Real-time and versatile laser-power stabilization with arbitrary amplitude modulation

J Phrompao¹, R Pongvuthithum², T Sucharitakul², K Srakaew¹ and W Anukool¹,³,*
¹ Department of Physics and Materials Science, Faculty of Science, Chiang Mai University, 239 Huay Kaew Road, Muang, Chiang Mai, 50200, Thailand
² Department of Mechanical Engineering, Faculty of Engineering, Chiang Mai University, 239 Huay Kaew Road, Muang, Chiang Mai, 50200, Thailand
³ Thailand Center of Excellence in Physics, Commission on Higher Education, 328 Si Ayutthaya Road, Bangkok 10400, Thailand
E-mail: waranont.a@cmu.ac.th

Abstract. We have demonstrated a technique to stabilize laser power at any point in an optical circuit. By employing a self-made Arduino-controlled stabilizer for real-time monitoring and generating feedback signal, the power fluctuation after an acousto-optic modulator (AOM) can be suppressed to 0.16% at an average power of 33.34 µW. Our arrangement also allows simultaneous amplitude modulation using an arbitrary waveform. The system design and principle of operation are described.

1. Introduction
Laser power stability is necessary for high-resolution and highly sensitive spectroscopy in contrivances such as atomic clock [1,2], atomic magnetometer [3,4], atom gravimeter [5], and neutral-atom quantum simulator [6–9]. Under a circumstance concerning considerably long optical path, there are usually many light-preparation processes between the laser emitter and the target where each part could inject electrical noises that tremble the baseline for optimal power. This simply means that even after direct stabilization at the light source, more stabilizers are often required at appropriate points in the optical circuit. To attain the constancy level demanded by precision spectroscopy and metrology applications, the typical stabilizing scheme involves multiple signals from the output of an optical circuit that can be sent back to regulate the light source and laser-power modulators. However, sufficient laser power is not always available, so dividing up to generate feedback signal at a pre-located point on the optical path is not feasible. In particular with manipulating individual quantum systems, the laser intensity needs dynamic adjustment to vary atomic energy shift so that each single atom in a trap array is optically addressable. For these difficulties altogether, we have designed and built a simple and inexpensive power stabilizer using Arduino controller. The technique to stabilize laser power at any point along a laser path has been demonstrated with a free-running laser diode. By employing a self-made Arduino-controlled stabilizer for real-time monitoring and generating feedback signal, the power fluctuation after an acousto-optic modulator (AOM) can...
be suppressed to 0.16%. With simultaneous amplitude modulation using an arbitrary waveform, our scheme provides versatility for laser-power stabilization.

In the following sections, we describe the working principle and scheme of laser-power stabilization (section 2) accompanied by illustrations of the experimental setup (section 3). Furthermore, the performance of the power system stabilizer is investigated in terms of respond time, long-time power stabilization and amplitude modulation by using arbitrary waveform (section 4). Finally, the advantages of our device are summarized (section 5).

2. Principle of Operation

The laser-power stabilizer consists of reference voltage ($V_{\text{ref}}$), feedback controller, photodetector voltage ($V_{\text{pho}}$), driving voltage ($V_{\text{dri}}$) and optical apparatus as shown in figure 1. The reference voltage, which can be either a constant signal or an arbitrary waveform, controls the laser output power. The feedback control operation is based on proportional-integral-derivative (PID) algorithm [10]. A commercial Arduino Nano V3.0 (ATmega328) functions as a real-time controller. With the use of programmable Arduino, the controlled parameters such as proportional gain ($k_P$), integral gain ($k_I$) and derivative gain ($k_D$) can be expediently optimized for broad different setups. Furthermore, the stabilization process can be controlled via trigger voltage ($V_{\text{tri}}$). For example, the stabilization is executed when $V_{\text{tri}}$ is set to the high value. In contrast, if $V_{\text{tri}}$ is relatively small, the stabilizing process is disable and $V_{\text{dri}}$ equals $V_{\text{ref}}$. Moreover, the constraint imposed on $V_{\text{dri}}$ is also computerized, and the value measured is repeatedly monitored to prevent equipment damaging. After such endurance over the voltage

