ANALOG REGULATOR FOR ELECTROCHROMIC WINDOWS

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Abstract: Optical transmittance of electrochromic (EC) windows can be varied by means of electrical signals, which enables a simple way to control the intensity of light transmitted through the window. For "smart" windows in buildings it is desired that the transmitted light is automatically kept on a certain level, regardless the changes in outdoors daylight illumination. Therefore we designed and built a prototype of analog three-state regulator, which automatically controls the optical transmittance of EC window - decreases, increases or keeps unchanged - maintaining the transmitted light intensity on a preselected value. In the paper, an electrical circuit and performances of the regulator are presented. Finally, demonstrational EC glasses controlled with handy battery-powered regulator are shown.

Analogni regulator za elektrokromna stekla

Ključne besede: kemija, EC stekla elektrokromna, EC okna elektrokromna, all sol-gel strukture, obarvanje, regulatorji analogni tri-stanjski, prepustnost svetlobe, prepustnost svetlobe spremenljiva, razbarvanje

Povzetek: Elektrokromna (EC) stekla omogočajo, da s pomočjo električnih signalov spreminjamo njihovo svetlobno prepustnost in s tem uravnavamo jakost prepuščene svetlobe. Ko se EC stekla uporabljajo kot "inteligentna" okna v zgradbah, je zaželeno, da se jakost prepuščene svetlobe avtomatsko ohranja na izbrani vrednosti, ne glede na zunanje spremembe v dnevni osvetlitvi. V ta namen smo načrtali in izdelali prototip tri-stanjskega regulatorja, ki avtomatsko krmili prepustnost EC okna - jo zmanjšuje, povečuje ali pa ohranja nespremenjeno - tako, da se jakost prepuščene svetlobe ohranja na izbrani prednastavljeni vrednosti. V članku sta prikazani električna shema in delovanje regulatorja. Na koncu so predstavljena demonstracijska EC očala, ki jih krmili prenosni baterijsko napajani regulator.

1. Introduction

Electrically controllable optical transmittance of electrochromic (EC) windows present an advantageous feature which can be beneficially used in different light applications. One of the most promising application are "smart" buildings´ windows, which in contrast to simple glass windows enable a control over the intensity of daylight, transmitted through the window, by varying their optical transmittance. Thus, in the case of obscure and cloudy days high transmittance can assure that more daylight enters the building interior, which may lead to lower lightning and heating consumption, while in case of cloudless and sunny days low transmittance can prevent excessive solar illumination and decreases the heating of the inside space, resulting in lower cooling energy consumption. In other words, a constant level of daylight inside the building, regardless the outdoors illumination level is desirable in terms of energy saving as well as building occupants´ comfort.

Different processing methods and types of EC devices have been investigated /1-4/ in order to produce low cost EC windows with good performances. Publications indicated that among several processing methods a sol-gel technique exhibits many advantages over other traditional techniques /3/. The performances of the EC devices produced with the sol-gel method are also very good, therefore we based our applications on "all sol-gel" EC devices /3,4/. Their structure and some performances are briefly presented in the paper.

For automatic control of the EC device a prototype of analog three-state ECW (electrochromic window) regulator was developed. It provides three different voltage states: negative for window colouring (towards lower transmittance), positive for window bleaching (towards higher transmittance) and open-circuit state for keeping the transmittance of EC window unchanged. The desired level of transmitted light is adjustable with a potentiometer. In this work a detailed electrical schematic of the prototype and the results of regulation are given. Finally, a demonstrational application of EC devices - EC glasses - and corresponding handy battery-powered regulator are presented.

2. "All Sol-gel" Electrochromic Device

The crossection of a typical EC device is shown in Fig. 1. The basic structure - WO_3 as an active layer, organically modified electrolyte (ormolyte) with Li^+ ions as an ionic conductor and $Li_{0.3}CeVO_4$ as a counter electrode - is to be found between two glass substrates covered with SnO_2:F transparent conductive oxide (TCO). All three layers of the basic structure were processed by the sol-gel technique therefore the device is called "all sol-gel" EC device /3,4/.

