Lodz University of Technology
Institute of Physics

Laboratory of electronics

Exercise E10IFE

Square wave generator

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Table of contents:

Before you start to perform an experiment you are obliged to learn the following theoretical subjects:

1. Properties of an ideal and real operational amplifier, including parameters describing the limited operating speed and the input offset voltage of the amplifier. [1, 2, 5, 6]
2. Principle of operation of a square wave generator implemented as an astable multivibrator using an operational amplifier, logic gates and discrete elements. [1, 3, 5]

1. Purpose of the exercise

The purposes of experiment are:

1. Investigate the properties of a square wave generator.
2. Getting to know the limitations occurring in real square wave generator circuit.

2. Hazards

Type	Absence	Low	Medium	High
electrical radiation hazards		+		
optical radiation hazards	+			
mechanical hazards (including acoustic hazards, noise)	+			
electromagnetic radiation hazards (invisible)	+			
biological hazards	+			
ionizing radiation hazards	+			
chemical hazards	+			
thermal hazards (including explosion and fire)	+			

The cables with banana plugs are designed exclusively for use in low-voltage circuits – do not connect them to the mains supply 230 V.

3. Introduction

Let us consider the generator shown in Fig. 1, assuming that the operational amplifier (op-amp) is ideal (the parameters of the ideal and real amplifier are given in the instruction for exercise E08 "Operational amplifier"). We will assume that the op-amp is powered with symmetrical voltages $+U_Z$ and $-U_Z$ relative the ground of the generator circuit.

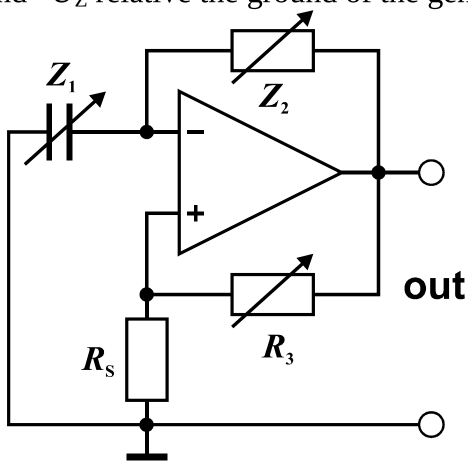

Fig. 1. Circuit diagram of the square wave generator.

The positive feedback loop implemented with resistors R_3 and R_S causes the op-amp to operate as a comparator with hysteresis. In the stable state, the output of such a circuit can only be in the saturation state, i.e. the output voltage takes the minimum $U_{out,min}$ or maximum $U_{out,max}$ value, which results from the supply voltage and the internal structure of the amplifier. Let us assume that the output voltage was switched from $U_{out,min}$ to $U_{out,max}$ at the moment $t_0 = 0$. The output voltage is divided across the resistors R_3 and R_S, so the voltage at the "+" input of the op-amp changes from $U^+_{in,min}$ to $U^+_{in,max}$, where

$$U^+_{in,max} = \frac{R_S}{R_S + R_3} U_{out,max} , \tag{1}$$

$$U^+_{in,min} = \frac{R_S}{R_S + R_3} U_{out,min} . \tag{2}$$

The output of the op-amp is connected to its "–" input through the capacitor Z_1 and resistor Z_2. Since these elements work as a low-pass filter, the changes at the "–" input do not occur as rapidly as at the output. If there were no subsequent switchings at the output, the voltage at the "–" input would increase asymptotically to the saturation output voltage $U_{out,max}$

$$u^-_{in}(t) = U_{out,max} + \left[u^-_{in}(0) - U_{out,max}\right] e^{-t/(Z_1 Z_2)} . \tag{3}$$

