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Development of a compact high-resolution digital microscope for the research of micro- and nanostructures

D.V. Shevchenko [1] ✉, D.S. Provodin [1], V.V. Davydov [1, 2]

[1] Peter the Great St. Petersburg Polytechnic University, St. Petersburg, Russia;
[2] The Bonch-Bruevich Saint Petersburg State University of Telecommunications, St. Petersburg, Russia
✉ dv@shevmail.ru

Abstract. The need to develop a compact mobile high-resolution digital microscope for the research is substantiated. Disadvantages of modern mobile digital microscopes designs are considered. The requirements for providing the necessary characteristics in a compact microscope in terms of resolution, image contrast and size are determined. The design of the low-cost compact mobile digital microscope is developed and assembled. The construction weight with micro-objectives, lightning system and power battery is less than 2 kg. In a disassembled state all components are placed in a case the size of 35×10×15 cm. The condition to ensure necessary magnification is introduced. According to this condition, various parameters of the microscope are evaluated and compared with laboratory microscopes parameters. The results of studies of different objects are presented with the resolution from 2 μm to 90 nm and magnification up to 1250x.

Keywords: nanostructures, digital microscope, image, resolution, different materials

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Разработка малогабаритного цифрового микроскопа высокого разрешения для исследования микро- и наноструктур

Д.В. Шевченко [1] ✉, Д.С. Проводин [1], В.В. Давыдов [1, 2]

[1] Санкт-Петербургский Политехнический университет Петра Великого, Санкт-Петербург, Россия;
[2] Санкт-Петербургский государственный университет телекоммуникаций им. проф. М.А. Бонч-Бруевича, Санкт-Петербург, Россия.
✉ dv@shevmail.ru

Аннотация. В статье обоснована необходимость разработки компактного мобильного цифрового микроскопа высокого разрешения для проведения исследований. Рассмотрены недостатки современных конструкций мобильных цифровых микроскопов. Определены требования по обеспечению необходимым характеристик в малогабаритном микроскопе по разрешающей способности, контрасту изображения и размеру. Разработана и собрана конструкция компактного мобильного цифрового микроскопа. Вес конструкции с микрообъективами, системой подсветки и аккумулятором не превышает 2 кг. В разобранном состоянии микроскоп размещается в контейнере для транспортировки размером 35×10×15 см. Также в работе введено условие для обеспечения необходимого увеличения и выполнена оценка параметров микроскопа для достижения кратности 1250 крат. В результатах исследования представлены изображения различных объектов с разрешением от 2 мкм до 90 нм. Проведено сопоставление полученных результатов с параметрами лабораторных микроскопов для исследования различных сред.

Ключевые слова: наноструктуры, цифровой микроскоп, изображение, разрешение, различные материалы

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Introduction

It is impossible to imagine many areas of scientific activity without optical measuring devices in the world today [1–3]. Among them, a special place is occupied by microscopes and their modifications [4–7]. They are used in a wide range of scientific fields, including biology, medicine, chemistry, material science, engineering, etc. In fact, microscopy provides many advanced discoveries and especially makes the invaluable contribution to the development and testing of new medications [4, 5, 8].

Nowadays, various microscopes designs allow to obtain the following results. Using light microscopy, it is possible to see objects with a distance up to 0.2 μm with a magnification about 1000x. For some digital microscopes, resolution up to 0.1–0.05 μm can be obtained. This requires a magnification approximately 1200x and above. With the increasing of magnification, size of the microscope and complexity of its use increase. In a stationary laboratory, it does not play a significant role, but the development of technologies in electronics, chemistry, food industry, environmental fields have required mobile devices, including microscope, for various purposes [4, 5, 9, 10]. The best option for express control of the state of various media, objects (for example, micro assembly) or surfaces is a digital microscope. Research results can be immediately stored in the computer, analyzed, and transmitted over distances. To solve the main problems of express control, a resolution in the resulting image of the order of 0.1 μm is required.

Modern digital microscopes designs that allow to obtain such magnification have a number of disadvantages [5–7, 9, 10]. As a rule, they are large and heavy, making them difficult to transport to different locations. In some cases, designs are difficult to mount, so they require the calibration of optical part after assembly. Unfortunately, it is often impossible to do the calibration without special tools. Additionally, the cost of high-quality models can be high, so it causes limited affordability to many researchers. For instance, OPTIKA B200 Series is the closest analog to the technical characteristics and functionality. The model has 10x ocular and nosepiece with 4x, 10x, 40x and 100x objectives. Therefore, the maximum magnification is 1000x. There are also a lighting system and real-time image output on a tablet. Nevertheless, the microscope has all the above-mentioned disadvantages: the construction has difficult assembling, and its weight is more than 12 kg.

In our work, we offer the microscope design that has not these disadvantages. Our approach is based on using light materials and 3D printing in creating microscope components. We develop the design which allows to use industrial lenses, and our microscope elements must not impair image quality. Moreover, these components have to be easily taken apart and accessible for maintenance.

