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Research Article

Ultra-stable, low-noise two-stage current source concept for electronics and laser applications

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Abstract: This study presents a two-stage current source concept which features low-current noise, excellent drift and stability for higher operating currents. Generally, it is much easier to obtain higher stability and lower-noise parameters for small operating currents rather than large ones. This fact was used within this concept, where a precise low-current source (the second stage) corrects the fluctuations of high-current one (the first stage). In details the theory of operation for setup, the noise-sources analysis and measurement results are presented. For a maximum operating current equals 1 A, the current noise density of 126 nA/√Hz (at $f = 1$ kHz), long-term stability of ±2.1 ppm and temperature coefficient equal 2.8 ppm/°C, were obtained, whereas the current noise below 1 nA/√Hz was obtained for lower operating currents. Presented circuit is inexpensive to construct, non-thermally stabilised and very small size (1 × 1.2 in^2). The obtained parameters are competitive to commercial current drivers designed for laser applications. The two-stage current source has been successfully implemented in a fully integrated diode-pumped solid-state lasers.

1 Introduction

Nowadays, semiconductor laser diodes are widely used in industry, medicine, experimental and measurement laser applications. Many areas of scientific research and laser measurement techniques require low-noise, monochromatic and frequency-stable laser sources or high stable current sources. Generally, stable operation of the semiconductor laser (in power and frequency domain) depends on the diode junction temperature and injection current. This is particularly evident for single-mode, narrow, linewidth laser applications in laser spectroscopy. Therefore, an ultra-stable, low-noise and low-drift laser current drivers are necessary. However, a low-noise electronic apparatus with higher current efficiently are needed, because the ability to use low-noise controllers is often limited by its maximum operating current and laser diode type. Most semiconductor laser diodes with output power higher than 100 mW and spectral range above 1 µm, typically require operating currents above 200 mA. For example, the fibre Bragg grating-stabilised laser diodes or the laser pump diodes used in the diode-pumped solid-state (DPSS) laser seeds are supplied with currents exceeding 0.5 A. Quantum cascade lasers (QCLs) are a very eloquent example. They are used in the mid-infrared (IR) range for gas sensing applications, IR imaging and terahertz generation [1]. They typically operate from 500 mA up to 1.7 A of junction current, generating optical output power in the range from 30 to 300 mW [2]. The QCL wavelength stability depends on ripples and broad-spectrum noise modulated onto the driving current. Thus, high stability and low-noise are the two most important characteristics for QCL current drivers. Reducing current noise from the QCL driver is critical in order to obtain a lower laser linewidth. In 2012, Tombez *et al.* [3] reported that the current noise below ∼1 nA/√Hz is required for QCL's current sources. Then, it is possible to observe the frequency noise of the QCL laser itself, without any extra noise induced by the current source. Additionally, the current noise below ∼1 nA/√Hz will not have a significant impact on the QCL laser linewidth broadening [4–6]. Higher laser operating current leads to a considerable rise in temperature of the current control semiconductor components (usually transistors), what is the one of the main problems to maintain an ultra-low-noise level of the laser driver. When current increases, the thermal power dissipation, electron mobility and, as a consequence, thermal noise of drain current and flicker noise are increased too [7], what can be clearly observed, especially for low-frequency range of current noise spectral density characteristics. For many years, a lot of well known and fundamental current source configurations such as Wilson's current mirror [8] or similar setups [9, 10] were designed. The most famous is the original Libbrecht–Hall configuration [11] (∼45 nA$_{RMS}$ at 1 MHz bandwidth for 100 mA of operating current) and its modifications presented by Erickson [12] and Troxel [13] which exhibits one of the lowest current noise levels currently reported. However, the authors obtained only an operating current range up to 200, 127 and 50 mA, respectively. For the Libbrecht–Hall setup, the equivalent current noise spectral density is equal ∼70 pA/√Hz (for bandwidth from 100 Hz to 100 kHz, at 100 mA of operating current), whereas the Erickson's current driver reached ∼2 nA/√Hz (for the same bandwidth and 74,5 mA). The presented two-stage current source configuration offers the equivalent current noise of ∼440 pA/√Hz (at 100 mA) and ∼1.2 nA/√Hz (at 200 mA). In [12, 13], Troxel *et al.* and Erickson *et al.* provided a possibility to extend the operating current range up to 1 A, but they did not show adequate current noise spectral density characteristics, nor total root-mean-square (RMS) current noise. The similar concept to the presented two-stage current source is used to improve noise properties of the electronic circuits, where a powerful source is combined with an active low-power filtering stage in the form of voltage source and is called a capacitor multiplier [14–17]. Very interesting QCL laser current source with implementing an idea of a capacitor multiplier was presented by Taubman [18]. However, the results were verified only for the DC test load current of 500 mA. He obtained excellent current noise levels around 2 and 4 nA/√Hz (at 500 mA). Another Taubman's current configuration, named switch-mode hybrid current controller [19], provides current noise ∼13 nA/√Hz at 500 mA. For the same operating current, the proposed two-stage current source provides ∼7 nA/√Hz. Last year the Alpes Lasers company reported that low consumption QCL lasers across the mid-IR range have been developed [20]. They reduced the threshold current to a few tens of mA and operating current below 200 mA. That means, the presented current source configuration can be successfully implemented as a laser diode driver for such QCL lasers, without linewidth broadening effect and operating in ultra-low-noise current regime (<1 nA/√Hz).