An ideal op-amp (that is, an op-amp with infinite voltage gain and no input offset voltage) switches when the voltages at its "+" and "–" inputs are equal, so the voltage at the "–" input at the switching moment $t = 0$ must be

$$u^-_{in}(0) = U^+_{in,min} . \tag{4}$$

Substituting condition (4) into equation (3) we obtain

$$u_{\mathrm{in}}^{-}(t) = U_{\mathrm{out,max}} + \left(U_{\mathrm{in,min}}^{+} - U_{\mathrm{out,max}}\right)\mathrm{e}^{-t/(Z_1 Z_2)}. \tag{5}$$

The next switching of the op-amp output will occur at the moment $t = T_1$, when the voltages at the amplifier inputs become equal again

$$u_{\mathrm{in}}^{-}(T_1) = U_{\mathrm{in,max}}^{+}. \tag{6}$$

Substitution of equations (1), (2) and (6) into (5) results in the following relationship

$$U_{\mathrm{out,max}} + \left(\frac{R_S}{R_S + R_3} U_{\mathrm{out,min}} - U_{\mathrm{out,max}}\right)\mathrm{e}^{-T_1/(Z_1 Z_2)} = \frac{R_S}{R_S + R_3} U_{\mathrm{out,max}}, \tag{7}$$

which allows to determine the duration of the high state $U_{\mathrm{out,max}}$ at the generator output

$$T_1 = Z_1 Z_2 \ln\left[1 + \left(1 - \frac{U_{\mathrm{out,min}}}{U_{\mathrm{out,max}}}\right)\frac{R_S}{R_3}\right]. \tag{8}$$

Similarly, a formula describing the duration of the low state $U_{\mathrm{out,min}}$ at the generator output can be derived

$$T_2 = Z_1 Z_2 \ln\left[1 + \left(1 - \frac{U_{\mathrm{out,max}}}{U_{\mathrm{out,min}}}\right)\frac{R_S}{R_3}\right]. \tag{9}$$

Formulas (8) and (9) show that the asymmetry of the amplifier's output saturation voltages leads to small deviations of the pulse duty cycle from 50 %. Such asymmetry often occurs in real op-amps even when the supply voltage is symmetrical. Moreover, the value of the ratio $U_{\mathrm{out,max}} / U_{\mathrm{out,min}}$ may change when the supply voltage changes, which leads to the instability of the oscillation period $T = T_1 + T_2$ and the instability of the pulse duty factor $T_1/(T_1 + T_2)$.

In special amplifiers, called "rail to rail" op-amps, the output saturation voltages are almost equal to the supply voltages. If a symmetrical power supply is applied, the voltage range at the output of such an amplifier is also symmetrical $U_{\mathrm{out,max}} = -U_{\mathrm{out,min}}$, the pulse duty cycle is equal to 50 %, and the formula describing the period of oscillations simplifies to

$$T = T_1 + T_2 = 2 Z_1 Z_2 \ln\left(1 + 2\frac{R_S}{R_3}\right). \tag{10}$$

4. Available equipment

4.1. Experimental module

The front panel of experimental module is shown in Fig. 2. The module is composed of an operational amplifier and sets of switched resistors and capacitors that can be used at the inverting "–" input of the amplifier (switch Z_1), as negative feedback (Z_2), as positive feedback (R_3), and as a load on the amplifier output (R_L).

