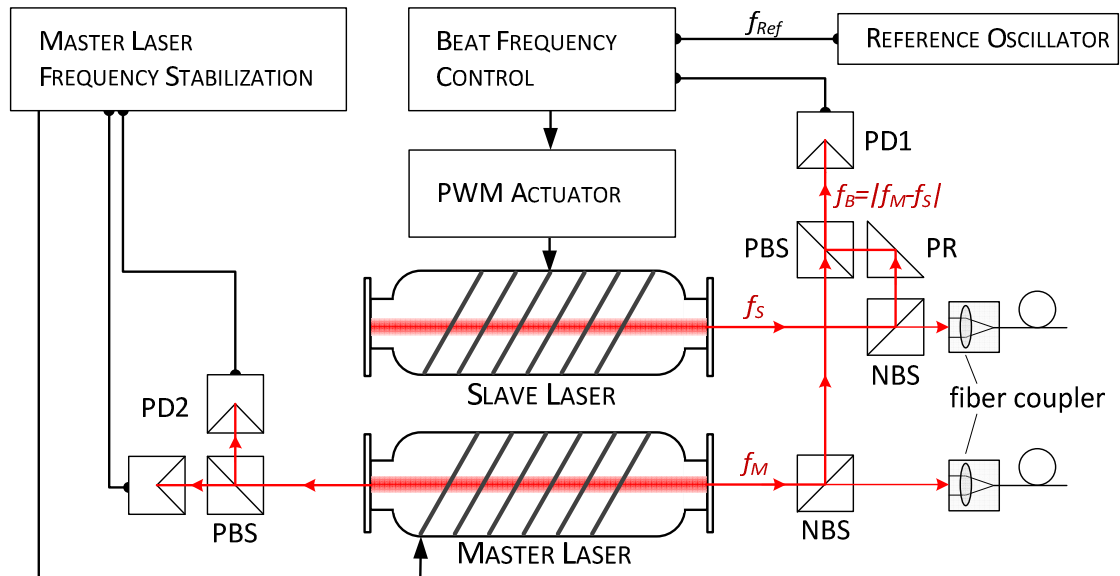

Figure 1. Basic setup of two coupled He-Ne laser cavities to generate a beat frequency according to [5]
(NBS: neutral beam splitter; PBS: polarized beam splitter; PR: prism; PD: photodiode).

Previous research has revealed that an alternative beat frequency generation by coupling the laser frequency of a master laser cavity with the laser frequency of an additional laser cavity is feasible [5]. In the presented setup the laser frequencies between two lasers were locked with a frequency offset of about 4 MHz. The system was capable to provide an increased output power of about 2 mW and used optical fibers to transfer the laser light to a dedicated interferometer setup. The basic principle is illustrated in figure 1. The light of both lasers was superposed to detect the beat frequency (f_B) representing the difference between both laser frequencies (f_M & f_S). This frequency offset was supposed to be locked using an analog control method to adjust thermally the resonator length of the slave laser.