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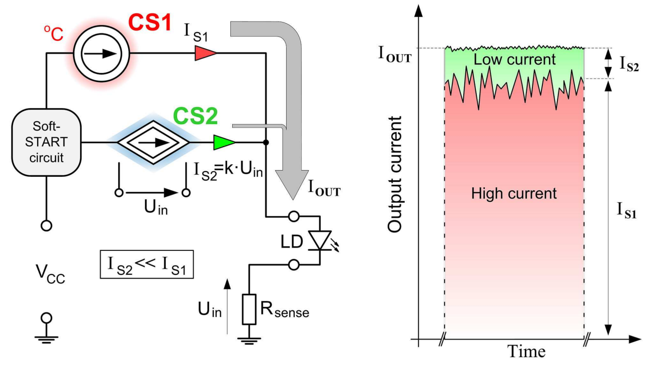
In this paper, the setup of ultra-low-noise and drift, two-stage current source configuration, which can operate up to 1 A of continuous current is presented. The described concept of current source combines large operating currents with very high long-term stability and low-current noise, what was experimentally verified. The proposed novel configuration, relying on adding an additional low correction current to the driving current was, up to our best knowledge, never presented before (recently, the circuit has been covered by a patent application no. P 418415). Presented circuit is inexpensive, does not require thermal stabilisation and very small size (only 1×1.2 in^2). The current source output can be easily increased by the first current stage replacement to much more current efficient (e.g. LT3083 provides 3 A of maximum current). The two-stage source parameters are competitive to commercial current drivers including QCL's current controllers, where the current noise level of few nA/√Hz is achieved [3].

2 Setup description

The main characteristic feature of the presented circuit is parallel connection of two current sources CS1 and CS2, where the currents are added to the load and sense resistor (see Fig. 1*a*). The CS1 is an autonomous source, which provides most of the load current (the first current stage). Its operating temperature reaches even 80°C for 1 A load current what causes a decrease in DC stability, higher noise and long-term drift. While the CS2 is a precise current source controlled by voltage across sense resistor (R_{SENSE}). Its operating current (I_{S2}) is only a few mA and is added to the main I_{S1} current, forming an output current – I_{OUT} (see Fig. 1*b*). Therefore, the contribution of current $I_{S2}$is negligible, but plays a crucial function. The task of CS2 source is a fast correction of the main I_{S1} current fluctuations and as a consequence I_{OUT} also. Since it is much easier to obtain higher stability and lower noise for small operating currents, this fact was used in presented two-stage current source configuration, where a precise CS2 source is an adjusting circuit (the second stage of current stabilisation). The schematic representation of the current source is shown in Fig. 2. This circuit can be supplied by any stable and filtered voltage regulator or low-noise power supply (VCC connector). During our experiments, a power supply with output voltage noise <350 μV_{RMS} was used (Rigol DS832A). The dummy load was built as a serial connection of three silicon diodes (1N5402) due to wide changes of DC operating current up to 1 A and approximation for a typical laser threshold voltage.



a *b*

Fig. 1 *Concept of two-stage current source*
(a) General scheme of the circuit, ***(b)*** Graphical presentation of the current source operation principle

Input voltage was filtered by low-pass filter sub-circuit, which typically consists of series of ceramic and tantalum capacitors (10, 100 and 47 µF) and electromagnetic interference suppression filter chip (NFM21PC105B1A3), with capacitance 1 µF. The system consists of two current sources CS1 and CS2. The current soft-start of CS2 source is realised by metal-oxide-semiconductor field-effect transistor (MOSFET) T1, C2 and R3 elements.

