PERIODICA POLYTECHNICA SER. EL. ENG. VOL. 37, NO. 1, PP. 31–42 (1993)

THEORETICAL ANALYSIS OF THERMISTOR TRIMMING

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Abstract

The application of thick film thermistors has been increased during the last decade. In order to achieve high sensing accuracy the thermistors should be trimmed. The error sources were thoroughly analyzed: the effects of the inaccuracies of the ambient temperature, the temperature measurement, the heat transients caused by the laser pulses, and the resistance measurement were discovered and examined. It was pointed out that the specific requirements can be fulfilled only by keeping the thermistor on its working temperature during trimming. If an on-line correction according to the in-situ measured temperature of the thermistor under trimming is applied, even the error caused by the ambient temperature can be eliminated. The requirements of a laser system suitable for thermistor trimming have also been outlined.

Keywords: thermistor; laser trimming; error analysis; resistance measurement.

1. Introduction

Thermistors (thermally sensitive resistors) are produced with positive (PTC) or negative (NTC) temperature coefficient. Their application and, in particular, the application of thick film type thermistors with positive temperature coefficient, has been increased during the past couple of years (HARSÁNYI, 1991). It is in close connection with spreading of household electronics, since one of the main fields of their application is the protection of household electronic appliances.

The application of a thermistor as sensing element can be as follows:

- temperature control,
- temperature compensation,
- over temperature protection,
- current overload protection (e.g. in electric motors),
- current control,
- sensing of liquid level, fluid flow, gas flow, pressure, humidity, etc. in different measuring systems,

- time delay in an electronic circuit or in a relay,
- speech level and bell ringing tone control in telephone technique, etc.

Because of the self regulating characteristic of PTC thermistors, their further consumption can be as heating elements in household and industrial instruments.

As a great variety of these applications are combined with hybrid circuits, the necessity has been risen to produce thermistors by thick film technology on ceramic substrates.

In order to increase the sensing accuracy, thermistors are usually trimmed. There are a lot of well-known physical and chemical processes for film resistor trimming. The most commonly used physical methods change the geometric length/width ratio of the resistors. It means that insulating cuts are machined into the resistive film in order to increase the current path and thus the resistance. Cuts can be engraved by different ways (sand blasting, electro-erosion, etc.). The most effective method, however, is laser cutting due to the high quality of the cut and the extremely high speed of processing.

The optimum tracing of the laser trimming cuts has been investigated and determined for thermistors by PAPP (1992 and 1993).

A laser trimming system has been developed for film resistors with high positive or negative temperature coefficient (BECSEK, 1991). The system trims the thermistors on their working temperature provided by a heated sample-holder plate. This table is heated by a copper wire meander, the temperature is measured by platinum sensors and regulated by an electronic controller.

The errors caused by the inaccuracies of the table temperature, the temperature regulation and measurement, the heat transients caused by the laser pulses, and the resistance measurement were analyzed and are discussed in the following part of the present paper. On the basis of the analysis conclusions will be drawn how to improve the accuracy of thermistor trimming.

2. Error Analysis of Thermistor Trimming

In comparison with resistor trimming, in the course of thermistor trimming additional problems have to be solved, since the temperature coefficient of thermistors is two orders higher, than that of resistors. For this reason the resistance of thermistors is highly influenced by the ambient temperature. Furthermore, thermistors should perform their resistance on the working temperature, which is usually different from the room temperature.

The different error sources of thermistor trimming are as follows:

- the inaccuracy of the table temperature, including the errors of the temperature measurement and regulation,
- the deviation of the temperature coefficient of the thermistor from the nominal value,
- the heat transient on the resistor caused by the laser pulses,
- the error of the resistance measurement,
- the geometric inaccuracies of the trimming cuts.

The first two of these error sources are in connection with the changing temperature, so they are treated jointly.