Materials and Methods

The design of microscope and the principle of operation. The development of our construction was based on the analysis of various industrial digital light microscopes designs, mainly made in 2022 (e.g. the model “Stormoff” by Optika). The diagram of the digital microscope design and its assembly are presented in Fig. 1 and Fig. 2.

The developed model implies the possibility of an objective replacing, allowing to increase microscope magnification without loss of image quality. Also, the microscope can be easily taken apart, compactly packed and moved for a long distance. Another design advantage is that

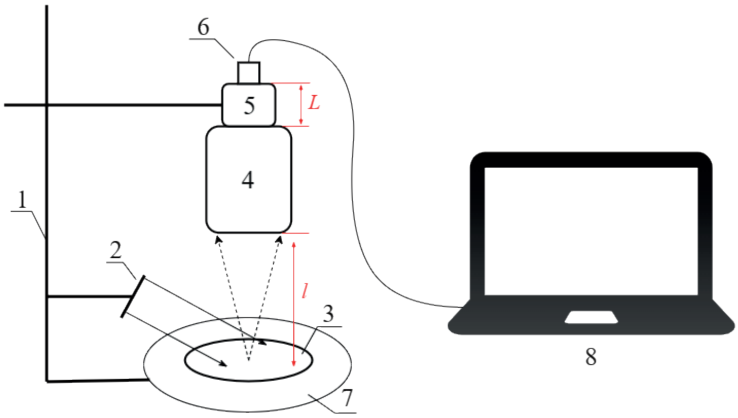

Fig.1. Diagram of the digital microscope: 1 – modular tripod, 2 – LED matrix, 3 –investigated object, 4 – objective, 5 – transitional cylinder, 6 – photosensitive matrix, 7 – object table, 8 – image reading laptop/PC

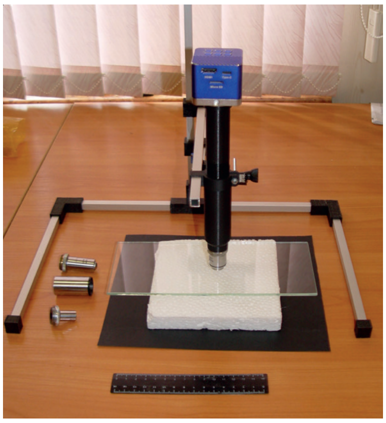

Fig.2. The digital microscope design in real life

the device can be powered by the PC or laptop that it is connected to. Besides, user can zoom in or out the image and increase the contrast of its investigated part with software. The PC or laptop screen displays a real-time data, which can be quickly saved and transmitted over long distances.

The feature of our developed design allows to vary the distance l (between objective 4 and object 3) within 220 mm. The distance L (between objective 4 and photosensitive matrix 6) also can be simultaneously varied by regulating the length of transitional cylinder. This feature makes it possible to obtain the maximum magnification. Moreover, the design of transitional cylinder provides for the installation of an ocular before photosensitive matrix 6. It allows to increase additionally the magnification in 2–3 times, while maintaining a contrast of image. The absence of rotating prisms and additional lenses in the design, which are in the classical microscopes' designs, excludes in image of an object formation prismatic and diffraction distortions, part of the glare caused by multiple reflection of light rays and parallax.

The investigated object 3 is placed on the object table 7. Depending on the object, image formation on photosensitive matrix 6 can be realized by either reflective or transmitted light. The required resolution is provided by choosing necessary objective and distances L and l. An ocular is installed if necessary. From photosensitive matrix 6, the real-time image is transmitted in a digital form to a computer. On the basis of the observed image, it is possible to configure the optical part of the microscope and adjust the power of light sources for maximum image contrast.

The calculation of the microscope magnification. To determine the microscope parameters, the light rays' propagation diagram was developed in case there are objective, ocular and correcting lens for photosensitive matrix in the design (Fig. 3).

Ocular and corrective lens were removed from the microscope to eliminate diffraction distortions and lens aberrations. In this case, the microscope magnification depends only on objective. The maximum useful objective magnification is calculated by the formula:

$$M_{\max} = 1000 \cdot NA \quad (1)$$

where NA is objective numerical aperture.

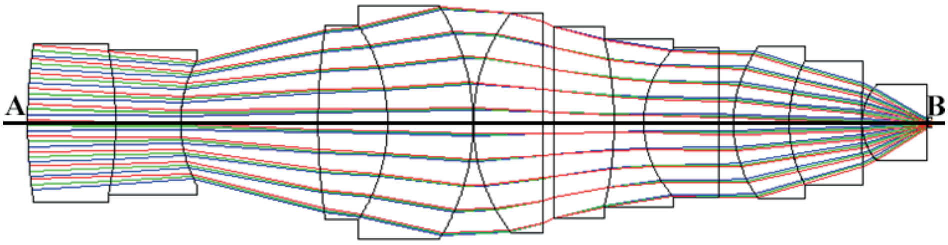

Fig.3. The path of light rays in the optical system. AB – optical axis

The highest numerical aperture among objectives (we used LOMO objectives) that can be used in our construction is equals 1.25. Consequently, from (1) the maximum magnification in this case is 1250x. To provide focused image with such magnification, the following condition should be satisfied:

$$\frac{L}{l} = M \qquad (2)$$

where L is distance between objective and photosensitive matrix; l is distance between objective and object; M is microscope magnification.

