УДК: 3937

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ДИНАМИЧЕСКИЕ ПРОЦЕССЫ ФОТОЭЛЕКТРИЧЕСКИХ ПРЕОБРАЗОВАТЕЛЕЙ ЭНЕРГИИ ПРИ ИМПУЛЬСНОМ ОСВЕЩЕНИИ

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ИМПУЛЬСТУК ЖАРЫКТАНДЫРУУ ШАРТЫНДАГЫ ФОТОЭЛЕКТР ЭНЕРГИЯ ӨЗГӨРТКҮЧТӨРҮНҮН ДИНАМИКАЛЫК ПРОЦЕССТЕРИ

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DYNAMIC PROCESSES OF PHOTOELECTRIC ENERGY CONVERTERS UNDER PULSED ILLUMINATION

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Аннотация. Макалада стационардык эмес жарыктандыруунун моментинде алардын көлөмүндө болуп жаткан физикалык процесстерди математикалык моделдөөнүн жардамы менен фотоэлектрдик энергияны өзгөрткүчтөрдү теориялык изилдөөнүн ыкмалары жана натыйжалары берилген. Эркин электрон чогултуу коэффициентинин динамикасы, чыңалуунун өзгөрүшү жана импульсивдүү жарыктын таасири астында фототоктун маанилери көрсөтүлгөн. Моделдөө иштеринин негизги параметрлери көрсөтүлүп, ар кандай жутуу коэффициенттери жана жарык интенсивдүүлүгү үчүн Q(t) жана u(t) убакыттын өзгөрүшү симуляция жолу менен көрсөтүлгөн. Изилдөөлөр Фоктун мыйзамын жана Эйнштейндин мамилелерин, Грин жана Гаусс функцияларын колдонушкан.

Негизги сөздөр: фотоэлектрдик өзгөрткүч, пульсация, жарык, стационардык эмес, программа, модель, моделдөө, параметрлер.

Аннотация. В статье представлены методы и результаты теоретических исследований фотоэлектрических преобразователей энергии с использованием математического моделирования физических процессов, происходящих в их объёме в моменты нестatsiонарного освещения. Показана динамика коэффициента сбора свободных электронов, изменения напряжения и значений фототока под воздействием импульсного освещения, обусловленного импульсным освещением. Указаны основные параметры для моделирования, а также показано изменение во времени коэффициента сбора Q(t) и напряжения u(t) при различных коэффициентах поглощения и интенсивности света. В исследованиях использовались закон Фока и соотношения Эйнштейна, функции Грина и Гаусса.

Ключевые слова: фотоэлектрический преобразователь, пульсatsія, освещение, нестatsіонарный, программа, модель, моделирование, параметры.

Abstract. The article presents the methods and results of theoretical studies of photovoltaic energy converters using mathematical modeling of physical processes occurring in their volume at moments of non-stationary illumination. The dynamics of the free electron collection coefficient, voltage changes and photocurrent values under the influence of impulsive illumination due to pulsed illumination are shown. The main parameters for modeling work are indicated, and the simulation shows the time variation of the collection coefficient Q(t) and voltage u(t) for different absorption coefficients and light intensities. The studies used Fock's law and Einstein's relations, Green's and Gauss function.

Keywords: photovoltaic converter, pulsation, illumination, non-stationary, program, model, modeling, parameters.

Introduction

In recent years, the global depletion of natural resources such as gas, oil, and coal, which are various forms of energy, has caused problems among the leaders of countries. As a result, there has been a need for alternative energy sources that are gifts from nature. At the heart of this need are issues such as the study, testing, and use of products with a crystalline structure. In the use of sunlight, photovoltaic cells made mainly of semiconductor materials are important, and their detailed study is a modern condition. Based on this, it is considered necessary to work on the following problem.