The inaccuracy of the table temperature is determined by the regulation of the table heating and by the error of the temperature sensor used for the regulation or for the measurement of the real temperature. On the other hand, the deviation of the temperature coefficient comes from the inhomogeneity of the composition of the resistor paste and from the spread of the manufacturing processes (screen-printing, firing, etc.).

On the basis of the simple equation of the temperature dependence of the resistance, the effects of these error sources on the accuracy of the thermistor can be calculated:

$$R'_t = R_w[1 + \alpha(t_t - t_w)], \tag{1}$$

$$R_t = R_w[1 + (\alpha + \Delta\alpha)(t_t + \Delta t_t - t_w)], \tag{2}$$

where

t_w = working temperature,

t_t = table temperature,

Δt_t = error of the table temperature,

R_w = resistance at the working temperature,

R_t = real resistance at the table temperature,

R'_t = required resistance at the table temperature,

α = temperature coefficient of the resistance,

$\Delta\alpha$ = error of the temperature coefficient.

The error of the resistance of the thermistor at the table temperature is:

$$\Delta R_t = R'_t - R_t\ . \tag{3}$$

Applying *Eq.* (2), the error at the working temperature ($\Delta R_{w;(t,\alpha)}$) can be calculated from ΔR_t:

$$\Delta R_{w;(t,\alpha)} = \frac{\Delta R_t}{1 + (\alpha + \Delta\alpha)(t_t + \Delta t_t - t_w)} \tag{4}$$

and the relative error is obtained:

$$\frac{\Delta R_{w;(t,\alpha)}}{R_w} = \frac{-\alpha\Delta t_t - \Delta\alpha(t_t + \Delta t_t - t_w)}{1 + (\alpha + \Delta\alpha)(t_t + \Delta t_t - t_w)} \ . \tag{5}$$

The subscripts t and α refer to the origin of the errors. If the errors are separated according to their origin, the following formulas occur:

$$\frac{\Delta R_{w;(t)}}{R_w} = \frac{-\alpha \cdot \Delta t_t}{1 + \alpha(t_t + \Delta t_t - t_w)} \ , \tag{6}$$

$$\frac{\Delta R_{w;(\alpha)}}{R_w} = \frac{-\Delta\alpha(t_t - t_w)}{1 + (\alpha + \Delta\alpha)(t_t - t_w)} \ . \tag{7}$$

If the temperature related errors are small ($\Delta t_t \ll t_t$ and $\Delta\alpha \ll \alpha$) and the table temperature is not far from the working temperature (consequently $\alpha(t_t - t_w) \ll 1$), the denominator of the previous three equations is near to 1, and the following approximate formulas can be obtained:

$$\Delta R_{w;(t,\alpha)}/R_w \cong -\alpha \cdot \Delta t_t - \Delta\alpha(t_t - t_w) \ , \tag{5a}$$

$$\Delta R_{w;(t)}/R_w \cong -\alpha \cdot \Delta t_t \ , \tag{6a}$$

$$\Delta R_{w;(\alpha)} \cong -\Delta\alpha(t_t - t_w) \ . \tag{7a}$$

The negative signs in the formulas refer to the opposite effect of the deviations: if, for example, the table temperature is higher than its nominal value and the temperature coefficient is positive (i.e. a PTC thermistor is trimmed), the trimming process provides the nominal resistance on this higher temperature, that results in a negative deviation of the resistance on the exact working temperature. It is also apparent from *Eq.* (5a), that the worst case occurs when the signs of the temperature coefficient (α) and its deviation ($\Delta\alpha$) are the same.