![Figure 1. Schematic diagram of the laser-power stabilization system. The dashed line and solid line enclose the outlined algorithm of Arduino Nano and the programmable control unit. The Amp. stands for amplification circuit, and the operational amplifier is OPA1451D. $V_{\text{tri}}$, $V_{\text{ref}}$, $V_{\text{pho}}$, $V_{\text{amp}}$, $V_{\text{out}}$ and $V_{\text{dri}}$ represent the trigger voltage, reference voltage, photodetector voltage, amplified voltage, output voltage and driving voltage of which the minimum voltage, and maximum voltage are $V_{\text{min}}$ and $V_{\text{max}}$ respectively. DAC symbolizes digital-to-analog convertor (DAC:AD5660). Solid arrows show the directions of the output signal at each point while the dash ones indicate a two-valued formal logic.](image-url)
limitation, the Arduino microcontroller board will generate digital pulses to regulate the digital-to-analog converter (DAC:AD5660CRMZ-2) of which the output $V_{dri}$ is used to ensure the operational accuracy of commercialized standard AOM. The maximum voltage that the DAC can drive is 5.5 volts with typical output noise $80nV/\sqrt{Hz}$.

Stabilizing the laser power at the desired point in an optical circuit can be achieved as follows. After apportioning of the laser beam, a fast and sensitive photodetector (SFH213), i.e. $5\text{ns}$ response time with $95\%$ relative spectral sensitivity at $795\text{nm}$ wavelength, turned the laser power into measurable electrical current. The current output was then converted to a voltage by the amplifier circuit using an operational amplifier (OPA145ID) before entering to the Arduino as a feedback signal. By finely adjusting a $5\Omega$ variable resistor, the amplification circuit could increase $V_{pho}$ up to six times as great to make the amplified voltage ($V_{amp}$) comparable with $V_{ref}$. The source code used in this work to program the Arduino and electrical circuit diagram for power stabilizer can be found in reference [11].

3. Experimental setup

In this section, we demonstrate an experimental setup to evaluate the performance of the programmable control unit with a specific model of the AOM (1205C-2 ISOMET) as illustrated in figure 2. An ultra-low noise diode current source (DLC202 MOGLabs) with current noise below $100pA/\sqrt{Hz}$ was used to drive a $795\text{nm}$ laser diode (QLD-795-150S) in free-running mode. The laser source can generate a maximum output power of $150\text{mW}$ while manifesting $0.8\text{mW/mA}$ of the differential between laser power output and the operating current. By flashing the laser beam to the cavity, the output power dropped to $60\%$ of the maximum power of the laser diode laser. Added to the ultra-low noise current, mode hoping potentially arising because of the thermal fluctuation was kept minimized to within $\pm 5mK$ throughout the experiment. Due to then, the laser beam entered to an isolator (EOT-04-780) to prevent back reflection with $90\%$ transmission efficiency. After that, the laser beam was deflected into two beams by using the AOM, which was driven by an AOM driver (630C-80 ISOMET). There are two input voltages to control the frequency and the diffracted laser amplitude for the AOM driver. The voltage ranges to control the frequency and the deflected laser power are $0-10\text{ volt}$ and $0-1\text{ volt}$, respectively. In this case, the output radio frequency was fixed at $80\text{MHz}$, which relates to $5\text{ volts}$ of frequency voltage for the AOM driver. The amplitude voltage was used to stabilize the laser output power. The $1^{st}$ positive deflected laser beam was used to test the power stabilizer by having $50\%$ deflection efficiency at $0.9\text{ volts}$ of modulating voltage. The diffracted beam

