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Precision temperature controller for scientific research

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Abstract: A precision temperature controller was developed for scientific research with a resolution and temperature control accuracy of 0.001 K based on 24-bit LT2400 ADC and 16-bit LT1655 DAC from Linear Technology. Galvanic isolation of the analog part from the digital is based on ADuM1401 digital isolators. Information exchange control and digital RS-232/USB interface are built using a PIC16F84 microcontroller based on an FTDI232 converter. The parameters of this regulator were verified by studying the temperature dependence of dielectric permittivity in the neighborhood of the first-order phase transition in $Sn_2P_2Se_6$ crystals and showed exceptional stability without overshooting.

Keywords: Temperature controller, PID algorithm, Microcontroller, ADC, DAC, Digital isolator;

Precyzyjny regulator temperatury do zastosowań naukowych

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Streszczenie: Opracowano precyzyjny regulator temperatury do badań naukowych o rozdzielczości i dokładności regulacji temperatury 0,002 K oparty na 24-bitowym przetworniku ADC LT2400 i 16-bitowym przetworniku DAC LT1655 firmy Linear Technology. Izolacja galwaniczna części analogowej od cyfrowej oparta jest na izolatorach cyfrowych ADuM1401. Do sterowania wymianą informacji i cyfrowego interfejsu RS-232/USB wykorzystano mikrokontroler PIC16F84 oparty na konwerterze FTDI232. Parametry tego regulatora zostały zweryfikowane poprzez badanie zależności temperaturowej przenikalności dielektrycznej w pobliżu przejścia fazowego pierwszego rzędu w kryształach $Sn_2P_2Se_6$ i wykazały wyjątkową stabilność bez przeregulowania..

Słowa kluczowe: Regulator temperatury, Algorytm PID, Mikrokontroler, ADC, DAC, Izolator cyfrowy;

1. Introduction

When conducting research near phase transitions, a narrow temperature range (~0.1-0.5K) is of particular interest, in which relaxation phenomena and critical behavior of parameters due to system non-equilibrium are observed. Caused by the limited temperature range of the observed phenomena, there are increased requirements for the algorithm and the temperature change and stabilization system, which should provide an accuracy of about 0.01÷0.001K without "overregulation." The latter requirement means choosing the parameters of the automatic control law so that the system does not go through a phase transition when approaching the set point and directly during the temperature stabilization process. It is also necessary to consider the significant dependence of physical parameters (dielectric constant ε*, electrical conductivity σ, etc.) on the temperature change rate, especially in semiconductor materials [1].

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Most of the temperature controllers used in experimental practice [2] do not meet these requirements, so developing non-standard equipment to study critical phenomena in ferroelectric semiconductors is necessary.

2. Evaluation of temperature control system parameters

The main requirements that must be met by temperature measurement and control subsystems when studying phase transitions and critical phenomena are as follows

- operating range 80 - 480 K
- accuracy, r ± 0.001 K

Based on the above conditions, we can determine the main parameters of the measuring system's analog-to-digital converter (ADC). The dynamic range $D = (T_{max}-T_{min}) / r = 4 \times 10^5$ corresponds to an ADC with several bits greater than 2^{19}. Because the industry produces only 18, 20, 24, and 32-bit instrumental ADCs, considering the noise of the preamplifier and the ADC itself, the 24-bit analog-to-digital converter will best meet the requirements.

The voltage drops across the primary converter (platinum RT100 thermistor) (Figure 1) connected to a measuring circuit with a current of ~250 μA is, on average, U_{1K} = 100 μV per Kelvin (excluding nonlinearity). The current in the thermistor circuit is limited by the phenomenon of self-heating (in our case, ~10^{-4}K).

The maximum output signal from the PT100 is $U_{480K} = I \times R_{480K} \approx 44$ mV. This value is much lower than the upper limit of the ADC input voltage (U_{max} = 5 V). Therefore, to compensate for noise and increase the measurement accuracy, we can amplify U_{480K} by $K = U_{max} / U_{480K} \approx 114$ times. Thus, after scaling, the ADC input signal will be 11.4 mV/K. When using a 24-bit analog-to-digital converter, we get the lowest bit unit, in terms of temperature, of $2.8{\cdot}10^{-5}$ K, much less than *r*. However, considering the noise of the input amplifier, its temperature drift, and the noise of the ADC itself, the designed system must meet the requirements with a margin.