In the following paragraphs the effects of the different temperature related error sources and their relationship are illustrated by examples (*Fig. 1*). In all cases the calculated errors refer to the working temperature, and the subscripts in the place of w and t are the serial numbers of the examples. The temperature coefficient of a thick film PTC thermistor is in the range of $1500 \ldots 4000 \cdot 10^{-6}\mathrm{K}^{-1}$ with $\Delta\alpha/\alpha$ relative deviation of $\pm 0.02 \ldots 0.05$ ($\pm 2 \ldots 5$ %), and the t_t working temperature usually equals $40 \ldots 200$ °C. In the examples $\alpha = 1500 \cdot 10^{-6}\mathrm{K}^{-1}$, $\Delta\alpha/\alpha = \pm 0.03$ and $t_w = 80$ °C typical values are used.

In the first example the trimming process is carried out on room temperature ($t_t = t_{\mathrm{room}}$). The difference between the table temperature

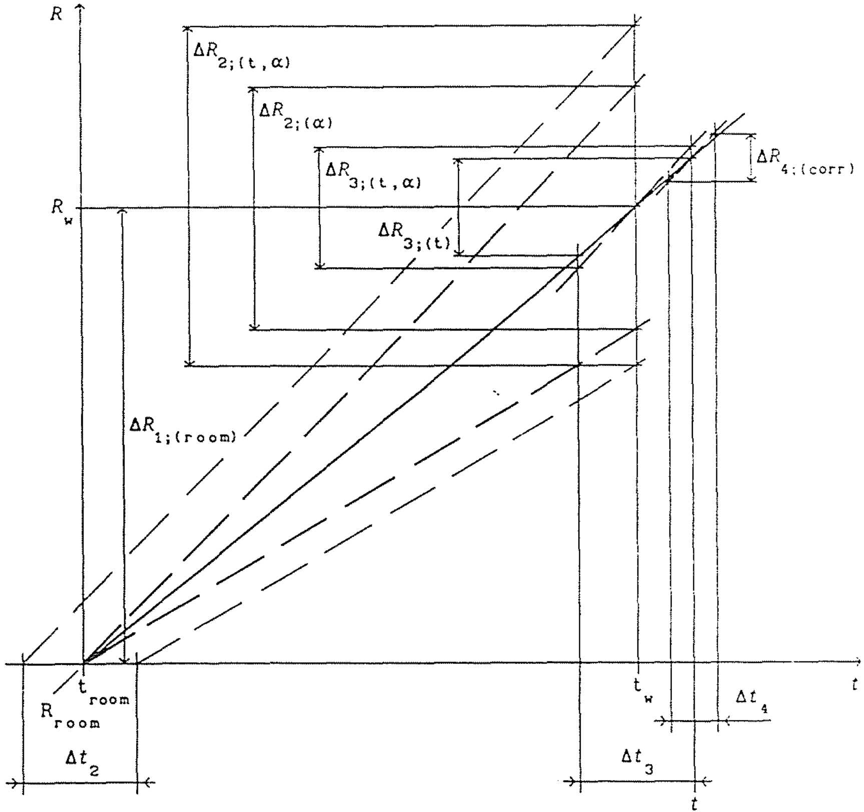

Fig. 1. Temperature related error sources of thermistor trimming

during trimming and the working temperature of the thermistor ($t_{\text{room}} - t_w$) causes, in accordance with *Eq.* (1), a very high deviation ($\Delta R_{1;\text{room}}$ in *Fig. 1*). For instance, if $t_{\text{room}} = 20$ °C, the resulting deviation is -0.09 (i.e. -9 %). As a consequence, it is advisable to apply a correction according to the difference of the table and the working temperatures or/and keep the table on the working temperature .

In the second example a simple correction is applied. The trimming is still carried out on room temperature, but the required resistance is corrected in accordance with the nominal value of the temperature coefficient. If the error of the table temperature is neglected, *Eq.* (7a) can be used for the calculation. With $t_{\text{room}} = 20$ °C and with the typical values $\Delta\alpha = \pm 45 \cdot 10^{-6} \text{K}^{-1}$ occurs, and the error, purely caused by the deviation of the temperature coefficient, $\Delta R_{2;(\alpha)}/R_w$ equals ∓ 0.0027 (∓ 0.27 %) Applying *Eq.* (5a), the effect of the deviation of the room temperature with a typical value of $\Delta t_2 = \pm 1$ °C (choosing from the usual $\Delta t_t = \pm 1 \ldots 2$ °C) can also be taken into consideration and $\Delta R_{2;(t,\alpha)}/R_w = \pm 0.0042$ (± 0.42 %) occurs. (In order to obtain the worst case, $\Delta\alpha$ and Δt_t were paired with their opposite signs.)