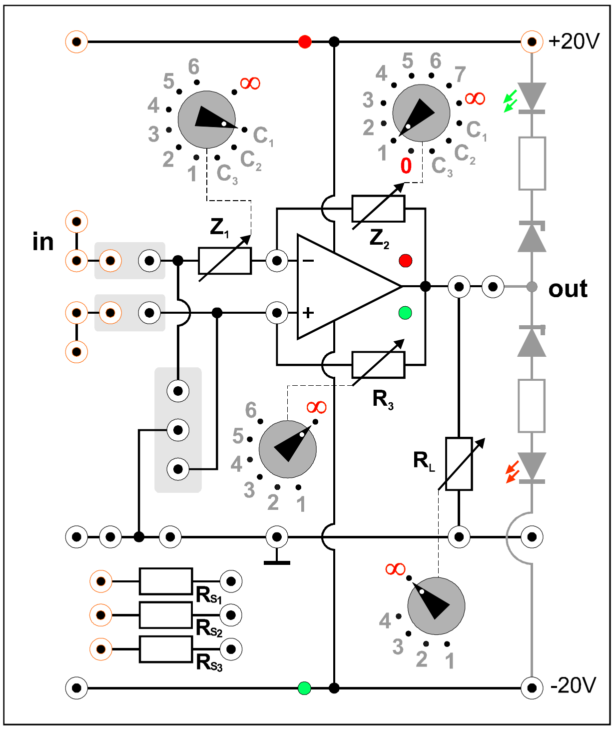

Fig. 2. The front panel of the experimental module.

4.2. Power supply

To supply power to the experimental module, the laboratory DC power supply SIGLENT model SPD3303D is used [7]. Before start the measurements, the power supply must be connected to the experimental module and the serial operation mode should be selected. After switching on the power, the symmetrical supply voltage must be set at ±20 V.

4.3. Function generator

In this exercise, the DF1641B function generator [7] is used only as a frequency counter of the external signal coming from the tested square wave generator.

4.4. Oscilloscope

In this exercise, a two-channel SIGLENT SDS1052DL digital oscilloscope is used [7]. This oscilloscope allows to save the oscillogram on an external USB memory stick as a BMP file. To save the image, press the PRINT button. Files with subsequent images are automatically named as SDS00001.BMP, SDS00002.BMP,… . The saved waveform images can be used instead of manual drawing waveforms. Students who wish to use this option should bring their own USB memory stick with a FAT32 partition.

5. Experimental procedure

1. Connect the circuit according to the diagrams shown in Figs. 3 and 4. Set the Z_1 switch to the C_1 position and connect the C_1 capacitor between the "–" input of the op-amp and the ground "⊥" of the experimental module using an external cable. Connect the R_{S2} resistor between the "+" input of the op-amp and the ground. Set the switches: Z_2 to the "1" position, R_3 to the "4" position, and R_L to the "∞" position. Connect the +20 V and –20 V supply lines and the ground of the experimental module to a laboratory power supply that will be used in serial mode. Do not turn on the power supply outputs yet.
2. Connect the output of the circuit to both the CH1 input of the digital oscilloscope and the INPUT connector of the frequency counter built into the function generator (use the BNC T junction or dual banana sockets in the experiment module to divide the output signal).
3. After the supervisor has checked the circuit, turn on the devices. Press the SER button to set the serial mode of the laboratory power supply, adjust the symmetrical voltage to ±20 V, and turn on the outputs of the MASTER and SLAVE channels. Check out the status of the red and green LED indicators on the +20 V and –20 V lines in the experimental module.
4. Press the button in the COUNTER section of the function generator to light up the following three LED indicators: EXT (select external signal for frequency counter), ATT (20 dB attenuator) and LPS (low-pass filter).
5. Press the DEFAULT SETUP button to restore the oscilloscope to its default settings. Set the oscilloscope to single-channel CH1 mode with a vertical scale of 5 V/DIV and a reference level of 0 V corresponding to the horizontal line in the middle of the screen grid. Make sure the oscilloscope is set to DC coupling mode (after pressing the CH1 button and expanding the context menu using the MENU ON/OFF button, look for the Coupling DC option).
6. Measure the minimum and maximum voltages $U_{out,min}$ and $U_{out,max}$ at the output of the tested circuit – these values can be read directly from the oscilloscope screen in numerical form using the MEASURE button. Write down the obtained results and assess whether these voltages can be considered symmetrical, which allows the use of the simplified formula (10) to calculate the oscillation period. Draw or save an oscillogram along with the oscilloscope setting [V/DIV] and [s/DIV].
7. Using the frequency counter build-in the function generator, measure the oscillation frequency f and write down the result in Table 1. The "theoretical frequency" column in Table 1 may be completed later when the report will be prepared.
8. Measure the slew rate of the signal edges using an oscilloscope. To do this, expand the TRIGGER on-screen menu by pressing the TRIG MENU button and select the rising edge, then stretch the waveform using the s ↔ ns knob in the HORIZONTAL section so that one selected edge reaches the width of several divisions on the screen. Use the ↔ POSITION knob to set the selected edge in a convenient position relative to the screen grid. Read the slew rate as the slope [V/μs] visible on the screen. Switch the edge type to falling edge and measure the slope as before. Write down the results in Table 1. Draw or save appropriate oscillograms along with the oscilloscope setting [V/DIV] and [s/DIV].
9. Repeat the measurements described in steps 7 and 8 for 10 ÷ 15 other combinations of the switches Z_1, Z_2, R_3 and the resistance R_S. The Z_1 switch should be set only in positions C_1 or C_2, the Z_2 switch can be set in positions 1 ÷ 7 (excluding positions $C_1 \div C_3$, 0 and ∞), the R_3 switch in positions 1 ÷ 6 (excluding position ∞), and the resistance R_S should be chosen between the R_{S1} and R_{S2} variants. The number of oscillograms can be limited to