Problem Statement

The study of the duration of light quanta incident on the surface of photovoltaic energy converters (PVECs) and their effect on the energy parameters of their output is important for all researchers. To date, despite the large number of studies devoted to the physical laws by which PVECs made of semiconductor materials change under the influence of light, in stationary light or under the influence of solar radiation that varies gradually throughout the day, the physical processes occurring in the volume of the photoconverter under the influence of impulsive or non-stationary light have been studied little. However, for physical science and in achieving effective results in practical work, the time dynamics of processes associated with photons and heat flows is of great importance in the design of energy converters (solar cells, photodiodes, thermoelectric batteries, etc.) [1,2.3]. In semiconductor photovoltaic cells, the diffusion and recombination of charge carriers under the influence of light pulses or short-lived quanta determine the time evolution of the photocurrent and voltage [3,4,]. In thermal systems, the distribution of heat flux in pulsed and steady modes affects the temperature distribution and thermoelectric power. In this article, several works on the modeling of photovoltaic systems are analyzed. The articles are presented in the MATLAB/Simulink environment [5,6,7] and the analytical formulas for each model and the implementation of numerical simulation methods form the main basis of the research.

Modeling methods

The basis of the methodology for studying the evolution of photocurrent and charge carriers under pulsed illumination conditions is the analysis of the spectral photocurrent generated in semiconductor photocells as a result of pulsed illumination and its integral effect - the accumulation coefficient Q(t) and the time-dependent evolution of the open-circuit voltage.

The diffusion and recombination of carriers are based on Fock's law and Einstein's relations [8,9]. The Gaussian error function [10] and the trapezoidal rule [6] are also used in the modeling:

$$I_f(t) = \frac{q\alpha_0\sqrt{D\tau}E_0}{a^2D\tau-1}\left\{\underbrace{\alpha_0\sqrt{D\tau}\left[1-erf\left(\alpha_0\sqrt{D(t-t_0)}\right)\right]\exp\left(a^2D(t-t_0)-\frac{t-t_0}{\tau}\right)}_{1} + \underbrace{erf\left(\sqrt{\frac{t-t_0}{\tau}}\right)}_{2} - \underbrace{\alpha_0\sqrt{D\tau}\left[1-erf\left(\alpha_0\sqrt{Dt}\right)\right]\exp\left(a^2Dt-\frac{t}{\tau}\right)}_{3} - \underbrace{erf\left(\sqrt{\frac{t}{\tau}}\right)}_{4}\right\} \quad (1)$$

Here $q=1.6\times10^{-19}$ Kl is the elementary charge of the electron, $\alpha_0=440\ m^{-1}$ (and other values) is the absorption coefficient of light, $D=25\bullet10^4\ m^2/s$ is the diffusion coefficient, $\tau=1\times10^{-6}$ s is the residence time (recombination time), $E_0=1\bullet10^{24}\ m^{-2}s^{-1}$ is the energy of the light pulse, $\alpha=1$ is the dispersion parameter, $t_0=3\bullet10^{-6}$ s is the decay time of the light pulse, $erf(x)=2/\sqrt{\pi}\int_0^x e^{-y^2}\,dy$ is the Gaussian error function.

Figure 1 presents the model constructed on the basis of the mentioned methodology, showing the dynamics of changes in the semiconductor photovoltaic converter under pulsed illumination.

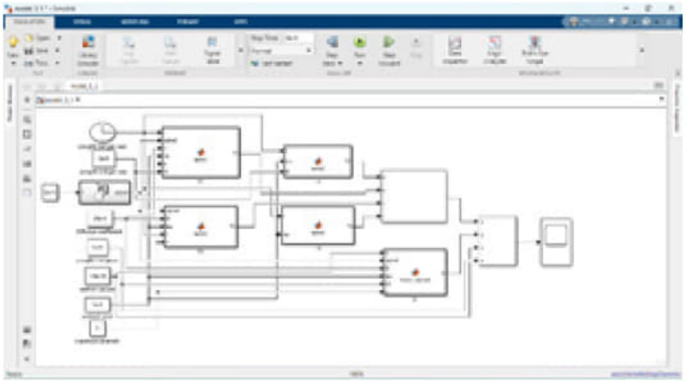

Figure 1. A simulink model of the dynamic response of a semiconductor photocell under pulsed irradiation

The main parameters in modeling are:

Component	Brief description
j(t) is the photocurrent density	This parameter is a product of exponential and error functions that take into account the distribution of charge carriers generated after a light pulse throughout the volume of the photoelectric converter, that is, their generation and recombination;
Q(t) – collection coefficient	Integral normalization of J(t). Since it is difficult to obtain the integral in closed form, numerical integration according to the trapezoidal rule was used;
Additional parameters [11]	Electron charge ($q = 1.6\cdot10^{-19}$ C), diffusion coefficient ($D = 25\ cm^2\cdot s^{-1}$), residence time ($t = 1\cdot10^{-6}$ s), absorption coefficient ($\alpha_0 = 50–440\ m^{-1}$) and light pulse duration ($t = 3\cdot10^{-6}$ s)
Open circuit voltage u(t)	Proportional to the thermal voltage and expressed as a logarithmic function of the accumulated photocurrent.

