BULLETIN OF THE POLISH ACADEMY OF SCIENCES
TECHNICAL SCIENCES, Vol. 69(5), 2021, Article number: e138236
DOI: 10.24425/bpasts.2021.138236

ELECTRONICS, TELECOMMUNICATION
AND OPTOELECTRONICS

High performance optical shutter design with scalable aperture

Piotr POKRYSZKA*, **Mateusz WOŚKO**, **Wojciech KIJASZEK**, and **Regina PASZKIEWICZ**

Wrocław University of Science and Technology, wybrzeze Stanislawa Wyspianskiego 27, 50-370 Wroclaw, Poland

Abstract. In this paper, design, construction and switching parameters of a self-made optical shutter with scalable aperture were reported. The aim of the study was to obtain the shortest possible switching times, minimum shutter open time and comparable with commercial shutter, the switch-on and switch-off times. For this purpose, numerical simulations were performed using Comsol Multiphysics 5.4. The design of the shutter and the control system have been optimized accordingly to the obtained results of numerical simulations. The optimized design was fabricated in a professional mechanical workshop and operational parameters of the constructed device were investigated. The switching parameters of the shutter, such as opening time, closing time, minimum shutter open time and other parameters were measured. The values of the parameters were determined from a statistical analysis of a sample consisting of 10,000 measurement results. The performed characterization showed that the tested device has the opening time of 0.8 ms, while the closing time is approximately 1 ms. The designed device is characterized by the minimum shutter open time of 6.4 ms.

Key words: optical shutter; numerical simulation; current source; jitter.

1. INTRODUCTION

The electromagnetic shutters are used to block the light beam [1], modulate or sample the optical signal [2–4]. Due to the application of a mechanical shield, the device can be applied as a protection in the optical path [5] where a light beam of up to several dozen watts is propagated. Depending on the application, there are different requirements for the optical shutter parameters such as minimum switching time, maximum operating frequency, reliability and maximum power transferred of optical signal.

Commercial solutions can have complicated control methods or may not meet the requirements of a specific application [6]. Research laboratories and specialized equipment often need a number of optical switches with strictly defined parameters. That is why many researchers have developed their own solutions based on various constructions, e.g. loudspeaker [7], computer hard disk [8], piezoelectric devices [9] and other designs [10–13].

This article presents a design of an optical shutter based on a loudspeaker. It depicts the shutter control system, electromagnetic simulations, switching times of the optical signal and jitter measurements. The main motivating factors for developing the presented construction were: short minimum shutter open time (MSOP), short switching times, high reliability and scalable aperture.

2. EXPERIMENTAL

In this chapter the construction of the optical switch, the results of electromagnetic simulations, the optical shutter controller and the control method are presented in detail. Moreover, the geometrical dimensions, elements included in the optical switch and the method of controlling the optical shutter are specified.

2.1. Mechanical construction

Figure 1a shows cross-section of the shutter, Fig. 1b shows the optical image of the device. The electromagnetic shutter consists of a magnetic core with dimensions of ⌀38×29 mm, an air gap of 2 mm width, 16 mm length and it also contains a neodymium magnet. The moving part of the shutter is mounted on a pin and limited by two 1 mm thick rubber stops. The diaphragm consists of a brass plate measuring 12×12 mm and 0.3 mm thick, a coil holder and a 20.5 mm diameter coil