2.1 First-stage (CS1) of the current source setup description

The CS1 circuit is built on basis of a 1.5 A low dropout linear regulator (LT3081), operating as a current source, with its own sense resistor R2, built using two 0.5 Ω metal strip (Vishay) resistors connected in parallel. The main current (I_{S1}) is set by trimpot PR1 (100 kΩ) according to the formula: $I_{S1} = (50\ \mu\text{A} \cdot \text{PR1})/\text{R2}$ and it is externally limited by R1 resistor according to the equation $R1 = (I_{LIMIT}/400\ \text{mA})[\text{k}\Omega] + 400\ \Omega$. Since LT3081 was used as a variable current source on the output of a power supply, the output bypass capacitance C1 was added to provide LT3081 stability [21]. The bypass capacitor C3 placed across the

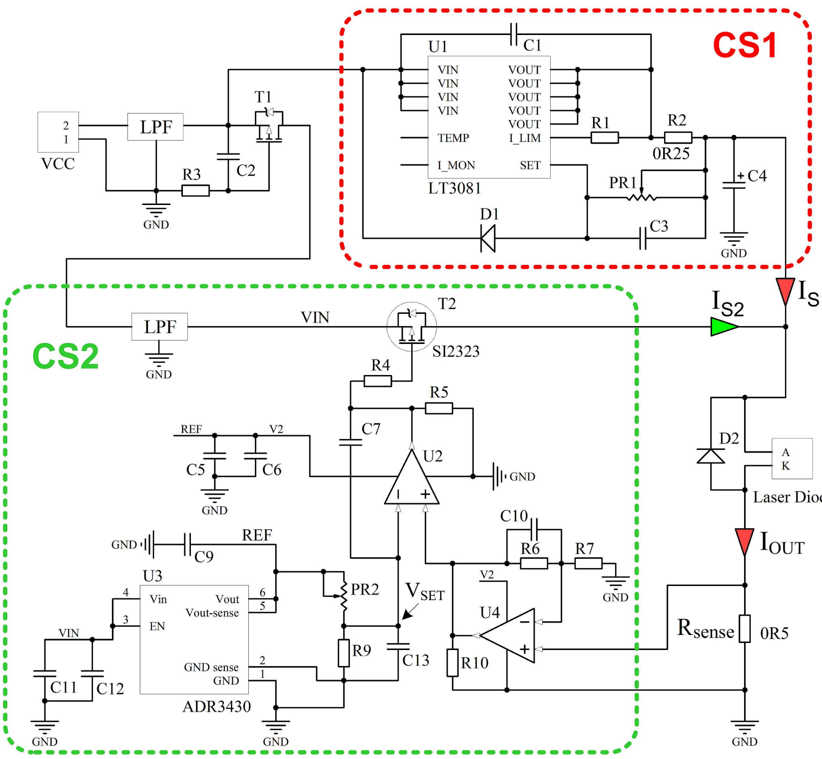


Fig. 2 *Schematic representation of the two-stage current source*

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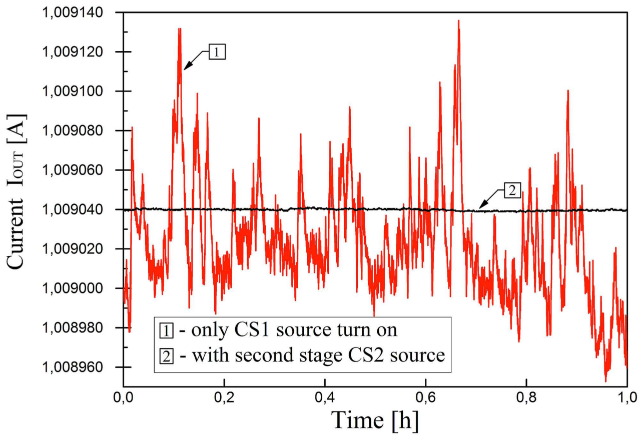

