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Device for Inactivation of SARS-CoV-2 Using UVC LEDs

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***Abstract*—In connection with the COVID-19 pandemic, there is an urgent need for disinfecting devices that can be used both indoors and in transport. Currently, the most common of these devices are ultraviolet (UV) germicidal lamps. However, they have significant disadvantages, such as short service life, presence of mercury, lack of flexible control, large dimensions, etc. The paper analyzes the sources of UV radiation to find an alternative to UV lamps. Although these elements currently have low efficiency and high cost, etc., it is proposed to use UVC LEDs as a UV source. Due to the COVID-19 pandemic and the general interest in the fight against viruses, as well as the ban on the use of mercury, investments have been attracted in the development of UVC LEDs, which will make them competitive in the future compared to germicidal lamps both in cost and efficiency. The paper presents a disinfection device developed on the basis of UVC LEDs. The principle of operation is described; the control system, the drawing, and the design of the UVC LED-based disinfection device are presented. Due to the described limitations of UVC LEDs, this design can be used for disinfection of small surface areas where frequent on/off switching is required and high power is not required.**

***Index Terms*—Ultraviolet sources; Light-emitting diodes; Automatic control; Microcontrollers.**

I. INTRODUCTION

The emergence of the SARS-CoV-2 virus, or, as is also called, the “COVID-19 coronavirus pandemic”, has posed serious challenges to humanity. They are associated with the individual and collective protection of people all over the world. Regarding personal protection, they are, first of all, vaccination, hygiene, the use of protective masks or respirators, social distancing, and, in case of illness, self-isolation [1]. Individual protection is the responsibility of each person for his or her own health and the health of loved ones.

Collective protection is the responsibility of the state and various public and commercial structures for the safety of citizens. It includes the requirements of citizens to comply with personal protection measures, if necessary, the implementation of measures to restrict population movement (quarantines, lockdown, etc.), as well as the development and implementation of additional measures to prevent the spread of a dangerous virus [2].

These activities include many ways to disinfect public spaces and vehicles. Particular attention should be paid to public transport, which includes tightening control over the work of personnel, providing personal protection, cleaning and disinfection of the environment, sanitary and educational activities [3].

In addition to this, it is necessary to develop additional methods and devices for disinfection, which will make it possible to inactivate viruses during all working hours without harming people. Such devices should be installed at bus stops, in crowded places, and can operate on “green” energy sources, e.g., from solar panels, power generating platforms, etc. [4]–[6].

It is also necessary to provide technical disinfection methods in the modernization and design of all types of public transport, namely, buses, trolleybuses, trams, trains and airplanes [7]–[9].

For example, the authors in [10] presented a portable disinfection device that combines the spraying of a disinfectant liquid and disinfection methods based on ultraviolet (UV) radiation with a wavelength of 222 nm–254 nm (UVC). This device is designed to work both in transport and indoors. However, its disadvantage is that it is designed to disinfect non-living creatures. This UV radiation can be harmful to the skin and eyes.

To develop and implement measures to prevent the spread and reduce the risks of COVID-19 spread, the structure, mechanism of infection, and the lifetime of the virus should be analyzed. Analysis of international reports on study and prevention of COVID-19 virus spread allows us to draw the following conclusion. At room temperature 20 °C to 25 °C, SARS-CoV-2 is able to remain viable in

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various environmental objects:

– In dried form - up to 3 days;

– In a liquid environment - up to 7 days;

– The virus remains stable in a wide range of pH values (at pH 4.0 - up to 6 days, from 5 to 9 days; at pH 11.0 - up to 2 days);

– At a temperature of + 4 °C, the stability of the virus is maintained for more than 14 days. When heated to +37 °C, the complete inactivation of the virus occurs in 1 day; at +56 °C - within 45 minutes; at +70 °C - within 5 minutes;

– The virus is sensitive to ultraviolet (UV) irradiation with a dose of at least 25 mJ/cm^2 and to the action of various disinfectants in a working concentration.

An increase in temperature and exposure to ultraviolet radiation have a positive effect on the inactivation of the SARS-CoV-2 virus.