Applied voltage, U, is connected to the top and bottom TCO layers. Fig. 1 shows a situation when the value of U is negative (positive potential at top and negative potential at bottom TCO layer). In this case Li^+ ions are inserted from ionic conductor to WO_3 layer. Higher concentration of Li^+ ions in WO_3 layer results in higher colouration of the WO_3 film (it becomes blue) decreasing its optical transmittance. The structure remains in coloured state, even if the voltage supply is disconnected (memory effect) because the Li^+ ionic conductor has low electronic conductivity (~10^{-9} S/cm). When the positive polarity of U is applied, Li^+ ions are extracted from WO_3 layer and transported through the ionic conductor and become inserted into the counter electrode. Since WO_3 layer does not contain Li^+ ions anymore, blue colour typical for tungsten bronze ($Metal_xWO_3$) is lost (bleaching effect) and becomes transparent layer.

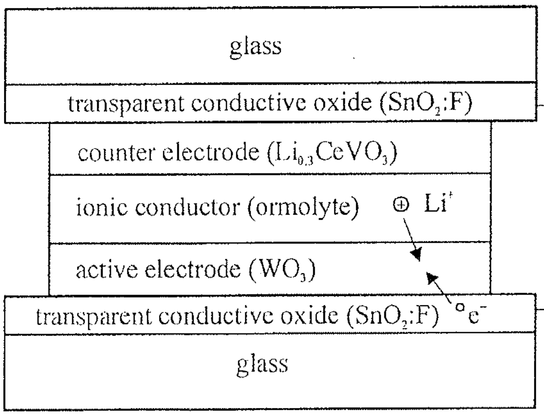

Fig. 1: Structure of the EC window

The variation of the transmittance of EC device between coloured and bleached state when applied voltage is changed from -2 V to +2 V is shown in Fig. 2. Higher applied voltage potentials would lead to larger difference between coloured and bleached state, but should be avoided because too high intercalation levels destroy the basic structure and consequently worsen the device performance. Another limitation which affects the device durability /5/ is electrical current, I. Higher electrical current, supplied from the regulator, results in higher colouring/bleaching speed rate, but it also detrimentally influences the device stability. Therefore, for a particular EC window the optimal voltage level and current limitation should be pre-determined. For our "all sol-gel" EC devices of size 3x3 cm^2 the corresponding values were found to be $U = \pm 2$ V and $I_{max} = \pm 15$ mA, respectively.

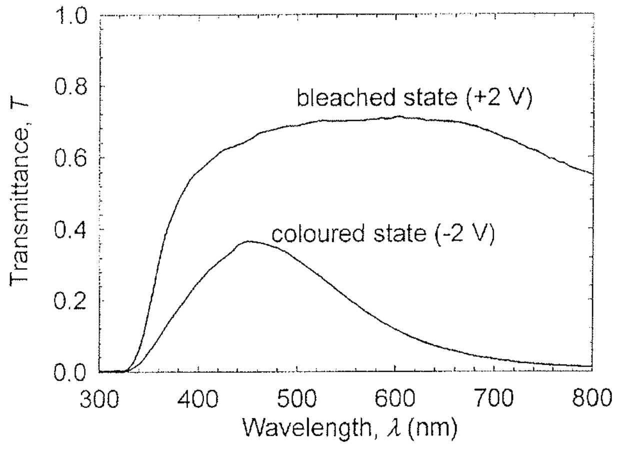

Fig. 2: Transmittances of the EC window in coloured and bleached state

3. ECW Regulator

The primary task of our prototype ECW regulator is to automatically control the transmittance of EC window to keep the transmitted light intensity on a constant preselected level during the variation of the intensity of incident light ($J_{ph\ incident}$). Fig. 3 shematically shows the complete EC system: EC device and regulator with a photodiode for detection of transmitted light intensity.