To control the temperature with an accuracy of 0.001K, changing it with the same accuracy (or better) is necessary. The amount of current that will change the temperature of the crystal holder by ΔT can be estimated by the formula:

$$I = \sqrt{\frac{c \cdot m \cdot \Delta T}{R \cdot t}} \qquad (1)$$

where *c* is the specific heat capacity (J/kg·K), *m* is the mass (kg), *ΔT* is the temperature change (K), *R* is the heater resistance (Ω), and *t* is the time (s).

If the speed of the digital-to-analog converter (DAC), which sets the current through the heater, is 0.1 s, the crystal holder weighing 0.04 kg is made of copper (*c* = 0.385 kJ/kg·K), and the heater resistance is 30 Ω, then a current of 72 mA must flow through the heater to change the temperature by 0.001 K.

To prevent the system from overheating above 480 K, the maximum output current of the amplifier that sets the heater power is limited to 1A. If the bit depth of the control DAC is 16, then a unit of its lowest bit corresponds to a current of $1A/2^{16} = 15\mu A$. This means that 16 bits of the DAC are enough with a significant margin. This situation can be explained by the fact that the amount of heat on the heater is a function of time. Accordingly, the temperature control system partially operates on the principle of pulse width modulation. The redundancy of the DAC bits is not necessary for stabilization but for a linear temperature change with a tiny step.

3. Description of the experimental scheme

A simplified diagram of the thermostat is shown in Figure 1. The input signal from the primary converter is fed to the scaling amplifier A1, from where it is fed to the input of the analog-to-digital converter. The resulting digital code corresponds to the amplified voltage drop across the PT100. A table method is used to convert it to temperature. A graduation table of R→T correspondence is stored in the computer memory with a step of 1 K. Temperature values falling in the interval between two points of the table are determined by interpolation using a spline passing through ten neighboring points of the graduation table (five points above and five points below the interval). The resulting T value is compared to the required stabilization temperature, and the power of the heater needed is determined using a standard proportional integral-differential (PID) algorithm. The code corresponding to the set power is sent to the RS-232/USB bus via the digital-to-analog converter. The voltage from the DAC is fed to the input of a power amplifier (in our case, a current amplifier) and then to the heater.