When developing devices that allow the disinfection of the environment (public premises and transport), the use of high temperatures is far from always possible. At the same time, the use of ultraviolet radiation is very promising. Therefore, the purpose of this work is to develop a device to inactivate the SARS-CoV-2 virus in public buildings and transport. To do this, it is necessary to solve the following tasks:

– Analyze the sources of UV radiation to determine the most effective in the fight against the SARS-CoV-2 virus;

– Develop a control system for a disinfection device based on UVC LEDs;

– Develop the design of a device for inactivation of the SARS-CoV-2 virus;

– Describe the principle of operation of the developed device.

II. UV Radiation in the Fight against SARS-COV-2

A. *Types of Ultraviolet Radiation*

The biological effect of ultraviolet radiation is based on chemical changes in the biopolymer molecules in the body. Under the influence of small doses of ultraviolet rays, biologically active substances (histamine, group vitamins, etc.) are formed on the skin of humans and animals, which contributes to resistance to infections. The cells of microorganisms die under the influence of ultraviolet rays, or their mutation frequency increases. As a result of a strong mutagenic effect, ultraviolet radiation is used in genetic research, plant breeding, microorganisms, etc. In plants, ultraviolet radiation changes the activity of enzymes and hormones, affects the synthesis of pigments, and the intensity of photosynthesis. In some cases, ultraviolet rays have a carcinogenic effect on humans. Under the influence of ultraviolet radiation, redness of the skin is observed, usually turning into a protective pigmentation, tan.

According to the international classification (ISO-DIS-21348 standard), solar UV radiation is divided into areas and subareas presented in Table I [11].

There are natural and artificial sources of UV radiation. The main natural source of UV radiation is the sun.

Artificial sources of ultraviolet radiation are those devices, technical means that have been designed by man to obtain the desired spectrum of light with specified wavelength parameters.

TABLE I. ULTRAVIOLET RADIATION ACCORDING TO INTERNATIONAL CLASSIFICATION.

Name	Abbreviation	Wavelength, nm	Photon energy, eV
Near ultraviolet	NUV	400–300	3.10–4.13
Ultraviolet A Long-wave UV, black light	UVA	400–395	3.10–3.94
Ultraviolet B Medium-wave UV	UVB	315–280	3.94–4.43
Ultraviolet C Short-wave UV	UVC	280–100	4.43–12.4
Vacuum ultraviolet	G	200–10	6.20–124
Far ultraviolet	FUV	200–122	6.20–10.2
Extreme ultraviolet	EUV	121–10	10.2–124

Artificial sources are of practical interest for the development of a device for disinfection of the environment.

B. *Artificial Sources of Ultraviolet Radiation*

Artificial sources of ultraviolet radiation include erythematic lamps, tanning machines, attraction lamps, mercury-quartz devices, fluorescent devices, xenon lamps, gas-discharge devices, etc.

Due to the creation and improvement of artificial sources of UV radiation, today specialists working with UV radiation in medicine [12], [13], preventive, sanitary and hygiene institutions, agriculture [14], etc., are provided with significantly greater opportunities than with the use of natural UV radiation.

Several of the largest electric lamp companies, such as Philips, Osram, Radium, and others [15]–[17], are currently engaged in the development and production of UV lamps [14] for photobiological installations. However, it should be noted that many scientists are raising the question of the degree of safety of these lamps [18]–[20].

The first UV lamps, created in 1908, were quartz. The radiation received from such lamps had the required power, but at the same time the spectral characteristics had shifted to the region of short-wave radiation. Long exposure to such radiation could lead to negative consequences. The industry has not stood still, and as a result, two types of UV lamps have emerged: UV lamps of long-wave and UV medium-wave radiation.

Electrical sources of radiation, whose spectrum contains radiation in the range of wavelengths 205 nm to 315 nm, intended for disinfection purposes, are called “bactericidal lamps”.

According to the method of obtaining ultraviolet radiation, lamps can be divided into two types [21], [22]:

– High-pressure arc discharge lamp;

– Low-pressure glow discharge lamp.