Fig. 3 *Output current fluctuation at 1 A of operating current when only CS1 current source is turned on (trace 1 – red) and second stage of CS2 adjusting current source is operational (trace 2 – black)*

voltage setting resistor PR1 reduces system noise as well, damps the ringing and provides soft-start function for CS1. The time constant of PR1·C3 is smaller than R3·C2; therefore, the current turn-on sequences are I_{S1} and I_{S2} sequentially. According to the LT3081 datasheet [21], the output voltage noise notably depends on noise of reference current source, internal error-amplifier and voltage setting resistor PR1. The 50 µA reference source has a current noise level of 18 pA/√Hz (5.7 nA$_{RMS}$ over 10 Hz–100 kHz bandwidth). The RMS current noise multiplied by the PR1 resistor value gives the equivalent voltage noise equals 29 µV$_{RMS}$ at 1 A of DC current. The setting resistor PR1 generates a Johnson noise, which is equal to $\sqrt{(4\,kT\cdot PR1\cdot \Delta f)}$ and that gives noise level of 2.9 µV$_{RMS}$ (PR1 = 5 kΩ for operating current of 1 A and 100 kHz bandwidth). Finally, internal error-amplifier noise is typical 85 nA/√Hz (27 µV$_{RMS}$ over a 10 Hz–100 kHz bandwidth). Summing up, the theoretical calculation of CS1 output noise level is equal to $\sqrt{(29\,\mu\mathrm{V})^2 + (2.9\,\mu\mathrm{V})^2 + (27\,\mu\mathrm{V})^2}$ that finally gives 40 µV$_{RMS}$. Obtained noise spectral density characteristic measured with a spectrum analyser (SR760) for 1 A of DC current over 0.001 Hz–100 kHz bandwidth verified the LT3081 output voltage noise level of 52 µV$_{RMS}$.

2.2 Second-stage (CS2) of the current source setup description

The second-stage current adjusting source (CS2) uses a sense resistor in series with the laser diode. The voltage drop is amplified (U4) with factor of 1 + R6/R7 and compared (U2) with highly stable voltage reference (V_{SET}). The output signal of the op-amp in comparator configuration drives a gate of the SI2323 MOSFET, which controls the current I_{S2} according to (1). The SI2323 transistor (T2) has a very small input capacitance (which reduces switching delay) and low on-state resistance. The 47 Ω resistor (R4) in series with gate capacitance (C_g) was used to limit a gate current peaks occurring while charging of C_g, what reduces the bandwidth and prevents oscillations

$$I_{S2} = \frac{V_{SET}}{(1 + (R_6/R_7)) \cdot R_{SENSE}} - I_{S1} \rightarrow$$
$$I_{OUT} = \frac{V_{SET}}{(1 + (R_6/R_7)) \cdot R_{SENSE}} \tag{1}$$

Equation (1) clearly shows that the I_{S2} depends on I_{S1} current with opposite sign, which leads to stabilisation of output current ($I_{OUT} = I_{S1} + I_{S2}$) and I_{S2} itself. The V_{SET} value was set properly to obtain I_{S2}/I_{S1} ratio around 1%. This ensures the value of adjusting current $I_{S2}$is only over a dozen mA at 1 A of output current, what reduces noise level connected with thermal processes within CS2 circuit. The I_{S2} corrects the I_{S1} current fluctuations (I_{OUT} consequently). Fig. 3 shows the results obtained for the second-stage current stabilisation loop when it is turned on/off. The usage of second stage of current source CS2 significantly improves output current stability (58 times), compared with single operation of CS1 source (trace 1 – red).

To obtain satisfying current stability and low-noise level, attention should be paid to the selection of several circuit components. The R_{SENSE} resistor should be precise and thermally stable. That leads to better current drift properties. For high operating current source, it is troublesome to set a value of this resistance. Its value should be higher to provide high enough voltage drop for better current regulation accuracy and dynamics, but small enough to reduce thermal power dissipation, Johnson noise and unwanted reduction of voltage drop at the laser diode. In the presented configuration, a pair of 1 Ω surface mount 1206 size resistors were connected in parallel for a total resistance of 0.5 Ω. It provides a thermal noise ten times smaller than 50 Ω sense resistor used in [11, 13] and very low source impedance of the signal, thus reducing an influence of op-amps input current noise. On the other hand, to increase current regulation accuracy and dynamics (they are also limited by single supply operation), the voltage drop across R_{SENSE} is amplified within non-inverting op-amp configuration (U4) with the gain equal 5. Additionally, this resistor should be wired in a Kelvin connection (also called as a four-terminal configuration), thus providing the most precise current measurements and DC current stability in consequence.