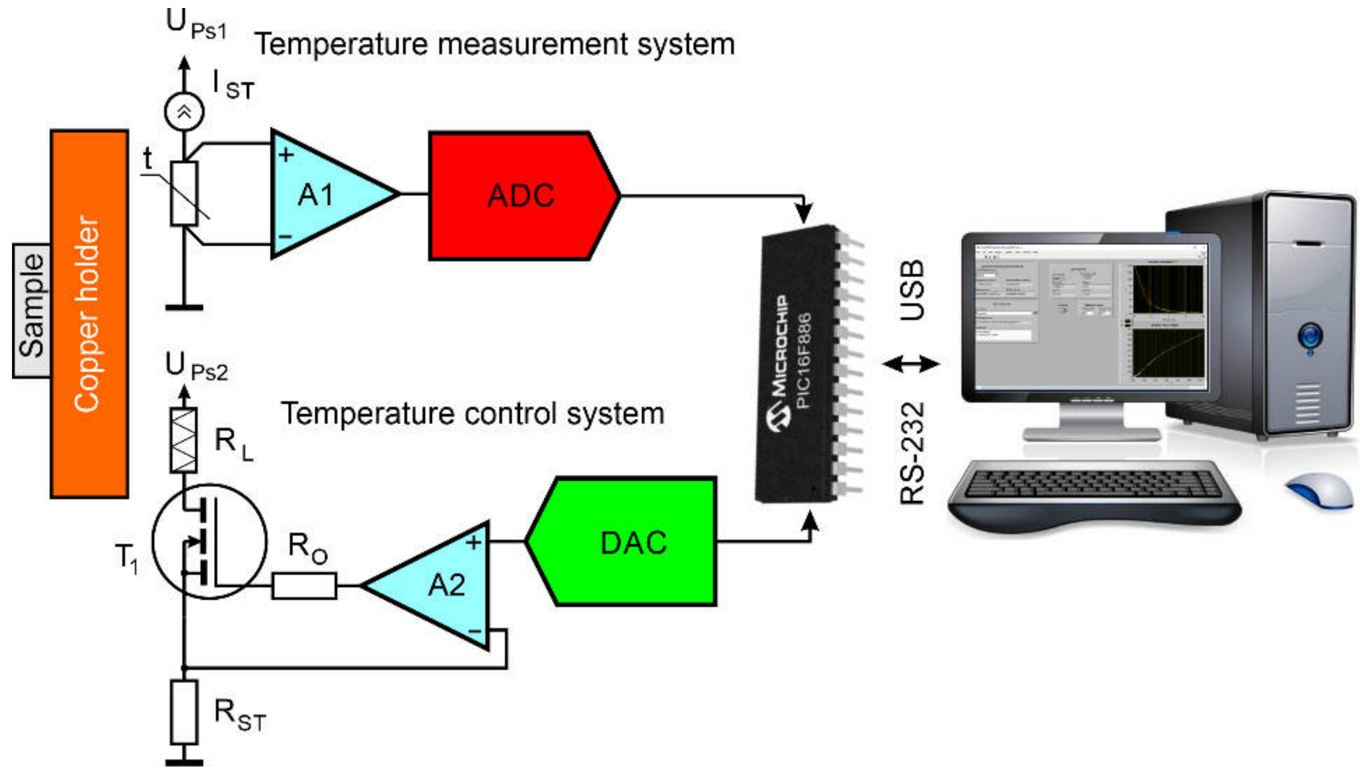

Figure 1. Block diagram of the temperature controller

The schematic diagram of the device is shown in Figure 2. As mentioned above, a platinum thermistor PT100/1509A manufactured by TDI Ltd. (England) [3] is used as a temperature sensor. Its diameter is 0.9 mm, length is 10 mm, time constant is 0.01 s, and the body is beryllium ceramic. The current in the thermistor circuit is set using two series-connected precision resistors, R31 and R32, with a resistance of 9.09 kΩ. To power this part of the circuit, a precision reference voltage source MAX6250 is used, which ensures that the instability of the R→U conversion system is less than one unit of the lowest bit of the analog-to-digital converter (ADC).

The PT100 sensor (as shown in Figure 2) is connected by a four-wire circuit, which reduces the influence of the resistance of the connecting wires on the measurement accuracy. A voltage proportional to the temperature is supplied to a DC amplifier based on the LT1028 ultra-low-noise precision operational amplifier.

The gain of this stage is 114. The operational amplifier (OA) feedback loop includes a frequency-dependent circuit R33 C7, which limits the bandwidth and reduces the amount of noise at the output. The amplified signal from the LT1028 output is fed through the resistor R34 to the Linear Technology LT2400 ADC input. The resistor R34 and capacitors C8 and C12 form a low-pass filter and further reduce the influence of the input stage noise. As a source of the ADC reference voltage, the supply voltage of the input converter (which sets the current in the PT100 circuit) is used, which reduces its influence on measurement accuracy.

The digital code corresponding to the measured temperature is transmitted through galvanically isolated circuits to the PIC16F84 single-chip microcontroller, which controls the ADC operation and sends the results via the standard RS-232 interface (or via the FTDI232 converter through USB) to an IBM PC-compatible computer for further processing. The galvanic isolation is built using the ADuM1401 four-channel integrated digital isolator chip from Analog Devices, which significantly reduces noise and interference generated by the “digital part” of the measuring system (microcontroller, MAX232 level converter, USB interface, and the IBM PC itself). Compared to optocouplers, widely used in similar circuits, digital isolators require much less current, are faster, and generate less interference.

The temperature control channel is based on a 16-bit LT1655 digital-to-analog converter (DAC) from Linear Technology. The main advantage of this instrumented DAC is that it contains a precision reference voltage source (which greatly simplifies the circuit) and operates via a serial digital interface (which reduces the complexity of galvanic isolation).

The code corresponding to the required heater power is transmitted from the control computer via RS232 (or USB) to the PIC16F84 microcontroller, which sends it via the SPI interface to the LTC1655 DAC through the galvanic isolation circuits. The voltage corresponding to this code (the range of 0÷5V) is supplied to a dual operational amplifier (OPA) OP213 from Analog Devices.

One of the op amps of this circuit operates in the voltage repeater mode and reduces the influence of subsequent circuits on the DAC accuracy. The second op-amp of the OP213 chip is used in the current source circuit, which sets the current I_P in the heater circuit. A powerful field-effect transistor with an insulated gate is used as a power element, significantly reducing the op-amp load. The voltage corresponding to the current in the heater circuit is obtained from the powerful low-resistance resistor R39, connected in series with the heater and the transistor and fed into the current source feedback circuit.