To determine the dynamic nature of electron collection in the volume of the photovoltaic converter under non-stationary illumination, the collection coefficient formula was applied:

$$Q(t) = \left(\frac{2\sqrt{D}}{\sqrt{\pi}}\right) \alpha_0 \sqrt{t}, \quad t \to 0 \tag{2}$$

For the case of pulsed illumination, the open-circuit voltage is expressed as:

$$(t) = \frac{kT}{q} \ln\left(1 + n_0 \int_{-\infty}^{t} e^{-\frac{t-t'}{\tau}} \cdot E(t')\alpha_0 \left[1 - erf\left(\alpha_0 \sqrt{D(t-t')}\right)\right] \cdot\right.$$
$$\left. \alpha_0^2 D(t-t')\, dt'\right) \tag{3}$$

was determined through this expression.

As part of the theoretical studies, a dynamic PV model based on the Green's function was used. Here, the processes of photogeneration, diffusion and recombination were studied by means of the dynamic modeling of photovoltaic cells under non-stationary lighting conditions based on the Green's function. The photogeneration rate is expressed as an exponential decrease in the absorption in the semiconductor. The evolution of the resulting excess carriers in space and time was expressed by the diffusion equation, which contains the terms photogeneration, diffusion and recombination. The equation was solved using the Green's function method and as a result, an expression for the photocurrent in terms of time was obtained; this expression covers the phases of accumulation during illumination and decay after the illumination is turned off.

Diffusion distribution via Green's function:

$$G(x, x_0, t, t_0) = \frac{1}{2\sqrt{\pi D(t-t_0)}} exp\left(-\frac{(x-x_0)^2}{4D(t-t_0)}\right) \cdot erf\left(\frac{x-x_0}{\sqrt{4D(t-t_0)}}\right) \tag{4}$$

where $D=2.5\times10^{-3}$ cm²/s is the diffusion coefficient. x_0 and t_0 are the initial time and coordinates.

The integral normalized form of the photocurrent is defined as the coefficient Q(t). The diffusion coefficient and residence time are assumed to be constant in the model, the p-n junction effect is limited; the case where the load resistance is included requires numerical integration.

The third theoretical approach is to determine the dynamics of charge carriers under non-stationary illumination conditions, where the dynamics of charge carriers in a photovoltaic cell under non-stationary illumination was modeled by numerically solving differential equations in the MATLAB/Simulink environment [12,13]. The spatially discretized concentration of carriers was written as the sum of the time derivative of diffusion, recombination, and photogeneration terms. The spatial differential operator was discretized with a central differentiation scheme, and the resulting set of ordinary differential equations was integrated using the Runge–Kutta method. Three types of light signals (sinusoidal, pulsed, and linear array) were generated in the Signal Builder block.

Results and analysis of theoretical research

Figure 2 below shows how the charge carriers in the volume of a photodiode change depending on the duration of the light when illuminated with non-stationary light.

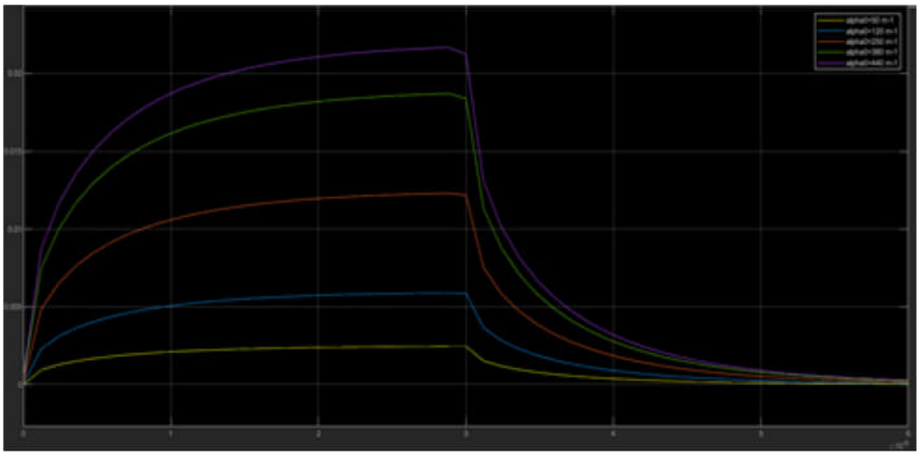

Figure 2 – Time dependence of Q(t).