In the third case a heated and temperature controlled table is used. The error of the table temperature is $\Delta t_t = \pm 1 \ldots 2$ °C, caused by the inaccuracies of the sensor and the regulation. With the typical value of $\Delta t_3 = \pm 1$ °C the error, purely caused by the deviation of the table temperature, $\Delta R_{3;(t)}/R_w \cong \mp 0.0015$ (∓ 0.15 %) is calculated from *Eq.* (6a). Using *Eq.* (5a), both effects can be taken into consideration, and $\Delta R_{3;(t,\alpha)}/R_w \cong \mp 0.001545$ (∓ 0.1545 %) is obtained. (For the worst case, $\Delta\alpha$ always with the sign of α should be substituted.)

The last example demonstrates how the inaccuracy of the regulation can be decreased by a correction according to the real temperature of the table, or, even better, according to the measured temperature of the thermistor under trimming. For this purpose some kind of precise infrared temperature sensor (e.g. semiconductor or pyroelectric type) can be used. In this example the previous typical values and the inaccuracy of the temperature measurement $\Delta t_4 = \pm 0.2$ °C are used. If before or during the trimming process the required resistance is calculated and corrected by the controlling computer, an error as small as $\Delta R_{4;(\mathrm{corr})}/R_w \cong \mp 0.000345$ (∓ 0.0345 %) can be achieved (from *Eq.* (5a)).

The successful decrease of the effects of the first two error sources highlights the importance of the other three problems, especially that of the determination of the requirements of the resistance meter. Although the accuracy requirement and the range come from the application of thick film thermistors, the magnitude of the prescribed accuracy should be compatible with the deviations caused by the other error sources.

On the other hand, the time requirement is in close connection with the repetition rate of the Q-switched laser pulses. If the repetition rate is fixed at 4 kHz (which is the best compromise between the increasing average power of the laser beam and the decreasing energy of the individual pulses), then the time interval between two laser pulses is 250 μs. This time interval should be sufficient for the relaxation of the film and for the precise measurement of the resistance. The relaxation time is necessary to eliminate the error of the heat transient on the thermistor caused by a laser pulse. The reason of the heat transient is that only some part of the energy of each laser pulse heats up and removes away material from the exposed spot, the remaining part of the energy, however, warms the resistive film outside the spot and causes a disturbing change of the resistance. The change can be significant because of the high temperature coefficient of the thermistor. The resistance must not be measured till the heat transient falls down.

The time interval necessary for the relaxation was determined experimentally (*Fig. 2*). Thick film thermistors with 3 mm length and 1.5 mm width were exposed to Nd:YAG laser pulses with equal pulse energies but with different focal spot sizes, and the change of the resistance was recorded by oscilloscope. Large spot sizes produced reversible high peak heat transients, but when the spot size was smaller (0.1 mm $\leq d_{\text{spot}} \leq$ 0.25 mm), only a small peak preceded the irreversible change caused by material removal from the exposed spot. Under 0.1 mm no heat transient was observed and smaller irreversible change occurred because of the smaller insulating spot. In the upward slope of the resistance a time constant of about 50 μs was found. Since under real trimming conditions the disturbing effect of the heat transient is even smaller, it was concluded, that $2 \ldots 3 \times 50$ μs interval before the measurement was sufficient.