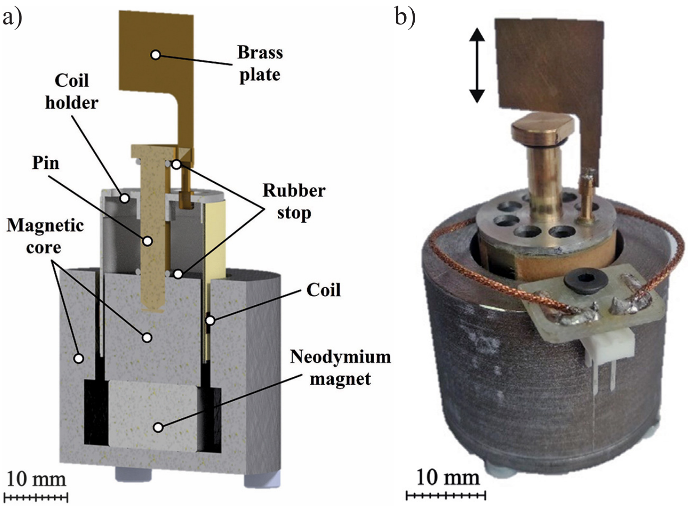

Fig. 1. Images showing the optical switch (a) cross section, (b) photo of the device

---

*e-mail: piotr.pokryszka@pwr.edu.pl

Manuscript submitted 2021-03-17, revised 2021-06-14, initially accepted for publication 2021-07-07, published in October 2021

(n = 90 coils, 7.9 Ω resistance and 280 μH inductance from the Tonsil GDM 10/60 speaker).

The operation of the optical switch can be illustrated in the following way, there is an air gap in the magnetic core of a certain length and width. As a result of the propagation of the magnetic field created by the neodymium magnet, a homogeneous magnetic field is created inside. A pin was permanently attached to the magnetic core and a coil holder with a coil was attached to the pin. As an alternating current flows through the coil, a magnetic field is created with the same or opposite sign to the magnetic field inside the air gap. A magnetic field with a matching sign causes the mechanical shutter to be pushed up and closes the aperture, while a field with the opposite sign causes the diaphragm to slide down and the diaphragm aperture is opened.

The surface of the brass plate has been roughened, therefore when the aperture is closed, the incident light beam is dampened by backscattering. The main limitations of the optical shutter operation are the magnetic field inside the air gap and the amount of time it takes for the induction coil to store energy. Reducing the length and width of the air gap will increase the magnetic field strength. Therefore, while designing, the smallest possible geometric dimensions are aimed at maintaining the design requirements and free movement of the coil in the air gap.

The application of materials with good magnetic permeability will increase the homogeneity of the magnetic field along the air gap. In the case of high heterogeneity, there may be a significant difference between opening and closing time of the shutter.

Another limitation of the switch operation is an applied induction coil. As the inductance of the coil increases, the speed of the individual switching times will be shorter at the expense of the maximum operating frequency. This is due to the time it takes to saturate the inductor.

2.2. Electromagnetic simulation

The designed optical shutter must meet certain design assumptions that result from the expected operating conditions. The device is designed for shuttering light beams with a diameter of up to 10 mm and it was determined that the movement range of the mechanical shutter must be at least 12 mm. Additionally, the opening and closing time of the shutter should be as small as possible. In the proposed design, the magnetic field has a significant impact on the switching times of the shutter. The authors have carried out electromagnetic simulations in order to achieve the maximum magnetic field inside of the air gap, which should result in an improvement of opening and closing times of the designed optical shutter.

Electromagnetic simulations using the finite element method were carried out with the Comsol Multiphysics 5.4 software, using the AC/DC module. The simulations were carried out in the Magnetic flux density norm, Revolved Geometry (mfnc) mode. The impact of the width (w) and length (l) of the air gap and the undercut (d) in the magnetic core on the magnetic field distribution along the air gap was investigated. Figure 2 shows the analysed geometric dimensions.