2.3 Op-amp's noise analysis and discussion

The op-amp AD8605 from analogue devices was used [22]. This is a single supply, precise and low-noise operation amplifier with specified input voltage noise typically 8 nV/√Hz at 1 kHz and current noise of 10 fA/√Hz. It is optimised for low source impedance. Taking into account a very low-current noise and input impedance (0.5 Ω) an equivalent voltage noise of 5 fV/√Hz was obtained. Hence, the op-amp current noise and Johnson noise of R_{SENSE} (86 pV/√Hz) are practically irrelevant compared with dominating input voltage noise. Additionally, the AD8605 op-amp has a very small value of input bias current (I_B = 0.2 pA) compared with the LT1028 (40 nA) and AD8671 (3 nA) op-amps used in [11, 13], respectively. The I_B current flows in external impedances and produces voltages, which add to system extra errors. In [11], Libbrecht and Hall used a dual supply AD8671 op-amps which are characterised by input voltage noise of 2.8 nV/√Hz @ 1 kHz, but if we take into account influences of its current noise (0.3 pA/√Hz) and source impedance of 50 Ω that total input voltage noise level for AD8605 is only twice higher than AD8671. The gain-bandwidth product is equal to 10 MHz for a both compared op-amps. In presented two-stage current source setup, we have to remember that bandwidth of second-stage adjusting source (CS2) has to be larger than the first-stage source (CS1) bandwidth. Fig. 4 shows the plots of the noise performance for the CS1 source and for the two-stage configuration. The trace no. 3 (black line) in both the graphs present a noise floor level characteristic which determines a detection limit of the measurements.

These measurements are well above the noise floor and they show the effectiveness of the noise reduction with two-stage current source configuration. The bumps visible in Fig. 4*a*) with short plateaus are the intrinsic features of the linear regulator LT3081 and their effects on the finale noise density of the circuit were also reduced (see Fig. 4*b*). The two independent sources have uncorrelated noise and it is not possible to obtain perfect noise elimination of the first current source by the second one, but it allows obtaining significant noise reduction. For example, the total current noise of CS1 source (±99 µA$_{RMS}$) for I_{OUT} = 1 A was reduced to ±9.5 µA$_{RMS}$ by the CS2 current source (second stage). Noise reduction is mainly observed at the lower-frequency range, where passive filtering is rather troublesome and ineffective.

The two current source configuration requires a double set-point current sub-circuits. In the CS1 and CS2 sources the current set-points are realised by potentiometers PR1 and PR2, respectively. For a non-fixed current source applications, the

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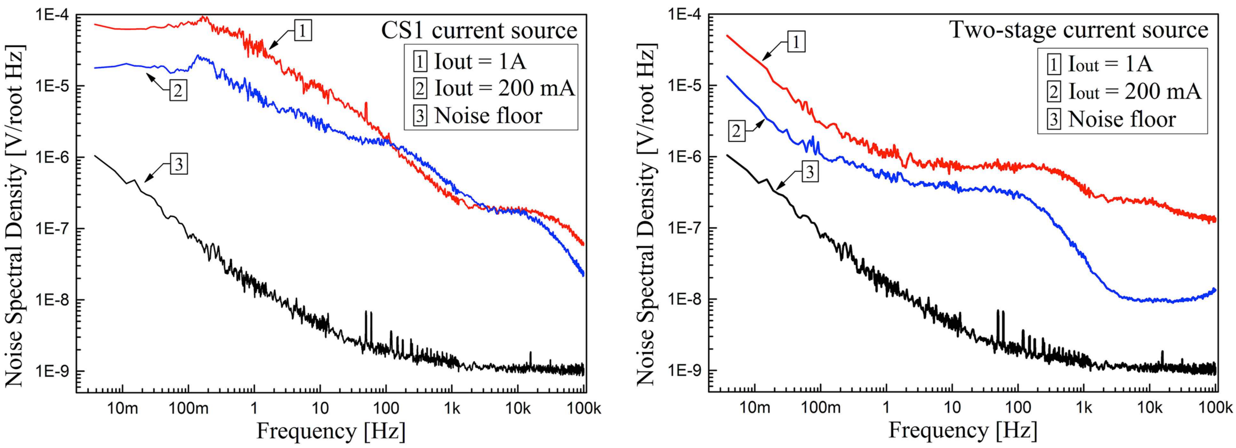