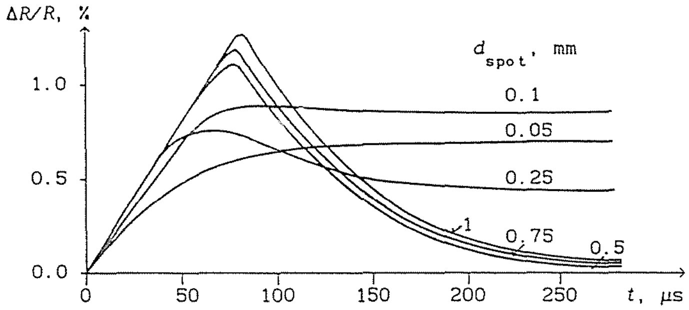

Fig. 2. Heat transients on thermistors

As a result, the requirements of the resistance meter are as follows:

- range: 4 Ω – 1 MΩ,
- accuracy: ± 0.15 %,
- response time: $150 \ldots 250$ μs,
- the instrument should be used for the measurement of unknown resistance and for resistor trimming, as well.

The block scheme of the resistance meter is shown in *Fig. 3*. The working principle can be described with respect to operating modes, as follows.

In case of the measurement of an unknown resistor the measuring principle can be understood starting from the V_{ref} reference voltage unit. The n bit D/A (Digital to Analog) converter attenuates V_{ref} according to the D numerical value given by the computer. The numerical value on the input of the D/A converter is maximum $D_{\max} = 2^n - 1$, and the corre-

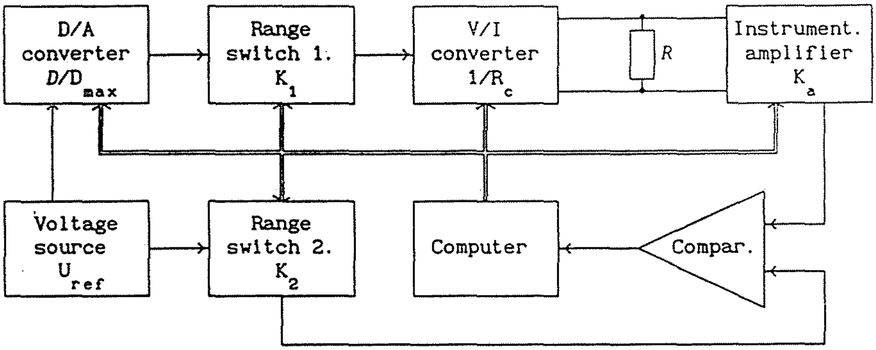

Fig. 3. The block scheme of the resistance meter

sponding output voltage is V_{ref} . Range switch 1. can attenuate this value by a scaling factor of K_1. From this voltage the V/I (Voltage to Current) converter with the transfer factor of $1/R_c$ produces the measuring current (with the maximum value of $I_{\max}$), which flows through the unknown R resistance. The V_x voltage drop on R is transferred by the instrumentation amplifier (with the gain of K_a) to the input of the comparator, where it is compared to K_2V_{ref}. In accordance with the result of the comparison, the computer selects the correct range and searches the numerical value (D) which corresponds to the unknown R. The algorithm sets the range switches (K_1, $1/R_c$, K_a and K_2) scanning towards the lowest range, and finds the numerical value applying successive approximation.

In the trimming mode the factors of the range switches and the numerical value corresponding to the required resistance is given by the computer. The resistance is smaller than the required value, and it is increased by the trimming process. When the output of the comparator changes, the required value is achieved and the trimming is ready.