Due to the highly efficient conversion of electrical energy, the most widespread are low-pressure discharge mercury lamps, in which, in the process of an electric discharge in an argon-mercury vapor-gas mixture, more than 60 % is converted into radiation of a wave of 253.7 nm. It should be noted that at this radiation wavelength, the most effective disinfection occurs [17]. High-pressure mercury lamps are not recommended for widespread use due to their low efficiency, since their part of the radiation in the required range is no more than 10 %, and the service life is approximately 10 times less than that of low-pressure mercury lamps [23].

Recently, UV lamps with bactericidal effect have become increasingly popular [24]. They make it possible to clean not only air, but also water of harmful particles and various kinds of radiation [25], which negatively affect human health and fill it with useful ions.

For example, the use of bactericidal salt lamps can reduce the harmful effects of electromagnetic radiation from various household appliances [26]. When heated, such lamps begin to emit negatively charged particles, ions that neutralize harmful particles that fly in the air. In addition, bactericidal salt lamps allow you to normalize the microclimate in the room where they are installed. They absorb excess moisture and, when heated, the salt in them begins to melt very slowly and enter the air, normalizing it.

Different types of microorganisms have different sensitivity to the action of ultraviolet radiation, and the resistance of bacteria is determined by both nature and the phase of their development. The most sensitive to ultraviolet radiation are bacteria in the air in a droplet phase, and spore forms of bacteria are extremely resistant to ultraviolet radiation. Since the middle of the last century, bactericidal installations have been widely used for air disinfection in premises, hospitals, industrial premises, office buildings, drinking and mineral water, food products, containers, etc. [27].

Lamps, in which spectral waves are shorter than 200 nm, are widely used. They cause an intense formation of ozone in the air. Ozone is an unstable triatomic oxygen with disinfecting properties, capable of actively destroying bacteria. It is highly effective against various pathogenic microbes and is a strong oxidizer of chemical and other pollutants. Ozone has a high penetrating power and, at the same time, has a powerful bactericidal effect. Exposure to low doses of ozone has a prophylactic and therapeutic effect and is actively used in medicine [28]. Ozone has proven to be highly effective in killing bacteria, fungi, and mold, as well as in reducing the activity of viruses both on the surface and in suspension in the air. Scientists suggest that ozone may also be effective in inactivating SARS-CoV-2, but this has not been proven to date [29].

III. UV LEDs

Today, along with gas-discharge lamps, semiconductor LEDs are gaining wide popularity. Replacing discharge lamps with LEDs in decontamination installations provides the following advantages:

– The possibility of creating a source of electromagnetic radiation with the most effective wavelength of 265 nm, without side radiation leading to the formation of ozone;
– High mechanical strength;
– Significant reduction in the weight of the installation;
– Unlimited number of on/off switches;
– Quick exit to the operating mode;
– The ability to adjust the radiation power over a wide range;
– Reduction of energy consumption;
– Due to the small size of the LEDs, the final design of the emitter can be given any shape;
– No mercury.

The shorter the wavelength, the more difficult it is to manufacture LEDs. Serial production of UVC LEDs for widespread use only began in the second half of the 2010s. Initially, they were developed as part of an international project to provide quality drinking water to the poorest countries in Africa. Compact LED water disinfection units can be powered by a battery, an individual wind turbine or directly from a small solar panel, while germicidal lamps require power from the mains or an inverter. They are now trying to use these developments for the disinfection of air and surfaces in rooms.

For UVC LEDs, semiconductors with an increased band gap are used. The most common material for such LEDs is aluminum-doped gallium nitride (AlGaN). For example, LEDs based on it are produced by the California Eastern Lab [30]. The advantage of AlGaN is the possibility of using already well-developed technological processes for the production of light sources. However, this material also has disadvantages, namely:

– A high level of crystal lattice defects, which reduces the efficiency;
– The radiation wavelength is 275 nm, which does not coincide with the optimal value.

As an example, let us take a series of XBT-3535-UV LEDs from Luminus Devices, which are now available on the MOUSER Electronics service at a wholesale price of 12€ to 17 € per piece. The LEDs of this line have a radiation wavelength of 270 nm, an operating current of 800 mA at a forward voltage of 6.5 V, while the radiation power is 35 mW. Thus, we obtain an efficiency of about 1 %, while the efficiency of a quartz lamp is 10 % to 15 %, and for a bactericidal lamp it is 35 % to 50 %.