Fig. 4 *Voltage noise spectral density comparison for two different output operating currents*
(a) Single CS1 current source *operation*, ***(b)*** With the second stage of adjusting CS2 current source is turned on

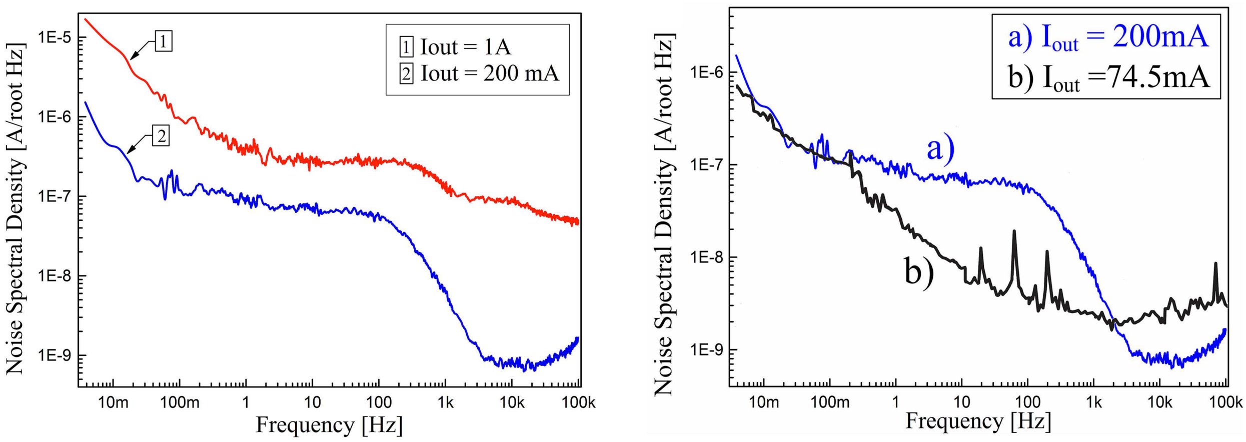

Fig. 5 *Current noise spectral density measurements*
(a) Obtained noise densities of two-stage current source, ***(b)*** Data from [11] is shown (trace b) and it is compared with result obtained for 200 mA of output current (trace a). The Erickson's current driver [13] provides equivalent current noise around 2 nA/√Hz at 74.5 mA, while presented two-stage source offers 1.2 nA/√Hz for almost three times higher operating current (equivalent current noise values were numerically calculated based on the noise spectral density data traces)

presented circuit seems to be troublesome, because the CS1 and CS2 current set-points have to be detuned simultaneously, while maintaining the relationship between the currents I_{S1} and I_{S2} ($I_{S2} \ll I_{S1}$ and $I_{OUT} = I_{S1} + I_{S2}$). This inconvenience can be easily eliminated by replacing potentiometers by two digital-to-analogue converters (DACs) or one DAC with an op-amp providing adequate gain and scaled set-point voltage for one of the current sources. Using a precise and low temperature coefficient DAC rather than potentiometer yields much better accuracy, repeatability and reduces noise and drift of current source [12, 13]. However, a practical implementation of DAC-based set-point circuit is not the main subject of this paper.

3 Results

To characterise the proposed current source noise properties, a series of noise spectral density measurements were performed. It was used the Standford fast Fourier transform spectrum analyser SR760. The measured signal was taken from the output of amplifier based on U4 op-amp, because a very small 0.5 Ω R_{SENSE} value produces lower voltage drop and consequently decreases a gap to the noise floor (detection limit). The intrinsic noise of spectrum analyser, op-amp amplifier and its gain value were taken into account in calculation of the final output current noise density characteristics, which are presented in Fig. 5. On the basis of current noise density characteristics, a total RMS current noise in a 0.01 Hz–100 kHz bandwidth were designated. It was achieved by calculating the integral of the current noise spectrum density in frequency domain (integration limits from 0.01 Hz to 100 kHz) and dividing by the square root of the bandwidth, whereas an equivalent current noise was calculated by dividing the RMS current noise by square root of the bandwidth. For an operating current of 1 A, it was obtained an equivalent current noise of 60 nA/√Hz which corresponds to ±9.5 ppm. The rest of results are shown in Table 1. The short-term (1 h) current stability for a three different output current values was measured with precise True-RMS FLUKE 289 multimeter. Data from multimeter were collected by means of self-prepared LabView application via FLUKE opto-coupled Universal Serial Bus (USB) interface. The obtained results are shown in Fig. 6*a* and presented in Table 1. The equivalent current noise is calculated for frequency bandwidth from 100 Hz to 100 kHz.