3. SYSTEM SETUP AND CONTROL SCHEME

A two-frequency laser source similar to the one described in the last paragraph consisting of two coupled He-Ne lasers has been provided by the SIOS company to PTB, which investigated its suitability for heterodyne displacement interferometry applications. The basis are two laser cavities [14] with a length of 280 mm, both were enwrapped with a thermal foil with a resistance of $13.4\,\Omega$. The two laser tubes were heated up independently with about 12 W to a temperature of about $69\,°C$ during the warm-up time of less than 10 min. Subsequently, each laser was stabilized internally using the two-mode power balance technique and an unstabilized beat frequency was generated representing the open-loop state. In this state the beat frequency had to be set to a value of less than 4 MHz. Then, the beat frequency stabilization can be activated and the laser frequency of the slave laser is controlled by a phase lock loop (PLL) technique to a fixed beat frequency of 4 MHz. This analog control system generated a pulse width modulated heating signal with 1 kHz switching frequency and offered a beat frequency stability of 11.3 Hz over a gate time of 0.5 s (private communication to C. Sternkopf). The status of both lasers have been monitored and changed with proprietary SIOS software using a serial RS-232 interface. The mechanical assembly of the two-frequency laser source was built into a conventional 19-inch enclosure and is shown in figure 2.
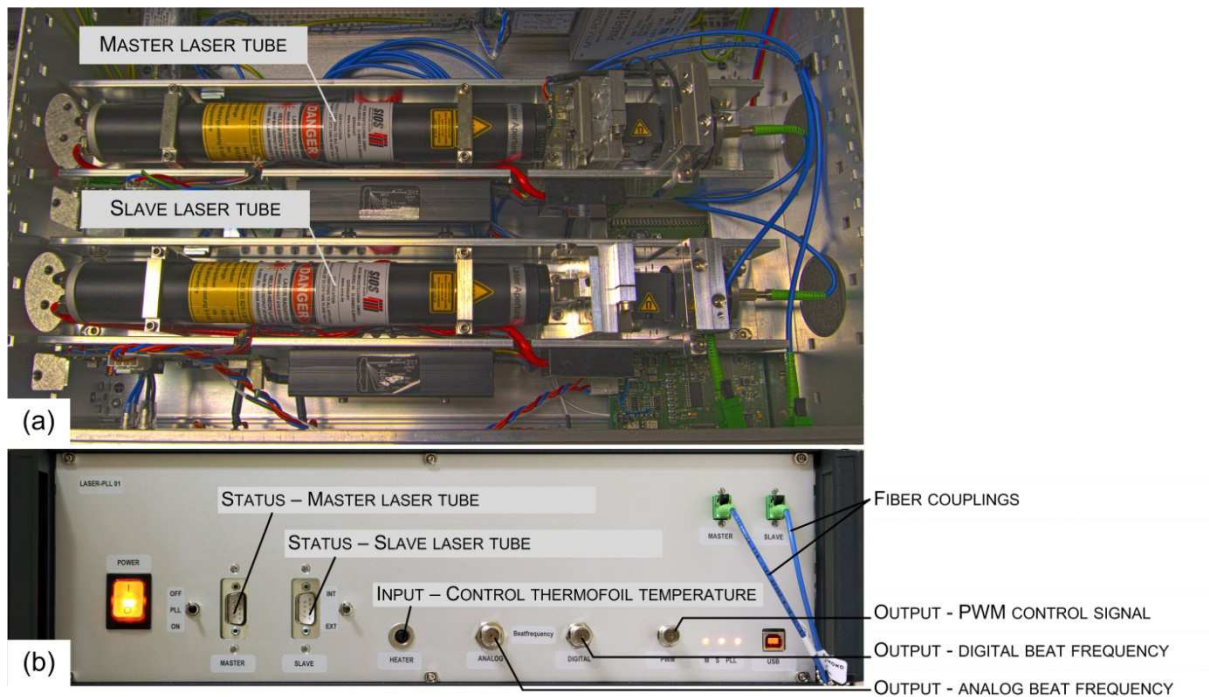

Figure 2. (a) Mechanical assembly of the coupled laser tubes generating a beat frequency of 4 MHz and (b) connectors to implement an external beat frequency control and to monitor the status of the laser tubes.

However, the proposed laser system provides the signals necessarily required for an external beat frequency control . Therefore, two signal taps were prepared to output the beat frequency in analog and digital fashion and an additional tap represented the actuating PWM signal. An input connector was provided to the thermal foil to close the control-loop.

Based on this arrangement, a digital control system was developed to stabilize the beat frequency externally. Furthermore, the proposed system was capable to determine the performance of the two-frequency laser system. The system is illustrated in figure 3 and contains two commercially available FPGA-based cards (model: NI-7854R and NI-7953R, National Instruments), which were attached in a PXI chassis with an embedded controller

providing a real-time operating system (model: NI-8115). The development environment was running with LabVIEW® software.