Everlight has also announced its 30 mW UVC LED. Data on operating current and forward voltage have not yet been published, but indirectly, at a wavelength of 280 nm, it can be assumed that the same AlGaN technology is used. Also, 275 nm LEDs are manufactured by Seoul Viosys, a subsidiary of Seoul Semiconductor. The radiation power is up to 50 mW, and the efficiency is about 1 %.

Aluminum nitride (AlN) is more promising as a material for UVC. It has less frequent crystal structure defects than AlGaN, which leads to a higher efficiency. This direction is being developed by the Klaran company. Its KL265-50W-SM-WD LED emits 80 mW of radiation with an average wavelength of 265 nm. The efficiency reaches 2 %. The range of UVC LEDs includes LEDs with a radiation power of 50 mW to 80 mW, and the average price is about 15 € per piece.

Already, Seoul Viosys has tested its UVC LEDs on the SARS-CoV-2 virus. According to the company’s press release published on March 3, 2020, the virus was eliminated with an efficiency of 90 %.

Furthermore, in [31], studies were carried out on the effect of UVC radiation on various pathogens, in particular the SARS-CoV-2 virus. The results showed that although UVC LEDs are still expensive and have low radiation intensity, the sensitivity of human coronavirus (HCoV-OC43, used as a surrogate for SARS-CoV-2) depends on the wavelength (267 nm–279 nm > 286 nm > 297 nm). This suggests that UVC LEDs with an emission peak of about 286 nm can serve as an effective tool to combat the SARS-CoV-2 virus.

IV. DEVELOPMENT OF AN OPEN-TYPE DISINFECTING DEVICE USING UVC LEDS

Our development is based on the room disinfection device described in article in [32]. There, the authors propose the design of a device for disinfection of the environment using UV lamps. However, the use of UV lamps in such devices has a number of significant disadvantages:

– Delayed exit to the operating mode. High-pressure UVC lamps take time to achieve the required radiation level (several minutes);

– Impossibility of reinclusion. Immediately after switching off, the hot lamp cannot be ignited, the device must completely cool down;

– The working life of the lamp depends on the number of turns of its on and off. The service life is reduced by about 2 hours for each on/off cycle;

– The device is sensitive to the supply voltage. With an increase in the voltage in the network by 20 %, the life of the lamp drops by 50 %, and when the voltage drops, the lamp will work less intensively or may go out altogether;

– Reduction of radiation intensity at the beginning of operation. During the first tens of hours of combustion, the radiation flux can drop to 10 %. Further incidence of radiation is significantly reduced.

The life cycle of UVC lamps is between 8,000 and 10,000 hours, but this life is only achievable with a minimum frequency of on/off cycles (almost constant operation without shutting down). But even then, annual replacement of UVC lamps is required to ensure reliable disinfection due to lamp degradation (drop in radiation intensity).

UVC LEDs can be turned on and off tens of thousands of times with almost no degradation. In addition, UV LEDs provide full rated power almost instantly, with no warm-up time. This means that the LEDs can be used by accumulating hours of operation only when switched on and performing a disinfection function.

The specified features of UVC lamps' operation significantly reduce the functionality of the device in question. Therefore, in this work, we propose the design of a device for disinfection of a room using UVC LEDs. The block diagram of the proposed system is shown in Fig. 1.

It consists of a microcontroller (MCU), sensors, and actuators.

Used as sensors:

– Object distance sensor (ODS);

– Human presence sensor based on the PIR module.

Executive devices are:

– Stepper motor with driver;

– A line of ultraviolet light-emitting diodes (UVC LEDs), the number of which is determined by the general design of the device.

To control the radiation power (brightness), each line of LEDs is connected through an individual driver, which is a current stabilizer.

The entire device is powered by an AC/DC converter with dual output of 24 V and 5 V. This circuit can be easily calculated and converted to a different supply voltage, such as 12 V DC for automotive applications.

Figure 2 shows a drawing of the installation developed for the disinfection of the environment to inactivate SARS-CoV-2.