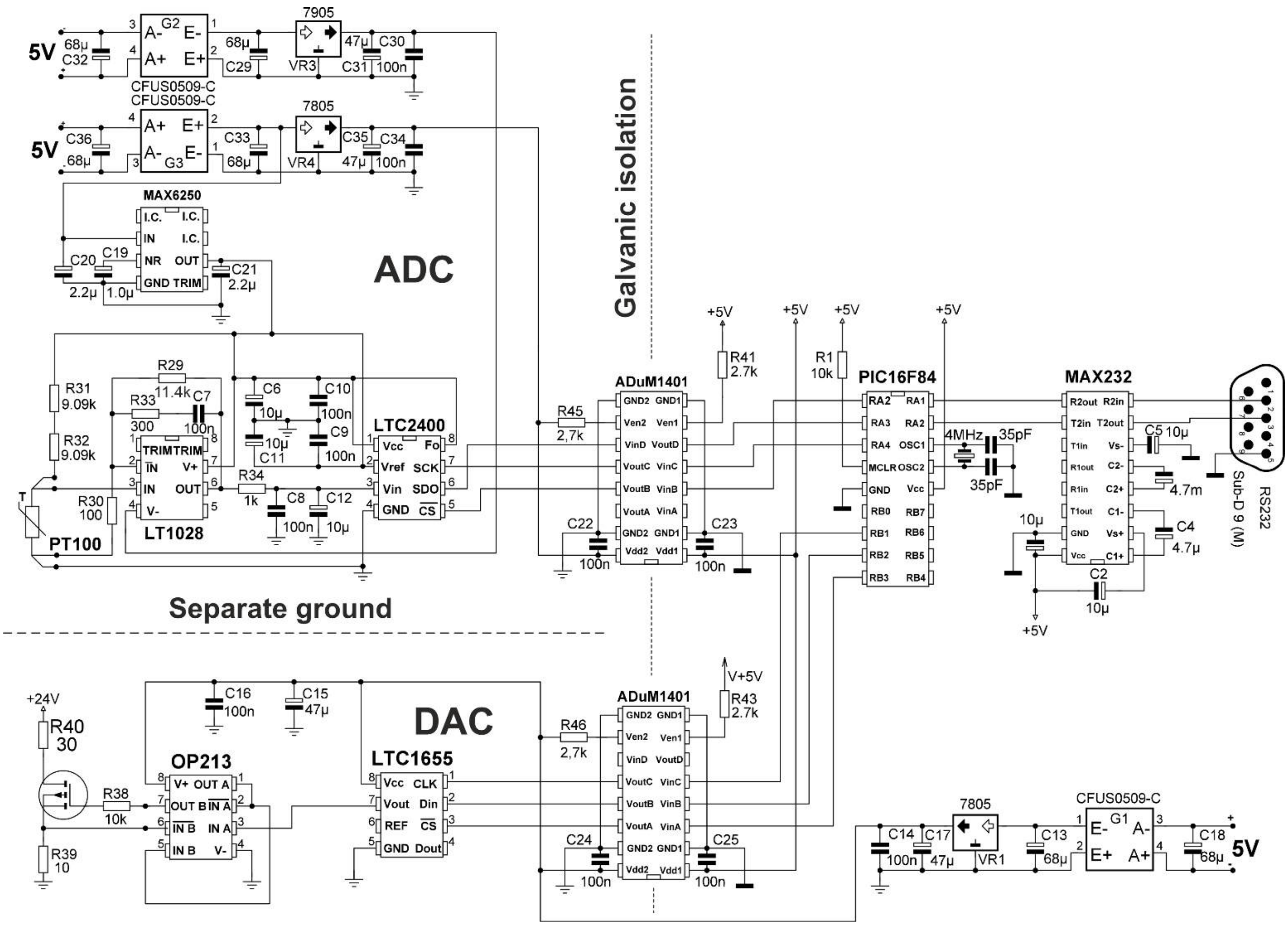

Figure 2. Circuit diagram of the temperature controller.

The use of a current source as a power unit in the heater power control circuit compared to a voltage amplifier allows you to:

- significantly simplifies the circuit
- increases the reliability of the system;
- eliminates short-circuit protection and overheating of power elements.

4. Temperature control algorithm

A PID controller was implemented in the LabView environment to stabilize the temperature.

A PID controller [4] is a device in the control loop of an automatic feedback control system that generates a control signal that is the sum of three terms. The first one is proportional to the difference between the input signal and the feedback signal (mismatch signal), the second one is the time integral of the mismatch signal, and the third one is the time derivative of the mismatch signal. The PID controller implements the control law:

$$Y(t) = K_P x(t) + \frac{1}{\tau_I}\int_0^t x(t)dt + \tau_D \frac{dx(t)}{dt} \quad (2)$$

where Y is the output signal (e.g., heater power), x is the input mismatch parameter $x = (T_{Current} - T_{Stab})$, and K_P is the object's transfer coefficient, the τ_I integration constant, and τ_D the differentiation constant. Sometimes, the so-called parallel form of the PID law is used:

$$Y(t) = K_P x(t) + K_I \int_0^t x(t)dt + K_D \frac{dx(t)}{dt}; \quad K_I = \frac{K_P}{\tau_I}; \quad K_D = K_P \cdot \tau_D \tag{3}$$

In some cases, the proportional, integral, or differential components may be absent, and these simplified controllers are called I-, P-, PD-, or PI controllers.