The graph shows the dependence of the collection coefficient Q(t) on time for different absorption coefficients. It can be seen that the absorption coefficient Q(t) increases rapidly and exponentially in the time interval 0–3 μs, i.e., carriers are collected during the light pulse. As the value of α0 increases, the maximum value of Q(t) also increases: at the largest $\alpha_0 = 440\,\mathrm{m}^{-1}$ (black line. Note: the results are shown in colored lines because they were obtained on a computer.), Q(t) reaches its highest value. At the smallest $\alpha_0 = 50\,\mathrm{m}^{-1}$ values, the values of the collection coefficient remain at a lower level. After 3 μs, the light turns off and the decay phase begins; Q(t) decreases sharply. This indicates the dominance of diffusion and recombination processes. The interesting fact is that for almost any value of α_0 the values of the collection coefficient decay exponentially, but rapidly. A comparison of the obtained results shows that it closely approximates the data of [14,15] with high accuracy.

Figure 3 shows the absorption coefficients determined by simulation to determine the dynamic process in the volume of the photoelectron, and the dynamics of changes in light intensity and charge carrier residence times over time.

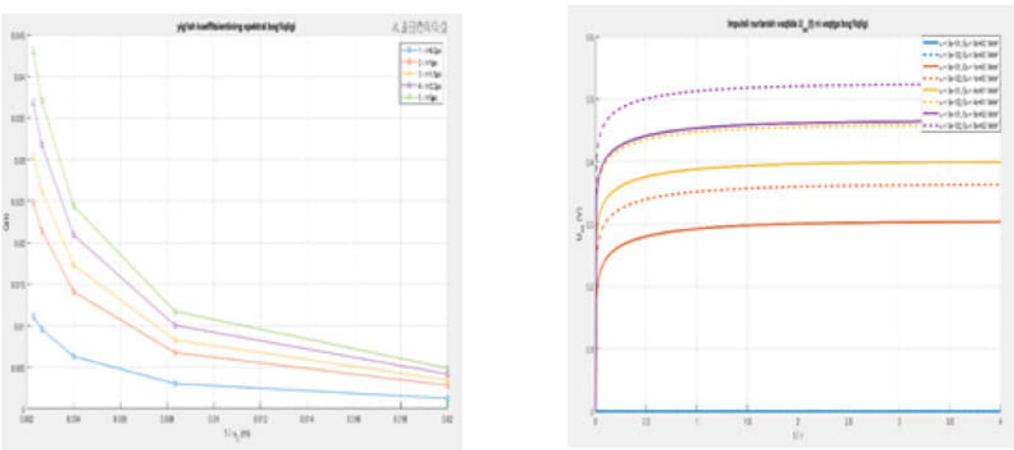

Fig. 3. Spectral dependence of Q(α0) and time dependence of Uxx(t) during pulsed radiation

The graph clearly shows that these changes occur in a sharp manner. The time-dependent changes of Q(t) and u(t) for different absorption coefficients and light intensities are almost vertical. During the illumination, the collection coefficient increases rapidly, and after the pulse ends, it gradually decreases due to diffusion and recombination; the open-circuit voltage reaches a maximum value and then slowly decreases. The simulation showed the time evolution of the Q(t), U(t) and dU/dt signals for different absorption coefficients. The collection coefficient reached a maximum value at a certain time interval, and increasing the absorption coefficient changed the rate of collection and decay. Figures 4 and 5 show the dynamic model of the identified FEO using the Green's function.