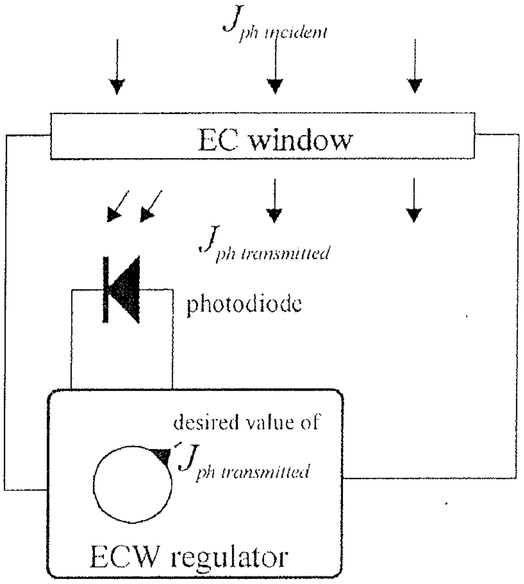

Fig. 3: Schematic view of EC system

To assure simple but efficient control over the EC window colouring/bleaching changes, we designed a prototype of three-state regulator, which consists of customary analog electronics components (resistors, potentiometers, capacitors, transistors, operational amplifiers). The output signal can assume three different voltage states: negative ($U = -2$ V, $I_{max} = -15$ mA) for colouring, positive ($U = +2$ V, $I_{max} = +15$ mA) for bleaching and open-circuit state ($I = 0$ mA) for stand-by position. Negative state is activated when the intensity of transmitted light exceeds the preselected value (colouring requirement), while positive state is applied in the case of too low intensity of light (bleaching requirement). When the intensity matches the preselected value, the open-circuit state appears. To avoid the continuous switching from bleaching to colouring or vice versa, which may occur if the transmitted light slightly deviates around the preselected value, we implemented a hysteresis circuits in the regulator. Therefore after the particular preselected value $J_{ph\ transmitted}$ has been achieved the minor fluctuations of the light intensity do not affect the regulator´s output if relative deviations of transmitted light ($\Delta J_{ph\ transmitted}/J_{ph\ transmitted}$) are smaller than the negative (-5 %) or positive (+5 %) hysteresis gap (Fig. 4).

Fig. 5 shows electrical circuit of the regulator. The basic sub-circuits are: photodiode, the circuit for adjusting the desired value of Jph transmitted, error circuit, low-pass RC filter, an amplifier with adjustable gain, hysteresis circuit, time limitation circuit and an output actuator.

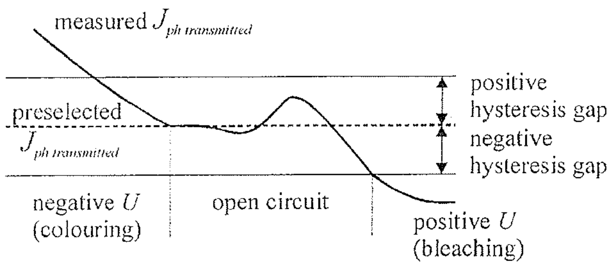

Fig. 4: Hysteresis behaviour of the regulator

Photodiode provides electrical current, I_m, which is linearly dependent on measured $J_{ph\ transmitted}$. I_m is connected to the same node as I_{adj}, which can be varied by potentiometer P_{1A} in the circuit for adjusting the desired value of $J_{ph\ transmitted}$, thus the difference between measured (I_m) and desired (I_{adj}) $J_{ph\ transmitted}$ can be established. The error circuits transforms $I_m - I_{adj}$ to voltage error signal, U_{error}. If the current difference $I_m - I_{adj}$ is positive, negative or zero the error voltage U_{error} is higher, lower or equal to $V_{CC}/2$, respectively. To smoothen the undesirable sudden short-term fluctuations of $J_{ph\ transmitted}$, voltage, U_{error} is smoothened by low-pass RC filter. Thus smoothening effect is necessary in EC devices with faster colouring/bleaching transition times (e.g. gasochromic EC devices /6,7/). The smoothened signal is then amplified by IC_{2A}. The gain of this amplifier is controlled by potentiometer P_{1B}, which is rotated simultaneously with potentiometer P_{1A} (for adjusting the desired $J_{ph\ transmitted}$), therefore the gain is light intensity dependent. In case of low $J_{ph\ transmitted}$ the gain is set to high value, while at higher $J_{ph\ transmitted}$ amplification is attenuated. This results in relative error signal, $U_{error\ rel}$, which means that e.g. 1% deviation between measured and prescaled $J_{ph\ transmitted}$ cause the same $U_{error\ rel}$ regardless the absolute value. Such relative form of the error signal is more appropriate for regulation, because it shows significance of the error with regard to the value of primary signal.