documenting only characteristic waveforms without repetitions, including at least one oscillogram for the rising edge and one for the falling edge.

10. Turn off the power and disconnect the circuit.

Table 1. The measurement table for the square wave generator.

Circuit settings				Measured frequency	Theoretical frequency	Slew rate [V/μs]	
Z_1 [μF]	Z_2 [kΩ]	R_3 [kΩ]	R_S [kΩ]	f [Hz]	f_t [Hz]	rising edge	falling edge

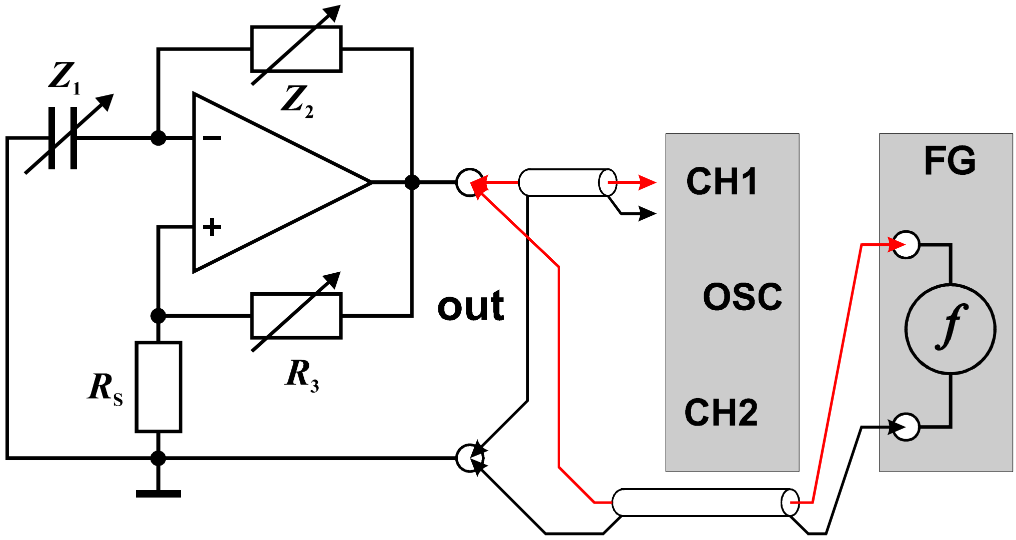

Fig. 3. Circuit diagram for testing the square wave generator.