The accuracy of the resistance meter is examined under the condition that the error of the comparator is negligible in comparison with the error of the D/A converter. The inaccuracy of the resistance meter can be characterized by the difference between the measured value and the real value of R. The resistance is determined from the parity condition of the comparator:

$$K_2U_{\text{ref}} = U_{\text{ref}}\frac{D}{D_{\max}}K_1\frac{1}{R_c}RK_a \ , \tag{8}$$

$$R = \frac{D_{\max}}{D}\frac{K_2R_c}{K_1K_a} \ . \tag{9}$$

The K_1, $1/R_c$, K_a and K_2 values are determined by passive components, and they can be reduced to a sole K transfer factor, whose nominal value equals $R_{\min}$, the minimal measurable resistance in the actual range:

$$R = \frac{D_{\max}}{D} K \, . \tag{10}$$

Since $D_{\max}$ is constant and $\Delta D = 1$, the absolute error of the resistance is as follows:

$$\Delta R = \left| \frac{\partial R}{\partial D} \right| \Delta D + \left| \frac{\partial R}{\partial K} \right| \Delta K \, , \tag{11}$$

$$\Delta R = K \frac{D_{\max}}{D^2} \Delta D + \frac{D_{\max}}{D} \Delta K \, , \tag{12}$$

$$\frac{\Delta R}{R} = \frac{\Delta D}{D} + \frac{\Delta K}{K} = KR \frac{\Delta D}{D_{\max}} + \frac{\Delta K}{K} \, , \tag{13}$$

$$\frac{\Delta R}{R} = \frac{R}{R_{\min}} \frac{1}{2^n - 1} + \frac{\Delta K}{K} \, . \tag{14}$$

The first part of the equation shows that the inaccuracy of the D/A onverter causes an error proportional to the measured resistance. The error is the smallest at $R = R_{\min}$, when the numerical value on the D/A input and the measuring current are the maximum in the selected range. The error is the maximum in a range at the value that just can be measured in the next upper range. There is no upper limit for the measured resistance in a range, but it is advisable to measure in the lowest possible range. On the other hand, it means that the error can be decreased by dividing the whole measuring interval into more ranges and increasing the bit number n of the D/A converter.

The other part of the error ($\Delta K/K$) depends on the inaccuracies of the range switches and the V/I converter. The errors are constant but different in the measuring ranges. This type of errors can be decreased by determining them in each range with the measurement of very precise resistors, and compensate the errors by means of software.

In *Fig. 4* the errors are plotted as the function of the resistance and, consequently, as the function of the measuring ranges.

Fig. 4 and *Table 1* illustrate the real data of a resistance meter realized by using 12 bit D/A converter and applying the value 4 for the ratio of the lower resistance limits of the consecutive measuring ranges. The ranges are mainly determined by the transfer factor of the V/I converter and the gain of the instrumentation amplifier. The application of the range switches and the utilization of the altering gain of the instrumentation amplifier are necessary to limit the value of the measuring current, while keeping the comparator voltage constant. It is also advantageous that less number of precise transfer factors of the V/I converter have to be realized.

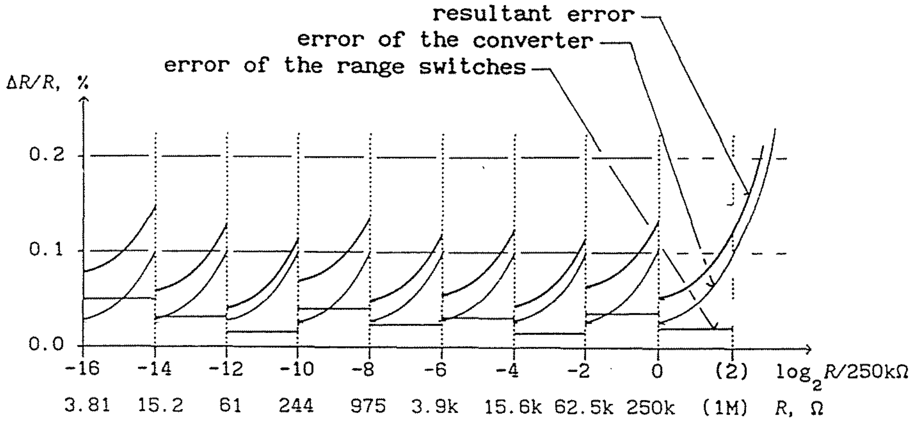

Fig. 4. The errors of the resistance meter

3. Conclusion

On the basis of the error analysis a laser trimming system has been developed to solve the special problems of thermistor trimming (*Fig. 5*). The trimming system consists of a commercial laser unit, in-house developed electronics for resistance measuring, for temperature monitoring and regulation, for the control of the beam delivery system and the laser power. Moreover, it contains mechanical units and an IBM PC with control software system.