The digital control of the beat frequency stabilization was operating on the 7854R FPGA card. This card is equipped with 8 analog outputs offering a resolution of 16 bit with a maximum update rate of $1\,MS·s^{-1}$ and 96 digital I/O channels with TTL logic level. The beat frequency information was the Schmitt triggered stream of the analog signal captured by the photo diode. The FPGA card received this signal by using a single digital I/O channel with a timing resolution of 8.3 ns. Following, the frequency of this converted signal was determined with a simple counting method accumulating the number of zero crossings. The frequency counter was adaptable to determine the beat frequency either with a high bandwidth up to 200 kHz or with a high frequency resolution down to 1 Hz. The evaluated beat frequency represents the current value, which was compared to a user-defined reference value and resulted in a control deviation. A PI control algorithm was computed on the FPGA with a maximum operating rate of 200 kHz and was applied to close the control loop by applying a feedback signal to the slave laser. For this purpose, the voltage signal generated by the FPGA card was converted by a transconductance amplifier to a current with a maximum value of 1 A. The basic principle of the digital control method using only a single digital input and one analog output is shown on the left side in figure 3. Measurements of the control system showed that the beat frequency was not adjustable to a frequency higher than 8.5 MHz due to limitations at the Schmitt-trigger circuit. Compared to the analog control system the digital counterpart was capable to lock at arbitrary beat frequencies of the open-loop system.
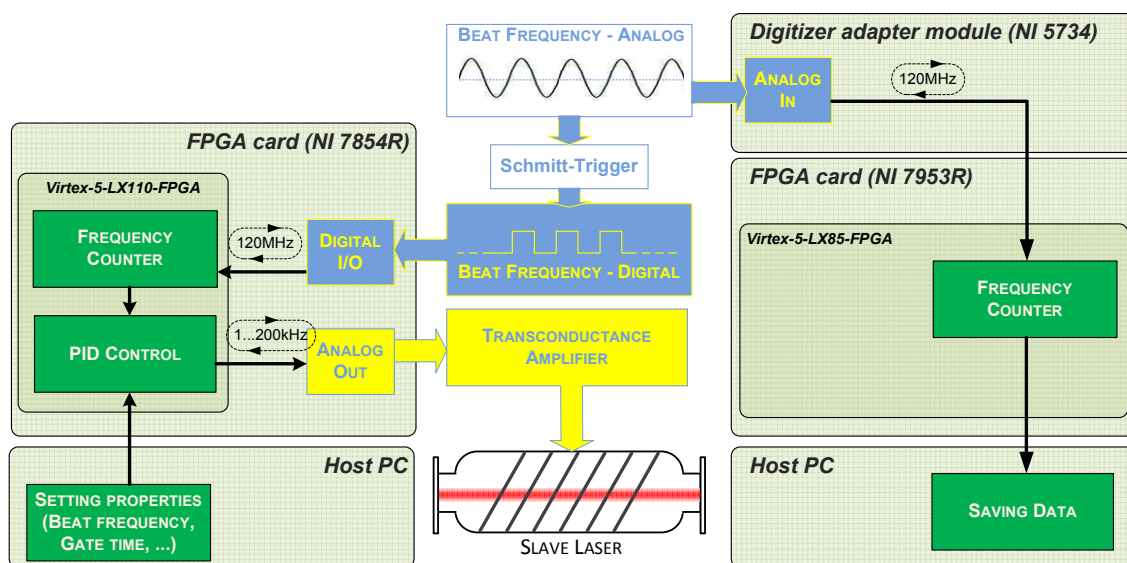

Figure 3. Schematic of the digital control system used to stabilize the beat frequency based on the NI 7854R FPGA card and the measurement scheme for characterizing the beat frequency stabilization based on the NI 7953R FPGA card.

In comparison to previous work [5, 7, 10] using commercially available frequency counter we strived to use a self-developed counter based on the 7953R FPGA card to characterize the beat frequency stabilization. This FlexRIO card was connected to a digitizer adapter module (model: NI 5734) equipped with 4 analog inputs offering a signal-to-noise ratio of about 70 dB and a maximum sampling rate of $120\,MS·s^{-1}$. This device received the analog beat signal provided by the photo diode with a maximum amplitude of 150 mV, converted the signal with the maximum sampling rate and determined the frequency by using its own frequency counting method. The proposed solution allows a user-defined adjustment of the gate time as well as the measurement time and thus enables an enhanced post-processing of the acquired dataset. However, an independent operation of the control and measurement system was in this way technically feasible.