![Figure 2. Schematic of laser power stabilization system. The Laser, ISO, AOM, PBS, BS, $P_0$, $V_{pho}$, $V_{dri}$, $V_{tri}$ and $V_{ref}$ indicate 780nm Littrow external cavity diode laser, optical isolator, acousto-optic modulator, polarization beam splitter, 70:30 beam splitter, output power, photodetector voltage, driven voltage, trigger voltage and reference voltage, respectively. The black arrows represent the direction of signal output at each point.](image-url)
was coupled into an optical fiber with 20% transmission efficiency. Due to the divergence of the laser beam profile, this leads to the poor coupling efficiency. Then, the output laser beam from the optical fiber (P1-780A-FC-1) was passed through a half wave-plate (HWP) and a polarization beam splitter (PBS). After that, the transmitted laser beam was split into two beams by a 70:30 beam splitter (BS). The 30% reflected laser beam was feedback signal and the 70% transmitted laser beam was a stabilized laser beam. The reflected laser beam was detected by the fast respond time photodetector and present as photodetector voltage ($V_{pho}$). Then, the photodetector voltage was amplified by the amplification circuit and adjusted the voltage to be in the range 0-1 volt to correspond with the AOM driver. The trigger and the reference voltages were generated by the FPGA signal generator (NI USB-7855). During the laser-power stabilization process, the trigger voltage was operated as high voltage. To avoid overvoltage for the AOM driver, the $V_{min}$ and $V_{max}$ in constraint code of Arduino was set to be 0 and 1, respectively. Alternatively, the laser power at any desired point of the optical path after the AOM can be stabilized by placing the BS and the photodetectors at the point such as point * in figure 2.

The investigation of long-time stability started from setting the modulating voltage and frequency voltage of the AOM driver to 0.8 volt and 5 volts, respectively. Laser powers from both outbound ports of the BS, i.e. with and without power stabilization, were separately and simultaneously measured for an hour by using an optical power meter (S121C and PM100USB (Thorlabs)), which has sample rate at 10 samples per second. Then, the laser power datasets were analyzed in term of average ($\bar{x}$), standard deviation ($\sigma$) and fluctuation ($\sigma \times 100 / \bar{x}$) of the laser power. To optimize the PID values, the $k_P$, $k_I$ and $k_D$ were set at any initial values, and the fluctuation of the laser power was observed in 10 seconds for each set of PID values. After that, each PID value was increased or decreased with a small step until the fluctuation was minimal. We have also extended the experiment to determine the fraction time of the total response when subjected to continuous input. Two arbitrary waveforms were applied as a reference voltage to investigate the respond of the laser-power stabilizer. The waveforms of the reference voltage were digitally synthesized minuscule staircase with an equal step of 0.05 volt displayed with blue lines in the figures 4(a) and 4(b). Similar to the long-time stabilization experimentation, the frequency voltage at the AOM driver as well as $k_P$, $k_I$ and $k_D$ were set at the same values. Instead of directly measuring transmitted laser power from the BS, the reflected laser power from the BS was amplified for subsequent comparison with the reference voltage. The rise time and fall time of the reference voltage and the amplified voltage were directly observed using a fast oscilloscope (DSOX3024T) at a sample rate of 5 Giga samples per second.