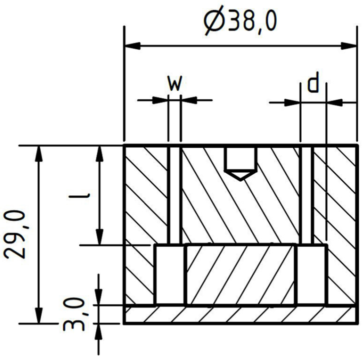

Fig. 2. Magnetic core cross-section with marked geometrical dimensions

The first simulation was performed to determine the shift area in which only a slight difference in the magnetic field will be observed for extreme positions of the mechanical shutter. The simulations were carried out along the air gap of various lengths, ranging from 10 to 20 mm with a step of 2 mm. The magnetic field distribution was analyzed in the middle of the air gap width (w/2) and 2 mm above and below the air gap (l + 4 mm). Figure 3 shows the dependence of the magnetic field distribution as a function of the length of the air gap and the magnetic field at half the length of the air gap, respectively. From the analysis of the obtained results it was determined that as the length of the air gap increases, the magnetic field exponentially decreases. The noticeable heterogeneity of the magnetic field inside the air gap is due to the influence of the reluctance of the applied material. Based on the simulations, it was determined that the length of the air gap must be at least 2 mm greater than the designed range of motion so that the coil does not leave the area with higher magnetic field. Extending the air gap will eliminate the inhomogeneous field at the edges, which will result in more stable switching operation of the optical shutter.

Subsequently, different widths of the air gap were analyzed for the determined length of the air gap. The analysis was performed for widths ranging from 1 mm to 3 mm in steps of 0.5 mm. The minimum width of the gap is limited by the thick-

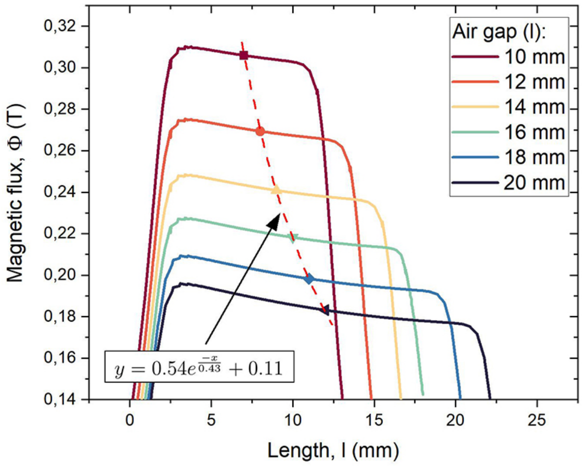

Fig. 3. Magnetic field distribution as a function of air gap length

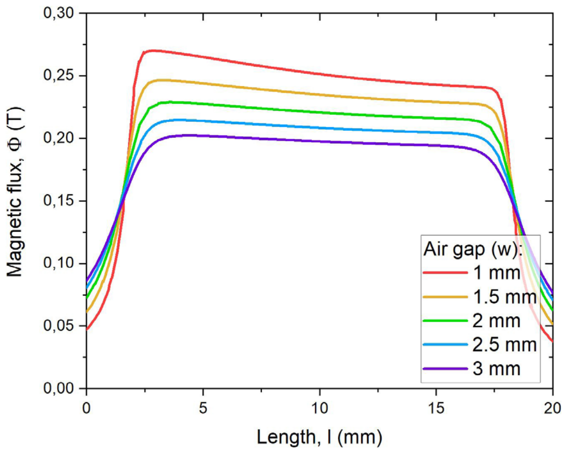

Fig. 4. Dependence of the magnetic field distribution as a function of width of air gap