4. RESULTS AND PERFORMANCE

In the first measurement the performance of the beat frequency stabilization was investigated. A control frequency of 2 kHz has been applied supported by a frequency counter gate time of 500 µs representing a frequency resolution of 1 kHz. Simultaneously, the measurement system was determining the frequency with a gate time of 20 ms and captured the data over 13 h to characterize the long-term stability of the system. In order to be able to distinguish the instrumentation noise floor of the measurement system, the measurements were realized in the same manner using a frequency generator (model: Tektronix AFG3101) able to generate a beat signal as well. The results of the beat frequency deviation, illustrated in the red curve at figure 4(a), have been computed with an integration time of 1 s and reveal a peak-peak value of 81 Hz as well as an Allan deviation of about 8.6 Hz. It was no long-term frequency drift observable during the whole measurement time and the performance is comparable to the analog control system. The instrumentation noise floor at an integration time of 1 s exhibited an Allan deviation of 0.07 Hz. In addition, the Allan deviations of the beat frequency have been computed over shifting observation bandwidths and are plotted in figure 4(b). The dependence is consistent with a 1/f nature of noise, which implies that the proposed digital control system is not the limiting factor [9].
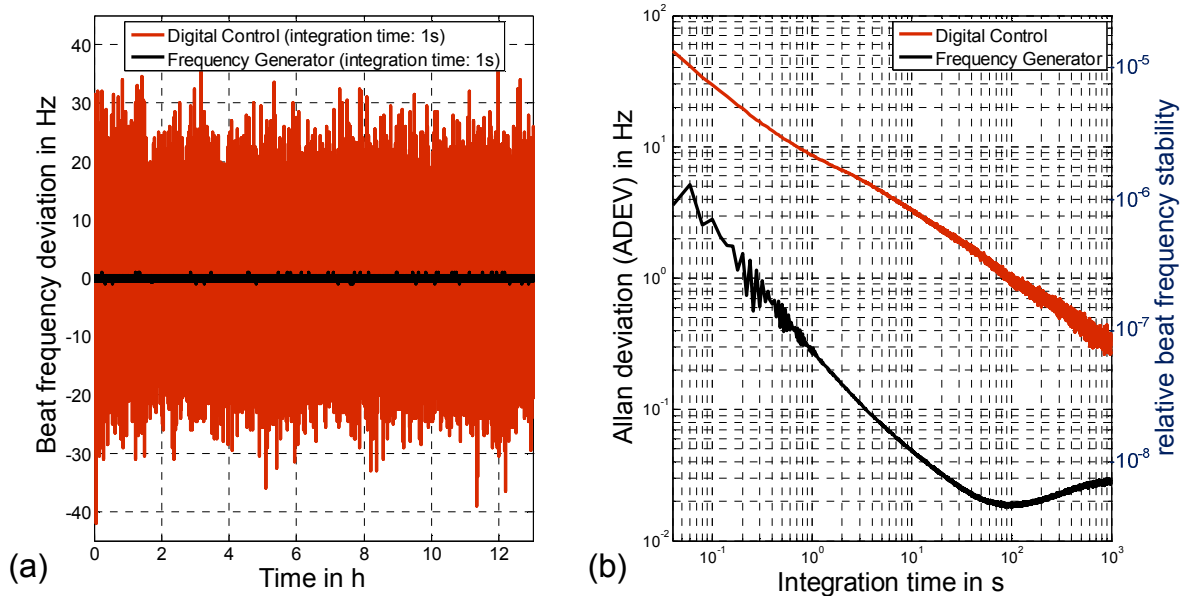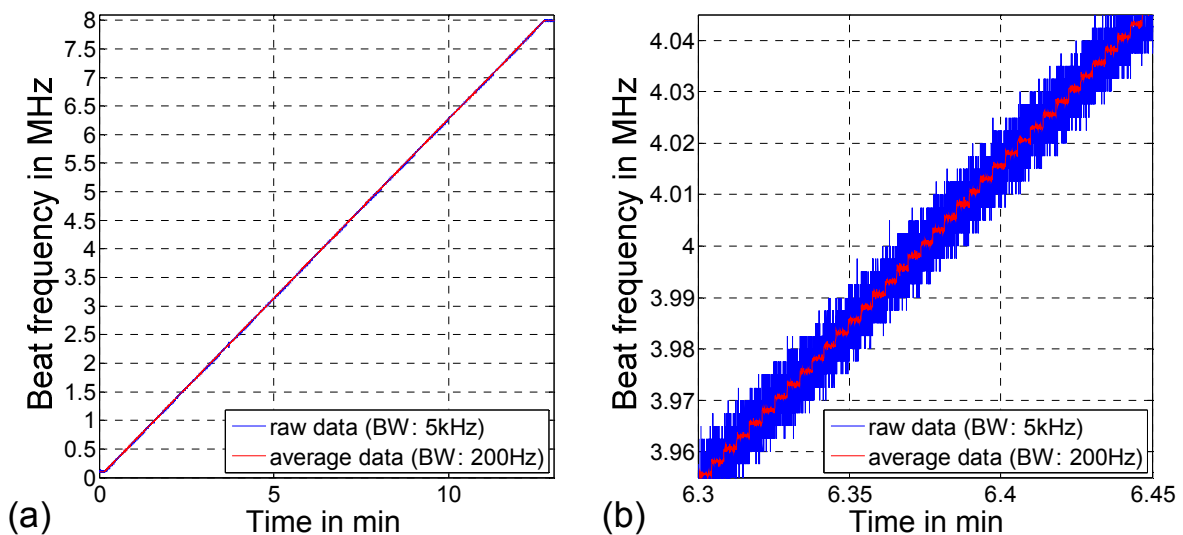