4. Results and discussion

4.1. Long-time stabilization

Even though the current noise and the temperature fluctuation are limited to below $100pA/\sqrt{Hz}$ and $\pm 5mK$ which are commonly applicable for atomic physics experiments, the optical power from a free-running laser diode rippled from 47$\mu$W to 95$\mu$W within a period as short as a hundred seconds. Without stabilization process (the red line in figure 3(a)), the rise and fall that persisted throughout the optical circuit cannot be easily filtered out because of its unpredictable pattern. The unstabilized laser power oscillated fast for the first 800 seconds and then changed slower in complete disorder. The contribution came from the other parts in the optical circuit, e.g. the polarization of output laser from optical fiber varied with the surrounding temperature, etc. This imposes an unneglectable effect on the laser output from the BS. As a result, the fluctuation of output laser power was 19.25% at an average power of 68.30 $\mu$W. After $k_P$, $k_I$ and $k_D$ were set to optimal values, i.e. 0.1, 0.1 and 0 for this particular setup, the laser-power stabilizer has suppressed power fluctuation of the transmitted laser to 0.16% from at an average power of 33.34 $\mu$W for an hour (the blue line in figure 3(a) and 3(b)).
Figure 3. (a) shows a comparison between the output laser power ($P_0$) with the laser-power stabilization (LPSP) in the red line and the $P_0$ without the LPSP in the blue line. (b) zoom in the $P_0$ with the LPSP in the dashed box from (a) to observe the fluctuation of the laser power.

4.2. Arbitrary amplitude modulation

Figure 4(a) and 4(b) show comparison between the amplified voltage and the reference voltage. In the figures, the yellow lines indicate the amplified voltage. The results show that during the laser-power stabilization process, the laser power can be modulated via the reference voltage. However, the 50ms rise time of the amplified voltage was slower than the 11ms rise time of the reference voltage. In addition, the 30ms fall time of the amplified voltage was slower than the 8ms fall time of the reference voltage. This is because of the respond time of the electric elements such as the operational amplifier, DAC, Arduino and the respond time of the AOM crystal and AOM driver. Nevertheless, the rise time and fall time of the measuring voltage can be improved by replacement with a faster Arduino, operational amplifier and DAC.

Figure 4. Shows a comparison between the amplified voltage (yellow) and a reference voltage (blue). The reference voltage has been modulated with rising (a) and lowering (b) steps of 0.05 volt of during stabilization.

With the potential of using Arduino as the main controller, the PID gains can be optimized
easily to get rid of laser power fluctuation in a different system. As well as, the power stabilizer can be used with active or passive mode to synchronize with the other apparatus by using an external trigger. Moreover, the power stabilizer can be used with an acousto-optic modulator (AOM), which is widely used in the experiments, or modified to use with other devices, e.g., acousto-optic deflector (AOD). Furthermore, the constraint of driven voltage from the power stabilizer can also be modified to avoid damaging driven equipment. In addition, the laser power at any point on the optical path can be stabilized by using the power stabilizer with 0.16% of laser power fluctuation as demonstrated above.

In the previous work that had done by Qi-Xue Li et al. [12], they used a power stabilizer based on Field-Programmable Gate Array (FPGA) as the main controller with an AOM to stabilized laser power. They reported the long-term stability was 0.21%. Even though the FPGA has a better internal clock rate than the Arduino, the FPGA is more expensive and complicated to program than the Arduino. Moreover, the ability of long-term stabilization of our power stabilizer was more stable with 0.16% laser power fluctuation.

On the contrary, the respond time of our power stabilizer was slower than their power stabilizer. They also reported that respond time for their power stabilizer was 90µs but our power stabilizer had respond time in order of ms. To improve this, an Arduino with a faster internal clock, an operational amplifier with faster time respond and a DAC with a higher slew rate should be replaced.

5. Conclusion

We have designed and built a simple and programmable laser-power stabilization device using Arduino Nano, of which the PID values can be optimized for a particular optical circuit. When stabilized, the laser power at a selected point in an optical circuit can be manipulated in real-time through the programmable control unit. The power fluctuation from the free-running laser diode was suppressed from 19.25% to 0.16% at the average power of 68.30 and 33.34µW, respectively. By successively applying a stepwise amplitude modulation, the output power was responsive to the waveform with the rise time and the fall time were in the order of 30-40ms. Thus, the potentials of the laser-power stabilization system such as high stability of laser power, the ability of laser power modulation in real-time and versatility to use with any system are useful for precision measurement in several atomic experiments.

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