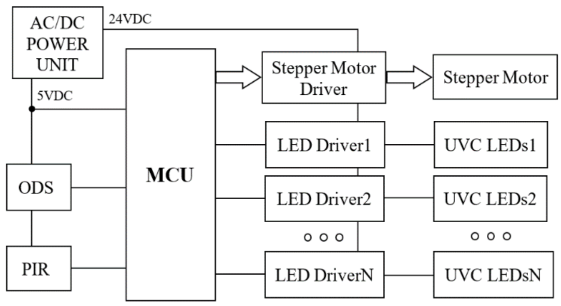


Fig. 1. Block diagram of a control system for a disinfection device based on UVC LEDs.

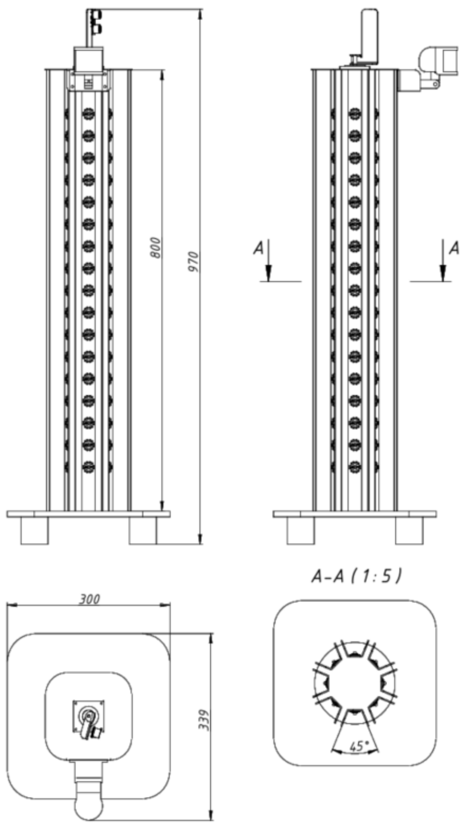


Fig. 2. Drawing of the installation for room disinfection using UVC LEDs.

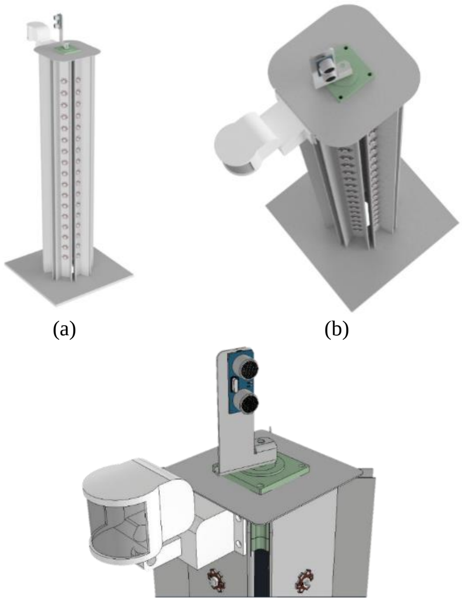
The appearance of the device from different angles is shown in Fig. 3.

This design consists of N vertical bars of UVC LEDs that are connected in a circle by LEDs. They are located outward and form a kind of cylinder. Each line of LEDs is connected via a separate LED Driver that can be adjusted. The LED

Driver current is regulated by means of a pulse-width modulation (PWM) signal: the higher the pulse duty cycle, the higher the current.

In the upper part of the device, there is a Stepper motor on the shaft of which the object distance sensor (ODS) is fixed. When the disinfection device is turned on, the stepper motor makes one revolution, while the ODS scans the room to determine how far away the furniture and walls are from it. This allows the current of each bar of UVC LEDs to be adjusted in proportion to the distance to the object closest to it. It is necessary not to irradiate the surfaces of walls and furniture with high intensity, since ultraviolet radiation has a detrimental effect on some materials.

Since it is not recommended to use open UVC devices when people or animals are in the room, the PIR module allows detecting and informing the MCU about their presence. When motion is detected, the MCU turns off the UVC LEDs for 3 minutes. Unlike UVC lamps, the number of LEDs on/off does not affect their resource; in addition, they can be turned on immediately after they turn off.



(a) (b) (c)

Fig. 3. External view of the disinfection device based on UVC LEDs from different angles: (a) front view, (b) oblique top view, and (c) detailed top.