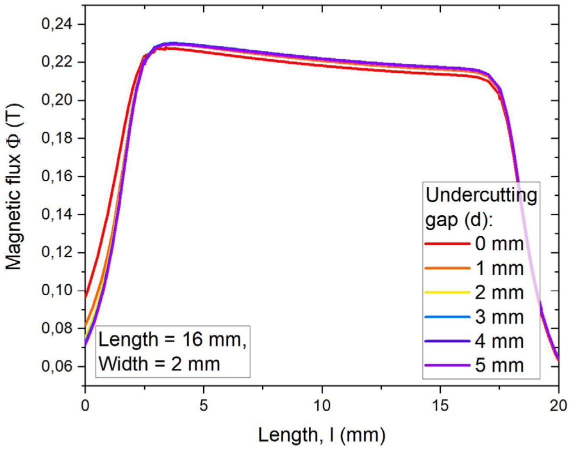

Fig. 5. Effect of air gap undercutting (d) on magnetic field distribution

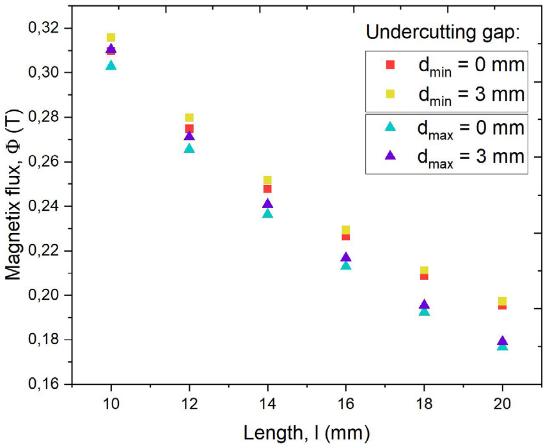

Fig. 6. Effect of undercutting inside the magnetic core on the field distribution in the half air gap

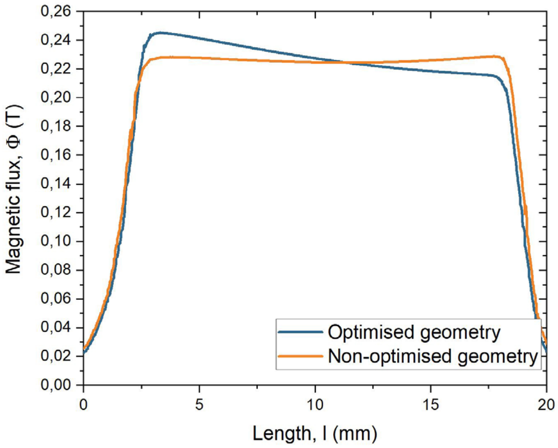

Fig. 7. Magnetic field distribution inside the air gap with and without geometry correction

ness of the coil and the possibility of free movement of the coil inside the gap. It was noticed that the value of the magnetic field and its heterogeneity increase with the decrease of the width of the air gap. Figure 4 shows the dependence of the magnetic field distribution along the air gap (l = 16 mm) as a function of different air gap widths.

An analysis of the effect of the undercut (d) on the magnetic field distribution inside the air gap was also carried out. The undercut inside the magnetic core can be defined as the distance between the magnetic core wall below the air gap and the magnet. The depth of the undercut was varied from 1 mm to 5 mm in steps of 1 mm. Simulations showed that enlarging the additional indentation beyond 2 mm does not change the magnetic field inside the air gap for predefined geometrical dimensions. Figure 5 shows the magnetic field distribution as a function of air gap length for different cavity depths.

The influence of the length of the air gap on the magnetic field in the minimum (min) and maximum (max) position of the mechanical shutter was also analyzed. The simulations were made without a cavity and with a cavity of 3 mm. It can be observed that the difference between the magnetic field in the minimum and maximum position increases with the increase of the length of the air gap, while the differences for device without and with the cavity are similar. The observed effect is due to the influence of the previously mentioned reluctance of the applied material. The results of the analysis are shown in Fig. 6.

During the simulation, the geometry of one of the walls was modified in order to obtain a homogeneous magnetic field. For this purpose, it would be necessary to make a chamfer along the entire length of the air gap, equal to 0.613° from the normal. The value of the chamfer angle depends on the heterogeneity of the magnetic field in the extreme positions of the air gap. The influence of the geometry correction on the magnetic field distribution is shown in Fig. 7.

2.3. Driver and control method

The mechanical shutter is controlled by value of the voltage signal ranging from 0 to 3.3 V. A simplified schematic diagram of the optical shutter controller is shown in Fig. 8. The fabricated driver has dimensions 60 mm × 65 mm and is shown in Fig. 9. The control signal is applied to the input OP1 operational amplifier. Then the signal is scaled and applied to the OP2 operational amplifier working as a current source. A complementary pair of bipolar transistors operating in the Sziklai configuration was applied as a final control element. The OP3 operational amplifier is used to amplify the signal across the resistor R1, which limits the maximum current of the current source.