$U_{error\ rel}$ is connected to the positive (IC_{1B}, R_6, R_7, D_1) and negative (IC_{1C}, R_8, R_9, D_2) part of the hysteresis circuit. In case that $U_{error\ rel}$ exceeds the margin of positive (negative) hysteresis - too high (low) value of measured $J_{ph\ transmitted}$ -, the output of IC_{1B} (IC_{1C}) becomes low (high) indicating colouring (bleaching) request. If zero error is achieved ($U_{error\ rel} = 0$) and afterwards $U_{error\ rel}$ is found to be inside the hysteresis margins, the open-circuit state is activated keeping the transmittance of EC window unchanged.

Time limitation circuits restricts the duration of the active output signal (negative and positive voltage state) to the time period which is required for transition of EC device from one saturated state (full coloured state) to the other one (full bleached state). The application of the active output signal longer than the transition time period would increase power consumption but does not affect the transmittance of EC device, therefore the limitation is justified. In the circuit, maximum time duration of positive and negative output voltage is determined by $(R_{10} + R_{12})C_3$ and $(R_{11} + R_{13})C_4$, respectively. In the case of low, 0 V, (high, V_{CC}) output level of IC_{1B} (IC_{1C}), the capacitor C_3 (C_4) starts charging through resistors $R_{10} + R_{12}$ ($R_{11} + R_{13}$), respectively. As long as the