Results and Discussion

The results of studies using the developed construction of microscope are shown in Fig. 4, *a*, Fig. 5.

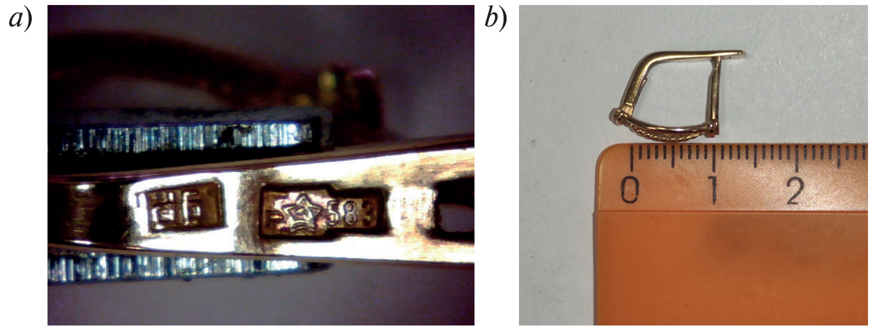

Fig.4. The image of the object obtained with the microscope (*a*) and size of the object (*b*)

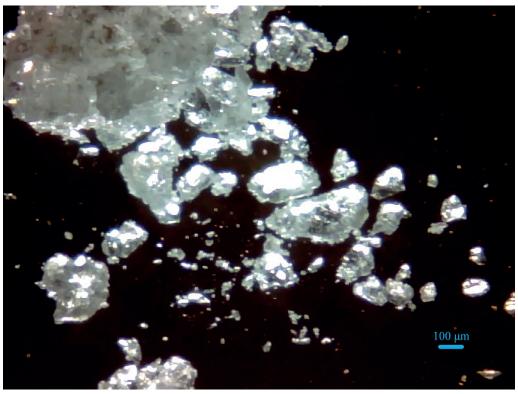

Fig.5. Sugar crystals under the microscope

In our studies photosensitive matrix Sony IMX377 was used, and distance L was approximately 160 mm. Thus, to reach the 1250x magnification, due to (2), distance l was 0.13 mm. Fig. 6 presents the image of human blood obtained with such magnification.

The microscope resolution were estimated on the basis of known sizes of investigated objects and their obtained images. The human eye is able to distinguish two objects on screen if the

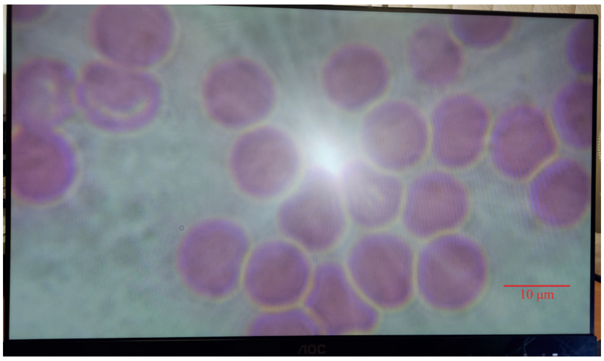

Fig.6. Human blood at the highest magnification

distance between them is more than two pixels width. In our studies we used 23.6" monitor with resolution 1920×1080. In this case two pixels width is about 0.54 mm. Then, knowing real size of the object, the microscope resolution can be found from the proportion. For the developed design, maximum resolution equals 90 nm.

Conclusion

Conducted research allowed to determine the possibility of using the developed microscope design. It can be used to obtain images of various objects, e.g. structures, defects and small details on a material surface. The microscope magnification can be varied in a wide range if necessary. This becomes possible due to the design features, which allow to change an objective, as well as to regulate the distance between objective and object and the length of transitional cylinder. The maximum microscope magnification amounts 1250 times. This makes it possible to study the structures of the order of micrometers in reflective light and hundreds of nanometers in transmitted light. The obtained condition to ensure the necessary magnification is confirmed by the results of studies. As a result of calculations and experiments, it was determined that to achieve the maximum magnification it is necessary to provide table shift adjustment with the step of 0.01 mm, what is acceptable for modern mechanical systems.

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THE AUTHORS

SHEVCHENKO Daniil V.
dv@shevmail.ru
ORCID: 0009-0005-3707-2221

DAVYDOV Vadim V.
davydov_vadim66@mail.ru
ORCID: 0000-0001-9530-4805

PROVODIN Daniil S.
provodindanya@gmail.com
ORCID: 0000-0002-7007-9215

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