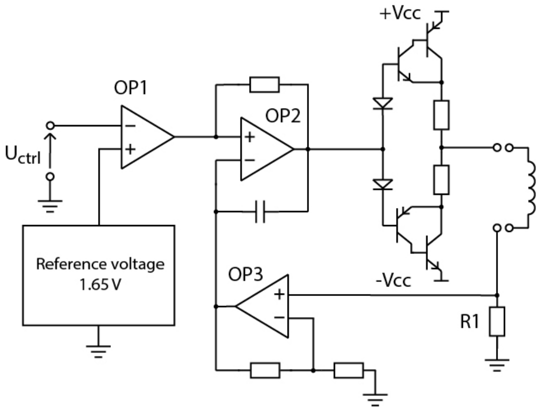

Fig. 8. Simplified circuit diagram of the optical shutter driver

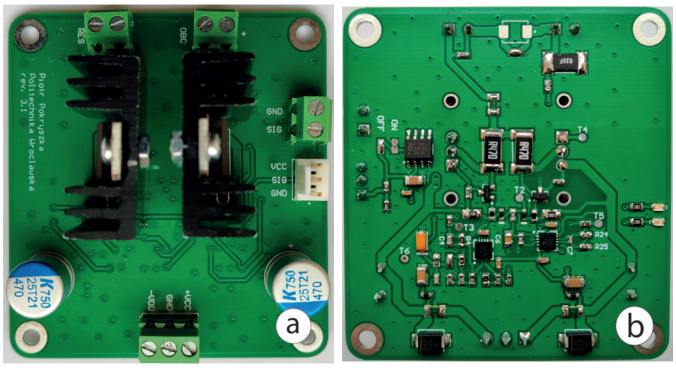

Fig. 9. Optical image of the fabricated optical shutter controller a) top view, b) bottom view

The maximum current of the designed current source is ±2 A, and the maximum operating voltage is ±14 V. As mentioned before, the optical shutter is driven by the voltage-controlled current source with feedback. Four values of the control voltage can be distinguished during the operation of the switch. The 1.3 V and 2 V voltages are responsible for keeping the shutter open or closed. Control voltages of 0 V and 3.3 V are applied during closing or opening of the shutter in order to increase the current flowing through the coil and to improve the switching times. The discussed voltages should be maintained through the switching operation, but no longer than necessary. For longer times, the maximum current flowing through the coil results in excess heat generation, which results in deterioration of the operating parameters. Therefore, the current is reduced when the switch is maintained in the steady-state. The values of control voltages for open and closed position have been experimentally determined.

For the proposed voltages values, the average of supplied power to the coil is around P = 1.3 W, which limits the self-heating phenomena and guarantees stable operation of the optical switch. The peak power dissipated in the coil during the switching amounts to 15 Watts.

The control voltage of the optical switch along with the marked areas is presented in Fig. 10:

1 – shutter opening,
2 – open state,
3 – shutter closing,
4 – shutter closed.

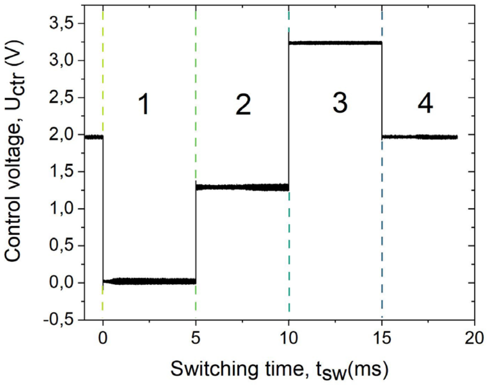

Fig. 10. Voltage waveform showing control of the optical shutter

3. RESULTS

Measurement of the opening, closing, minimum opening time and jitter of the shutter using Thorlabs OSL1-EC halogen illuminator from which the light is led into the optical fibre. The light is then collimated by the optical system, and then it hits the aperture. Behind the aperture, the light was fed through the optical system into the optical fibre and then fed into the Thorlabs PDA30B-EC photodiode and amplified by 40 dB. An Agilent 33250A arbitrary wave generator was used as the source of the optical shutter control signal. Switching times were measured with Tektronix DP07104 oscilloscope.