Fig. 6*b* presents a long-term current drift. The measurement was performed only for 1 A of output current and, as expected, the current drift and temperature are strongly correlated. On the basis of the obtained data, the temperature coefficient of 2.8 ppm/°C was determined. This result coincides with independent measurement obtained within the thermal-controlled VO200cool oven from MEMMERT and it was achieved of 2.6 ppm/°C.

4 Conclusion

The presented two-stage current source configuration is an original concept for laser diode driving applications, where the range of output operating current was increased up to 1 A, while maintaining excellent noise performance, long-term stability and temperature coefficient. According to the main idea, the implementation of the second stage adjusting current source

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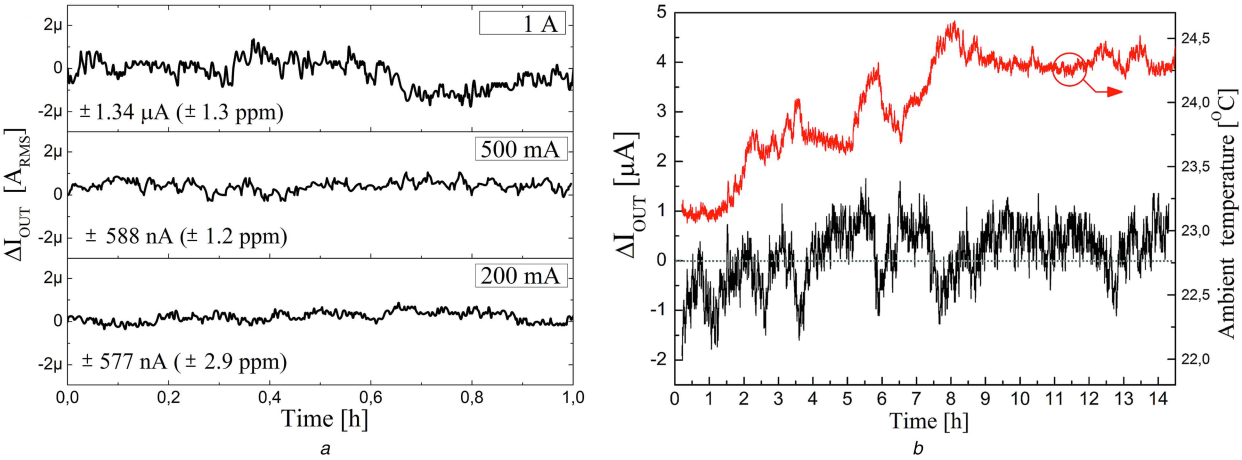

Fig. 6 *Output current stability measurements*

(a) Short-term (1 h) stability for a three different operating output currents, ***(b)*** Long-term drift of output current and ambient temperature (upper trace) as a function of time (obtained for 1 A of current)

Table 1 Two-stage current source parameters

I_{OUT}, A	Current noise density (f = 1 kHz), nA/√Hz	Equivalent current noise, nA/√Hz	Total current noise, ppm	Current stability (1 h), ppm	Current drift (14 h), ppm	Temperature coefficient, ppm/°C
0.2	6.4	1.2	±1	±2.9	—	—
0.5	65	7.3	±2.4	±1.2	—	—
1	126	60	±9.5	±1.3	±2.1	2.8

improves current noise reduction of the first source. The use of Surface-Mount Device components allowed to decrease a Printed Circuit Board dimensions up to 1×1.2 in^2. The first concept of presented current source was developed as a part of European Space Agency project and practically implemented in the single-frequency, miniature, fully integrated DPSS laser [23–25] (achieved frequency stability of 3×10^{-9} at 1 s). The two-stage source concept is still being upgraded in order to further improve its parameters, for example, by implementing additional modulation sub-circuit and digital controlled set-point module.

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