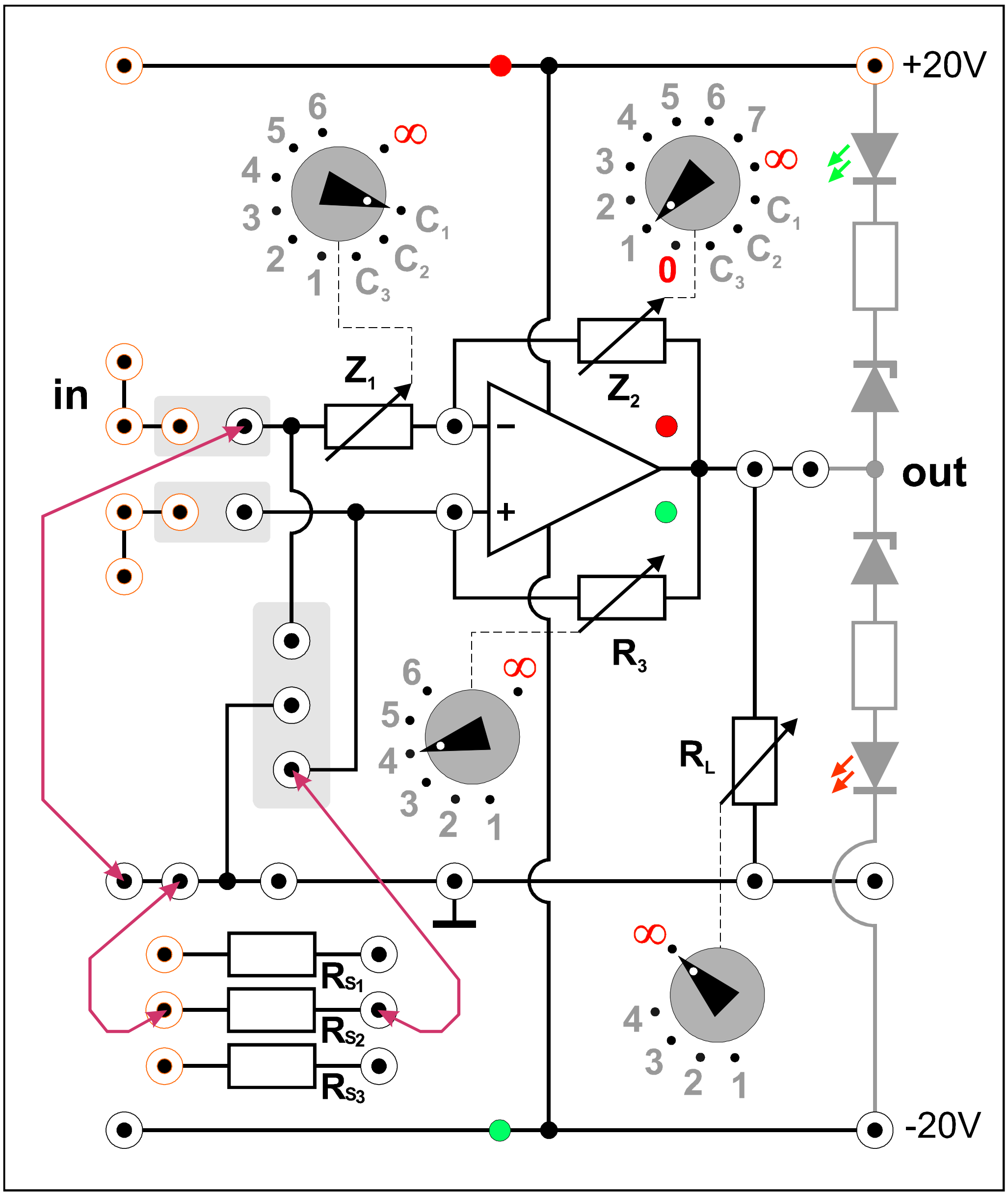

Fig. 4. The circuit of the square wave generator built using the experimental module.