The individual switching times are presented in Fig. 11 and are described by Thorlabs [6].

During the measurements, the optical shutter was controlled by a signal with a frequency of 10 Hz with duty cycle of 15%. The optical shutter switching parameters were determined on the basis of a measurement test of 10,000 cycles. The minimum pulse duration was determined by shortening of the con-

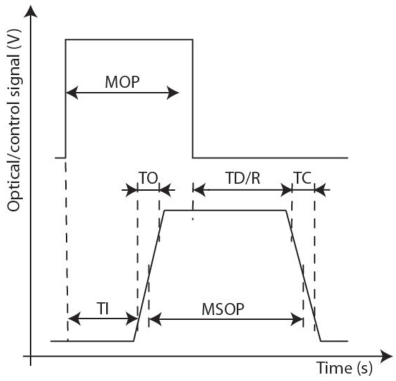

Fig. 11. Illustration of the measured parameters

trol pulse duration until the switch operation was stable. For this experiment the control signal was triggered by square signal (VL = 0 V, VH = 3.3 V). It has been found that the minimum shutter opening time depends on the TI time. Below 5 ms open time, the switch operation became unstable. It was found that for the investigated optical shutter MSOP is 6.4±0.1 ms, achieved for MOP of 5.2 ms. The analyzed signal waveforms for various measurements are shown in Fig. 12 and the acquired results are presented in Table 1.

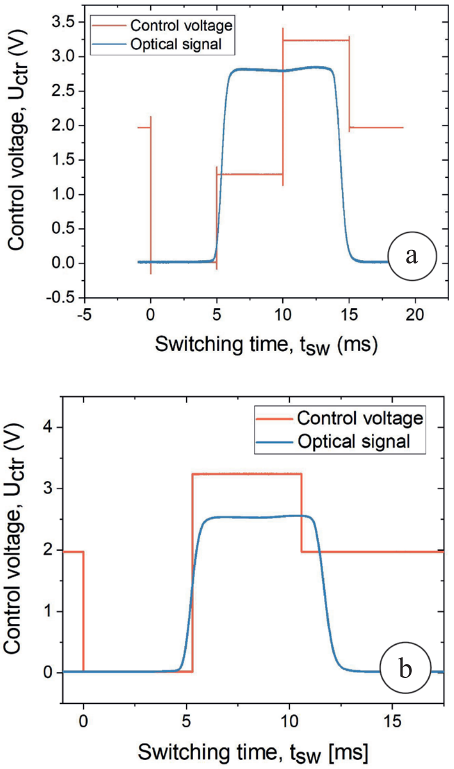

Fig. 12. Control signal and measured optical signal (a) measurements of the shutter parameters, (b) measurements of the minimum opening time

Table 1

Measurement results for a measurement sample of 10,000 and minimum opening time*

	Mean (ms)	σ (μs)
TO	0.8	25
TC	1	36
SOP	9.1	37
TI	5.3	9.7
TD/R	5.3	10
MOP*	5.2	10
MSOP*	6.4	36

The jitter parameters were determined from the performed measurements. These parameters inform about the deviations of the pulse duration from the expected value. It is a qualitative parameter that determines the switch operation. When designing switching circuits, the aim is to obtain the minimum value of jitter because it defines the stability of operation. Peak-to-peak and standard deviation jitter parameters are presented in Table 2, while a histogram showing the obtained measurement results is presented in Fig. 13.