Figure 4. Measurement results of the digital beat frequency control related to (a) its beat frequency deviation at an integration time of 1 s and (b) its relative beat frequency stability over a shifting integration time. The black curves represent the measured instrumentation noise floor using a frequency generator.

Secondly, the dynamic behavior of the digital closed-loop control system was investigated. Therefore, the set point specifying the desired beat frequency was alternated in discrete steps to investigate the step response of the system. The result was captured with a gate time of 200 µs is shown in figure 5 and verified that the beat frequency could be tuned up from 0.5 MHz to 8 MHz within a time of about 250 ms. The dynamic behavior in the heating and cooling mode was similar.
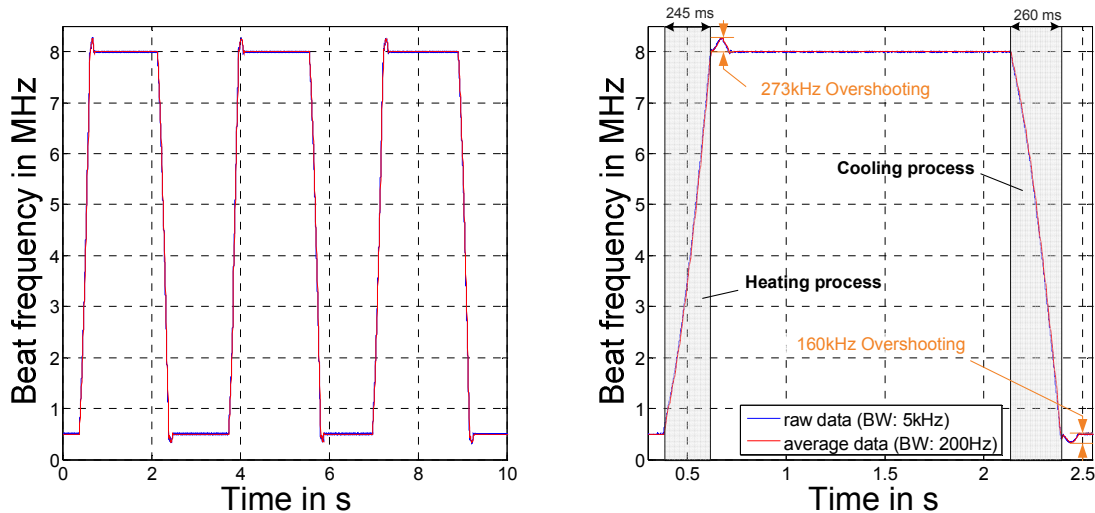
Figure 5. Measurement result verifying the step response of the closed-loop digital control system for stabilization of the beat frequency generation.

In a third measurement the control system was operated to change the beat frequency within a range of 0.1 MHz to 8 MHz by using step widths of 2.5 kHz. The measurement was acquired in the same way as the second measurement. The results showed that the working point of the digital control system can be adapted easily.

Figure 6. Measurement result presenting the tuning of the beat frequency within a range of (a) 0.1 to 8 MHz and (b) 3.96 to 4.04 MHz, respectively.

5. CONCLUSION AND OUTLOOK

In conclusion, a digital control system has been developed to stabilize the beat frequency between two coupled laser cavities. The system is fiber-coupled and provides a two-frequency light source with spatially separated beams for heterodyne displacement applications. The control system on the basis of an FPGA-based card requires only one digital input as well as a single analog output signal and can be modified by software easily. The approach described in detail allows a simple variation of the beat frequency and provides a lock-in range independent to the present beat frequency in the open-loop state. Finally, the digital control system was verified in closed-control loop mode and demonstrated a stability of about 8.6 Hz over an integration time of 1 s. Furthermore, the step response behavior of the system was determined by changing the beat frequency by a value of 7.5 MHz in about 250 ms.

The presented setup is highly sensitive to solid-borne sounds. Further developments strive for reducing this influence and focus on an in-depth analysis of the dynamic behavior of the closed-loop controlled system.

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