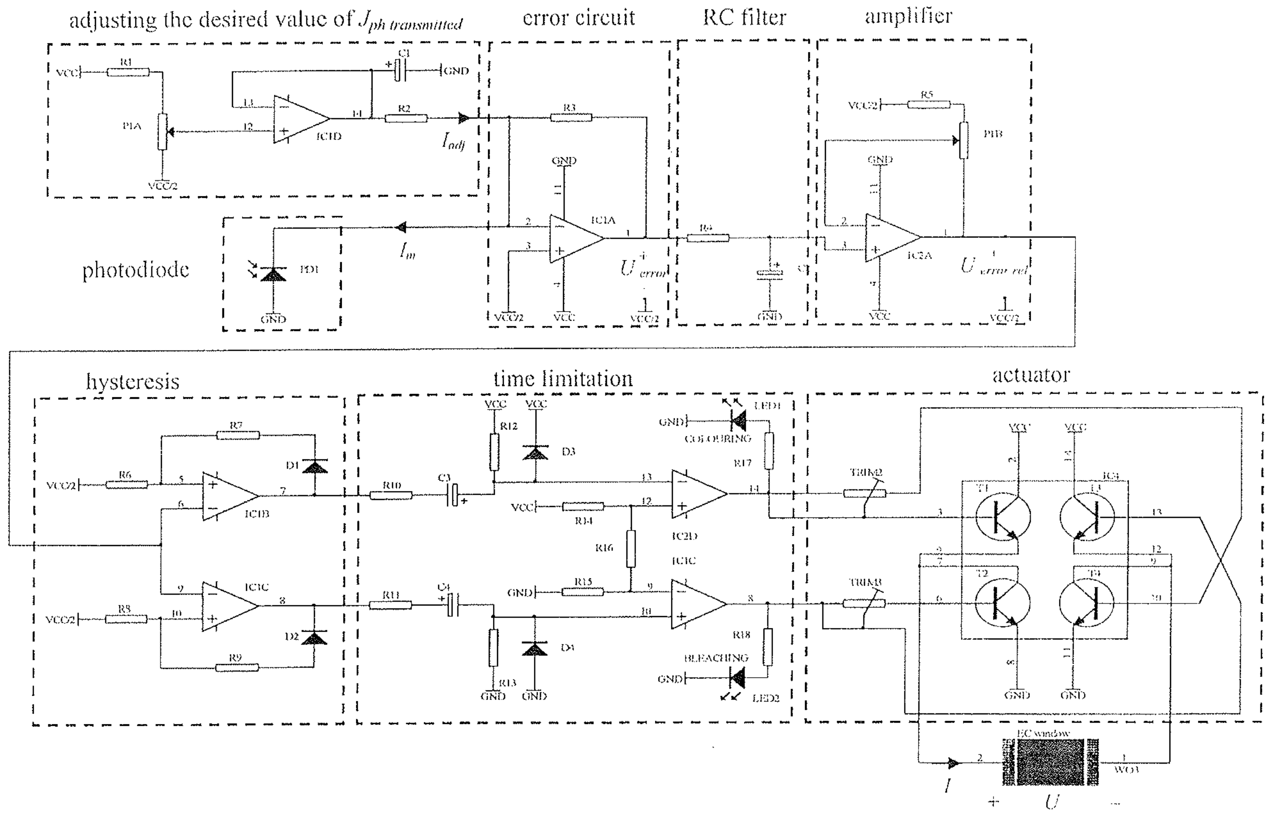

Fig. 5: Electrical circuit of the regulator

voltage of the activated capacitor does not exceed the treshold voltage, determined by R_{14}, R_{15} and R_{16}, the active output signal is applied to the EC device. High output level of IC_{2D} and the low of IC_{1C} cause colouring (LED_1 lights), while low output of IC_{2D} and the high output of IC_{1C} activate bleaching effect (LED_2 lights). In case of open-circuit state, both outputs are low.

The final actuator consists of four NPN transistors and two trimmer potentiometers for adjusting output current limitation. Voltage level of the active output signal is determined by V_{CC} potential. High output level of IC_{2D} opens transistors T_1 and T_4, which applies negative voltage state on EC device (colouring), while positive signal of IC_{1C} activates T_3 and T_2 resulting in positive voltage applied to the EC device (bleaching).

To control larger EC windows, which exhibit slightly different electrical characteristics than our EC samples (3x3 cm^2), some changes in actuator and power supply of our prototype regulator would be necessary, but the principle of the regulation and the basic regulator´s structure would remain the same.

4. Results

Fig. 6 shows the results of regulation. We applied a square pulse of incident light, $\Delta J_{ph\ incident}$, to the EC system, by switching on and off a light source (a 10 W bulb positioned at a distance of 10 cm in front of EC device). The incident $J_{ph\ incident}$ and transmitted light, $J_{ph\ transmitted}$, were detected with two additional reference photodetectors. The output signals of the regulator, U and I, as well as photodetectors´ electrical outputs were measured by digital oscilloscope HP 54601B. The measurements show that sudden increase of $J_{ph\ incident}$, results in sudden increase of $J_{ph\ transmitted}$, which is determined by multiplication product between $\Delta J_{ph\ incident}$ and initial transmittance, T_i, of EC window. After the increase of $J_{ph\ transmitted}$, the regulator applies negative voltage (- 2 V) to the EC device, which activates colouring effect resulting in exponential decay of $J_{ph\ transmitted}$. The output current, I, rapidly increases toward limitation of -15 mA when the switching occurs, afterwards it decreases significantly. The negative voltage is applied until $J_{ph\ transmitted}$ approximately reaches the preselected value $J_{ph\ adj}$. Then the open-circuit state is activated until the pulse ΔJ_{ph} is not finished. After the back front of the pulse EC window is found to be in coloured state, therefore $J_{ph\ transmitted}$ is too low. This activates the positive output state (+ 2 V) of the regulator, which causes bleaching effect and consequent exponential increasing of $J_{ph\ transmitted}$ towards $J_{ph\ adj}$.