Let us determine the number of LEDs corresponding to the UV lamp in terms of electrical and emitting powers. For example, a Philips TUV30W G30T8 25PK lamp consumes 30 W and has an emissivity of 11.5 W. If, for the implementation of a disinfecting device, choose a UVC LED KL265-50W-SM-WD, which consumes 4 W, then according to the electrical power of such LEDs, you can take 8 pcs. However, the radiation power will only be 640 mW. More than 140 LEDs are needed to obtain the radiation of such power.

As is known, the number of surviving microorganisms on surfaces and in the air decreases exponentially with an increase in the dose of ultraviolet radiation. According to the review [33], the average dose that kills 90 % of corona viruses is 67 J/m^2.

A maximum disinfection efficiency of 99.9 % is required for operating rooms, maternity hospitals, etc. For school classes, public buildings, etc., 90 % of destroyed microorganisms are sufficient. This means that, depending on the category of the room, one to three standard doses of 67 ... 201 J/m^2 are sufficient.

A rough calculation of the size of the room for which a device with a disinfection efficiency of 99.9 %, with a germicidal flow of 11.5 W, can be used showed that these characteristics correspond to a room of 25 m^2. Let us check the result. In the ideal case, all the flow goes to the surfaces being disinfected, but in a real situation, half of the flow will be wasted. Therefore, we will rely on a useful flow of 6 watts. The total irradiated surface area in the room is 25 m^2 floor, 25 m^2 ceiling, 57 m^2 walls, total 107 m^2.

On average, the flux of bactericidal radiation falls on the surface 6 W/107 m^2 = 0.056 W/m^2. For an hour, i.e., for 3,600 s, these surfaces will receive a dose of 0.056 W/m^2 × 3,600 s = 201.6 J/m^2. This corresponds to approximately three doses of 67 J/m^2. And since the calculated dose, before falling on the surface, passed through the entire volume of the room, it means that the air will be disinfected with high efficiency.

Thus, depending on the area of the surface to be disinfected, the exposure time, and the required efficiency, it is possible to determine the number of LEDs used in the device. The cost of the entire disinfector will depend on the number of LEDs.

Thus, the use of light-emitting diodes makes it possible to obtain a compact disinfection device that will have fewer restrictions in use compared with the installations currently used based on bactericidal lamps. In particular, the possibility of precise focus, as well as power control over a wide range, will allow the use of the disinfectant in rooms where people are constantly present, without prejudice to their health.

V. DISCUSSION

Despite all the advantages of UVC LEDs over UV lamps, UVC LEDs are still inferior to discharge lamps in terms of efficiency and cost. But, in connection with the COVID-19 pandemic, general interest in the topic of virus combating, as well as the ban on mercury use, attracts investment in the development of UVC LEDs, which in the future will make them competitive with germicidal lamps in both cost and efficiency [34]–[36]. In the last year alone, the cost of UVC LEDs has dropped more than fivefold. In the near future, UVC LEDs, which have already been proven to work effectively, will replace discharge lamps in large disinfection installations.

At the moment, to solve disinfection problems, UVC LEDs can be used locally for disinfection of small surfaces, where frequent on/off switching is required and high power is not required.

VI. CONCLUSIONS

Due to the COVID-19 pandemic, there is an urgent need for devices designed to inactivate the SARS-CoV-2 virus in the environment. Currently, the most common of these devices are UV germicidal lamps. However, they have a number of significant disadvantages, namely, short service life, presence of mercury, and lack of flexible control. These disadvantages are absent from UVC LEDs. Their effectiveness in fighting viruses has been confirmed in many studies.

It should be noted that today there are some limitations in the use of UVC LEDs, such as low efficiency and high price. However, active investment in the development of UVC LEDs will make it possible to make them competitive in the future in relation to germicidal lamps and in these parameters.

In this regard, the authors of this article have developed the design of a device for disinfecting a room using UVC LED, presented drawings and a block diagram of the device, and described the principle of operation of the device.

The value of this work lies in the fact that the proposed concept of SARS-CoV-2 inactivation allows the development of simple mobile devices with high efficiency and a long life cycle.

The results of this work can be used for the subsequent production of a low-power installation designed for the disinfection of small-area surfaces.

CONFLICTS OF INTEREST

The authors declare that that they have no conflicts of interest.

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