Table 2

Specification of the optical shutter parameters

	Mean (μs)
$\text{Jitter}_{peak-peak}$	460
σ_{Jitter}	57

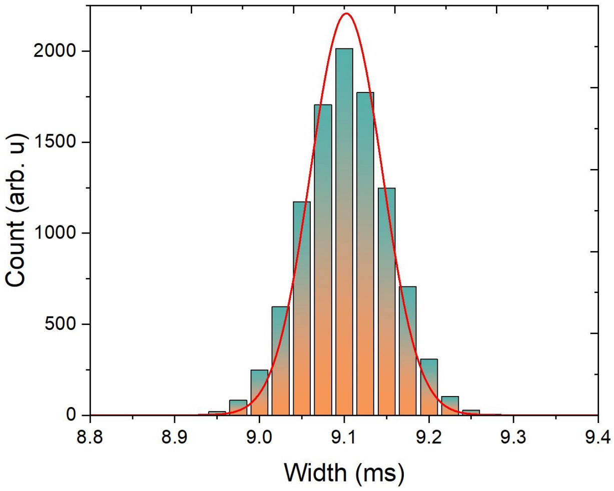

Fig. 13. Histogram of the measured optical signal width

4. DISCUSSION OF RESULTS

The proposed design of the optical switch allows a very simple modification of the aperture by changing the geometric dimensions. Thanks to the performed simulations, limitations of the proposed design and relationships describing the influence of geometrical dimensions on the distribution of the magnetic field inside the switch were determined. It should be noted that in the case of a large heterogeneity of the magnetic field along the air gap, it may result in different opening and closing times of the switch. Moreover, the inhomogeneous magnetic field can result in deterioration of other operational parameters and lower repeatability.

When analyzing the results presented in Fig. 3, it can be noticed that as the length of the air gap increases, the magnetic field inside decreases and the fields becomes more inhomogeneous, which will result in longer switching times. From the analysis of the results presented in Fig. 4, it was found that the magnetic field inside the air gap increases with the decrease in the width of the air gap. Unfortunately, the increase in the magnetic field is accompanied by an increase of its heterogeneity, which is especially noticeable in extreme positions of the shutter.

Therefore, for the best performance the designed optical switches should have dimensions scaled accordingly to the intended application. The analysis of the simulation results helped in the subsequent optimization of the switch geometry. The final geometry of the switch was selected according to the results of the performed numerical experiments. By optimizing the geometric dimensions, i.e. the length and width of the air gap and the undercut, a 15% improvement in the magnetic field strength in the air gap was achieved.

The operational parameters of the presented optical shutter were compared with commercial devices, characterized by a similar range of diaphragm movement. The comparison of the most important parameters of the described switch with the parameters of commercial solutions is shown in Table 3.

Table 3
Selected parameters of the designed switch and commercial solutions

	This work	76993 Newport [13]	SH05 + KSC101 Thorlabs [6]
TO (ms)	0.80	1.95	1.0
TC (ms)	0.95	3.90	1.2
MSOP (ms)	6.45	8.45	17.2

Besed on this comparision it could be stated that the designed optical switch combines the advantages of both commercial solutions. The presented design is characterized by short switching times, and at the same time allows for a short shutter opening time.

5. CONCLUSIONS

The paper presents an original design of an optical shutter based on the loudspeaker design. Due to the application of the electromagnetic simulation, the maximum range of aperture movement was selected, so that a relatively homogeneous magnetic field could minimize shutter switching times. Also, the geometry of the magnetowire on the magnetic field distribution along the air gap was analysed. The switch parameters were determined on the basis of a measurement sample consisting of 10,000 measurements and high operational reliability were confirmed during the measurements. The performance of the switch was compared with commercially available switches. It was shown that the original solution obtained better parameters. The proposed, simple shutter structure of the optical shutter guarantees high reliability with very good performance parameters and allows for easy aperture scalability. It's advantages make it suitable for application in medium-power optical lines, sampling systems and as an optical shutter.

6. DATA AVAILABILITY STATEMENT

The data that support the findings of this study is available from the corresponding author upon reasonable request. References for all other datasets are given in the text.