6. Report elaboration

Report has to be composed of:

1. A front page (by using a template).
2. A description of experiment purposes.
3. A list of used instruments and devices (id/stock number, type, setting and range values).
4. Schematic diagram of tested circuit.
5. Results of measurements, observations and calculations written in Table 1 and the formulas used to perform the calculations (without derivations). Consider whether the negative and positive saturation voltages at the output of the op-amp satisfy the equation $U_{out,min} \approx -U_{out,min}$. If so, calculate the theoretical frequency of the square wave generator f_t as the inverse of the theoretical oscillation period T given by formula (10). Otherwise,

calculate the oscillation period as the sum of the durations of the high and low states $T_1 + T_2$ according to formulas (8) and (9).

6. Oscillograms and analysis. In particular, include oscillograms of the signal at the output of the square wave generator with a description of the oscilloscope settings and the settings of the *R* and *C* elements in the generator circuit. Compare experimental and theoretical values of the oscillation frequency. Try to determine whether the discrepancies between experimental and theoretical values show any correlation with the values of the *R* and *C* elements in the tested circuit. Consider whether these discrepancies exceed the theoretical frequency uncertainties that can be estimated based on the tolerance of capacitances (±10 %) and the tolerance of resistances (±5 %)? Compare the slew rates of the rising and falling edges for various settings of the *R* and *C* elements and conclude whether they depend on these settings or are characteristic for the op-amp used. Unless the laboratory staff stated otherwise, assume that the OP07 op-amp was used and compare the measured slew rates with the data found in the op-amp's data sheet.
7. Final comments and conclusions.

The completeness, correctness, clarity of presentation of the results (in the form of tables, graphs, oscillograms and calculations together with descriptions) and the quality of discourse and conclusions will all be evaluated. Theoretical introduction is not required and is not included in the assessment.

7. References

7.1. Basic reference materials

[1] A. Chwaleba, B. Moeschke, „Pracownia elektroniczna. Część 2, układy elektroniczne", Wydawnictwa Szkolne i Pedagogiczne, Warszawa 1980.

[2] S. Kuta, „Elementy i układy elektroniczne. Część 1", Uczelniane Wydawnictwa Naukowo-Dydaktyczne Akademii Górniczo-Hutniczej, Kraków 2000.

[3] B. Moeschke, G. Płoszajski, „Elektronika", Wydawnictwa Szkolne i Pedagogiczne, Warszawa 1988.

[4] Z. Kulka, M. Nadachowski, „Liniowe układy scalone i ich zastosowanie", WKiŁ, Warszawa 1977.

[5] P. Górecki, „Wzmacniacze operacyjne", BTC, Warszawa 2004.

[6] M. Łakomy, J. Zabrodzki, „Liniowe układy scalone w technice cyfrowej", PWN, Warszawa 1987.

7.2. Other reference materials

[7] User manuals for power supply, function generator, and oscilloscopes available on the website:
https://fizyka.p.lodz.pl/pl/dla-studentow/information-technology/fundamentals-of-electronics/

8. Appendixes

A1. Tables of resistances and capacitances

Z_1	
Position	Value
1	5 kΩ
2	10 kΩ
3	15 kΩ
4	20 kΩ
5	25 kΩ
6	30 kΩ
∞	∞ Ω
C_1	0.1 µF
C_2	1.0 µF
C_3	10 µF

Z_2	
Position	Value
0	0 Ω
1	10 kΩ
2	20 kΩ
3	50 kΩ
4	100 kΩ
5	200 kΩ
6	500 kΩ
7	1 MΩ
∞	∞ Ω
C_1	0.1 µF
C_2	1.0 µF
C_3	10 µF

R_3	
Position	Value
1	20 kΩ
2	50 kΩ
3	100 kΩ
4	200 kΩ
5	500 kΩ
6	1 MΩ
∞	∞ Ω

R_L	
Position	Value
1	2 kΩ
2	5 kΩ
3	10 kΩ
4	20 kΩ
∞	∞ Ω

R_S	
Position	Value
R_{S1}	10 kΩ
R_{S2}	300 kΩ
R_{S3}	10 MΩ