The components of this equation have maximum influence each in its own time or frequency domain. The integral component is the lowest-frequency component, responsible for long-term processes in the control loop. The proportional component has the most significant influence in the medium-time domain. The differential component is the highest-frequency component, responsible for fast transients in the automatic control system.

It should be noted that:

1. The I-controller can be used only to automate objects with significant self-leveling; P-, PI-, and PID-controllers can be used to automate objects with and without self-leveling.
2. I-, PI-, and PID controllers provide control without static error (static error does not exceed the controller's insensitivity zone). When controlling with a P-controller, a static error is possible.
3. The dynamic error (maximum deviation of the controlled value) is most significant when using an I controller and significantly reduces in the case of P- and PI controllers. The dynamic error of the PID controller is even more minor.
4. Using P and PID controllers provides the minimum control time. Using a PI controller leads to a significant (up to 2 times) increase in the control time. The I-regulator offers an even longer (often unacceptable) control time.
5. For the most common systems, PI controllers are recommended. The PID controller is recommended for use in cases where the PI controller cannot meet the requirements for quality of control.

Experimentally, we have found that the most optimal controller to prevent "over-regulation" is the proportional-integral (PI) controller.

5. Results of experimental testing

The described system for measuring, changing, and stabilizing temperature was used to study the cooling rate's effect on the dielectric constant's dependence on temperature in crystals with a phase transition. As shown in Figure 3 (a). the controller provides almost perfect linearity of temperature change, even at ultra-low speeds (~ 0.002 K/min). It is also interesting to note the data indicating a nearly complete absence of phase transition blurring at the temperature of first-order Tc in $Sn_2P_2Se_6$ crystals (Figure 3(b)) [5].

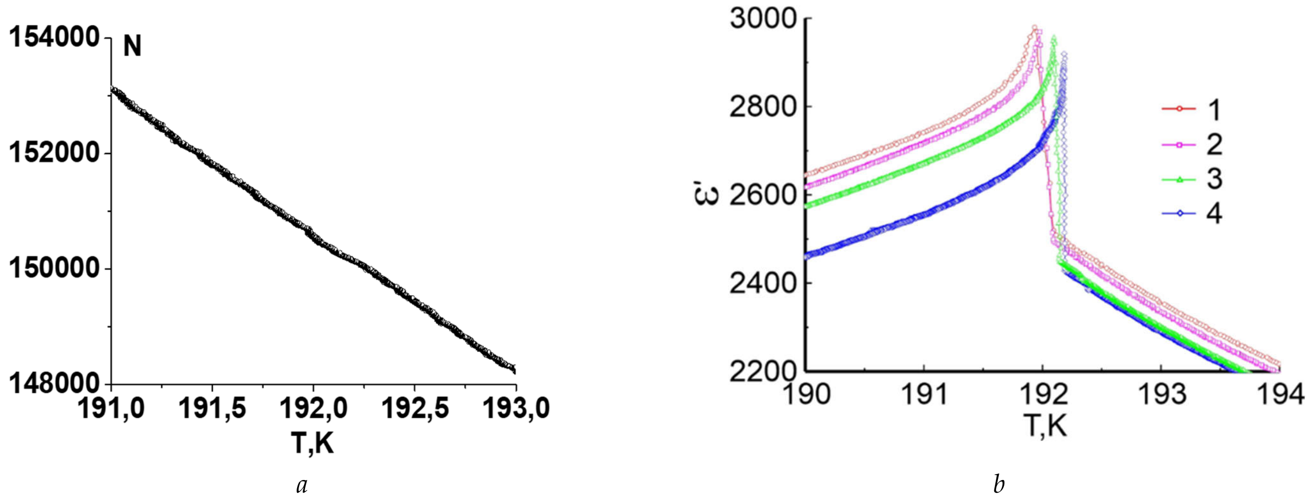

Figure 3. Linearity of temperature change (a) and precision of temperature stabilization at ultralow cooling rate. (1) 0.5 K/min, (2) 0.1 K/min, (3) 0.05 K/min and (4) 0.005 K/min.

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