ACKNOWLEDGEMENTS

This work was co-financed by the National Centre for Research and Development grants TECHMATSTRATEG No. 1/346922/4/NCBR/2017, Polish National Agency for Academic Exchange under the contract PPN/BIL/2018/1/00137 and Wroclaw University of Science and Technology subsidy of K70W12D02. This work was accomplished thanks to the product indicators and result indicators achieved within the projects co-financed by the European Union within the European Regional Development Fund, through a grant from the Innovative Economy (POIG.01.01.02-00-008/08-05) and by the National Centre for Research and Development through the Applied Research Program Grant No. 178782 and Grant LIDER No. 027/533/L-5/13/NCBR/2014.

REFERENCES

[1] H. Jo and D. Kim, "Observations of in vivo laser tissue ablation in animal models with different chromophores on the skin and modulating duration per laser exposure," *Lasers Med. Sci.*, vol. 34, no. 5, pp. 1031–1039, 2019.

[2] T. Osuch, P. Gąsior, K. Markowski, and K. Jędrzejewski, "Development of fiber bragg gratings technology and their complex structures for sensing, telecommunications and microwave photonics applications," *Bull. Pol. Acad. Sci. Tech. Sci.*, vol. 62, no. 4, pp. 627–633, 2014.

[3] W. Lamperska, J. Masajada, S. Drobczyński, and P. Gusin, "Two-laser optical tweezers with a blinking beam," *Opt. Lasers Eng.*, vol. 94, pp. 82–89, 2017.

[4] H. Kim, W.-K. Lee, D.-H. Yu, M.-S. Heo, C. Park, S. Lee, and Y. Lee, "Atom shutter using bender piezoactuator," *Rev. Sci. Instrum.*, vol. 88, no. 2, 2017.

[5] C. Colquhoun, A. Di Carli, S. Kuhr, and E. Haller, "Note: A simple laser shutter with protective shielding for beam powers up to 1 w," Rev. Sci. Instrum., vol. 89, no. 12, 2018.

[6] Thorlabs, "Optical shutters," https://www.thorlabs.com/ newgrouppage9.cfm?objectgroup_id=927, (Accessed on 20/02/2021).

[7] K. Singer, S. Jochim, M. Mudrich, A. Mosk, and M. Weidemüller, "Low-cost mechanical shutter for light beams," *Rev. Sci. Instrum.*, vol. 73, no. 12, pp. 4402–4404, 2002.

[8] L.P. Maguire, S. Szilagyi, and R. E. Scholten, "High performance laser shutter using a hard disk drive voice-coil actuator," *Rev. Sci. Instrum.*, vol. 75, no. 9, pp. 3077–3079, 2004.

[9] W. Bowden, I.R. Hill, P.E.G. Baird, and P. Gill, "Note: A high-performance, low-cost laser shutter using a piezoelectric cantilever actuator," *Rev. Sci. Instrum.*, vol. 88, no. 1, p. 016102, 2017.

[10] P.-W. Huang, B. Tang, Z.-Y. Xiong, J.-Q. Zhong, J. Wang, and M.-S. Zhan, "Note: A compact low-vibration high-performance optical shutter for precision measurement experiments," *Rev. Sci. Instrum.*, vol. 89, no. 9, 2018.

[11] G.H. Zhang, B. Braverman, A. Kawasaki, and V. Vuletić, "Note: Fast compact laser shutter using a direct current motor and threedimensional printing," *Rev. Sci. Instrum.*, vol. 86, no. 12, p. 126105, 2015.

[12] S. Martínez, L. Hernández, D. Reyes, E. Gomez, M. Ivory, C Davison, and S. Aubin, "Note: Fast, small, and low vibration mechanical laser shutters," *Rev. Sci. Instrum.*, vol. 82, no. 4, p. 046102, 2011.

[13] Newport, "Electronic fast shutters," https://www.newport.com/f/electronic-fast-shutters, (Accessed on 20/02/2021).