Measurements show that positive voltage (+2 V) is switched off a little bit earlier before the exact value of $J_{ph\ transmitted}$ is achieved. This deviation occurs because the photodiode of the regulator and the photodetector for independent measurement of $J_{ph\ transmitted}$ were not mounted exactly at the same position of the EC device. Thus, small non-homogenity in illumination level of the light source as well as slight non-homogenity of the layers of the EC device cause small spatial deviations in $J_{ph\ transmitted}$. Considering an average value of $J_{ph\ transmitted}$ over the whole device area, measured by many dislocated photodiodes, would decrease the effects of non-homogenity and render more precise regulation.

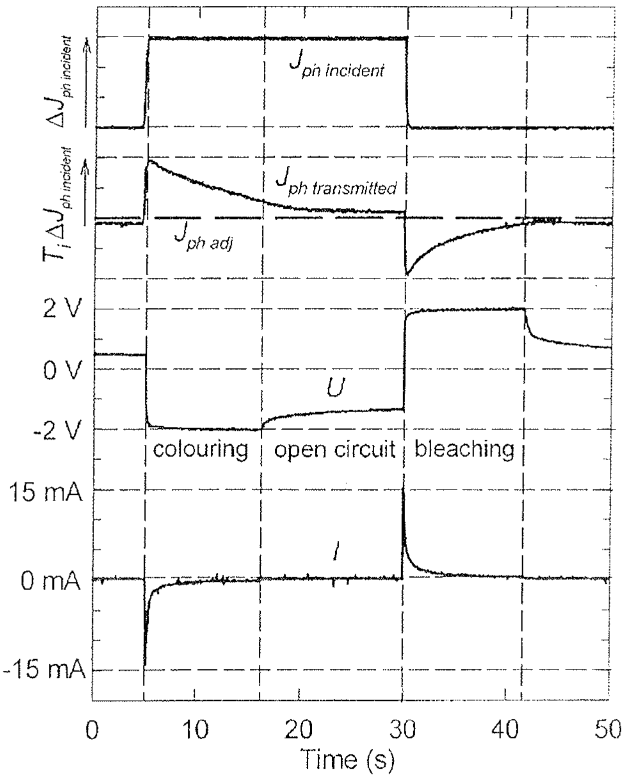

Fig. 6: Results of the regulation

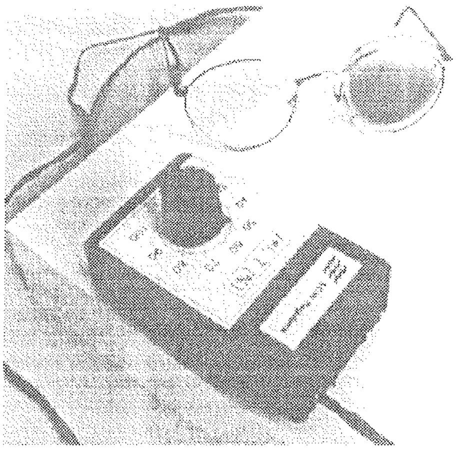

Fig. 7: EC glasses and handy ECW regulator

For demonstrational purposes we made glasses with one EC lens and one customary glass lens, for comparison between transmittances. To control the EC lens, a handy battery powered regulator was developed. Fig. 7 shows the regulator and glasses with EC lens in coloured state. The miniature photodiode for measuring the transmitted light was mounted directly on the back side of the EC lens, nearby the frame, so that the visual field is insignificantly restricted.

6. CONCLUSION

A prototype of three-state regulator for controlling "all-sol gel" EC devices was developed. It automatically controls the transmittance of EC device assuring the intensity of transmitted light on a constant preselected value. Such regulation is required in different applications with EC devices such as "smart" EC windows and demonstrational EC glasses.

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