The main specialities of the system are that trimming can be carried out on the increased working temperature of the thermistors and the required resistance can be corrected according to the precisely measured temperature. In this way an accuracy of −0.2 % of the temperature sensitive resistors can be achieved, even if the deviation in the temperature coefficient of resistance is relatively high.

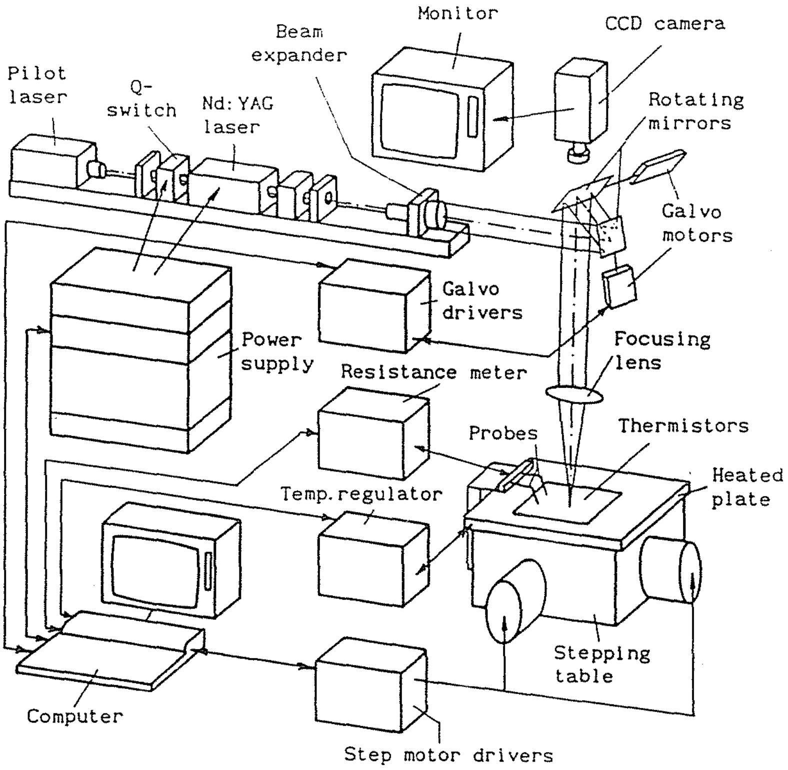

Fig. 5. Laser trimming system for thermistors

Table 1
The data of a realized resistance meter

No.	$R_{\min},\Omega$	$R_{\min}^{\log_2}/250k$	K_1	R_c,Ω	$I_{\max},A$	V_x,V	K_a	K_2	V_c,V
8	250	0	1/4	62.5 k	40 μ	10	1	1	10
7	62.5k	−2	1	62.5 k	160 μ	10	1	1	10
6	15.625k	−4	1/4	62.5 k	40 μ	0.625	16	1	10
5	3.906	−6	1	62.5 k	160 μ	0.625	16	1	10
4	975	−8	1/4	3.9 k	640 μ	0.625	16	1	10
3	243.75	−10	1	3.9 k	2.56 m	0.625	16	1	10
2	61	−12	1/4	244	10.24 m	0.625	16	1	10
1	15.25	−14	1	244	40.96 m	0.625	16	1	10
0	3.8125	−16	1	244	40.96 m	0.156	16	1/4	2.5

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