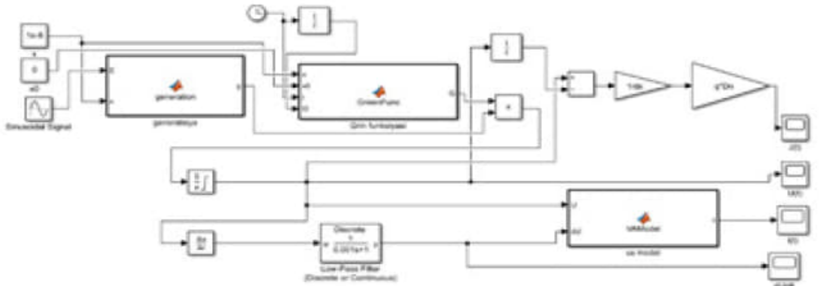

Figure 4. Dynamic model of photovoltaic cells based on the Green's function under non-stationary lighting conditions

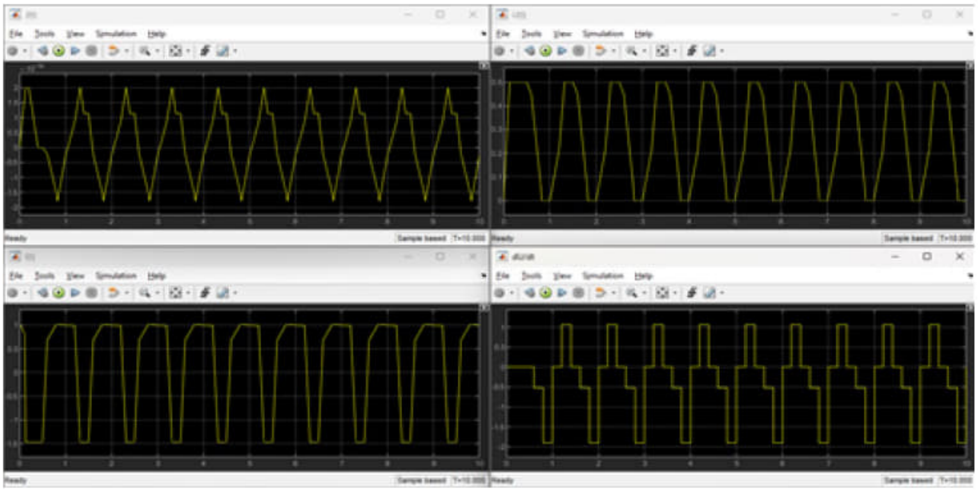

Figure 5. Graphs of the dynamic model of photovoltaic cells based on the Green function under non-stationary lighting conditions

The graph shows how the photocell (J, U, I and dU) change over time when exposed to pulsed (non-stationary) illumination.

Figure 5 shows the "impulse response" of a photovoltaic cell: during illumination, charges accumulate (J, U, I increase), and when the light is extinguished, all the values gradually decay due to diffusion-recombination and the capacitance of the p-n junction. This transient behavior is necessary to predict the temporary power changes in real systems under conditions such as cloud shadow and oscillating radiation. Figure 6 shows a simulation model of the dynamics of charge carriers under non-stationary illumination conditions, which takes into account an equivalent diode, an electrical circuit containing capacitance and resistance. The results are useful for protecting and optimizing the operation of photovoltaic cells in cases such as lightning or laser pulses.

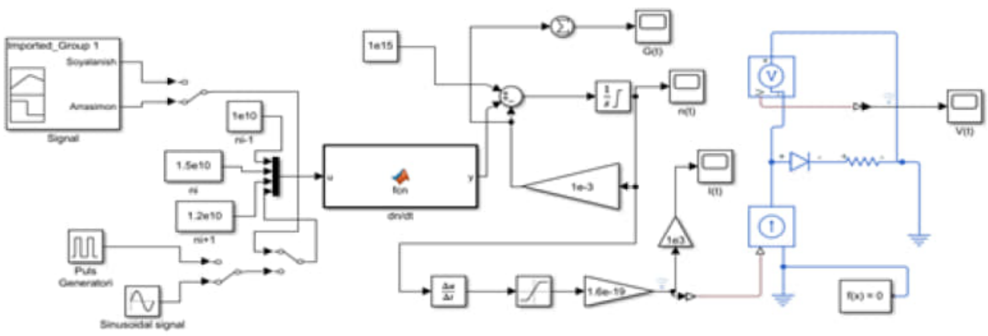

Figure 6. Simulation model of charge carrier dynamics in a photovoltaic cell under non-stationary lighting conditions.

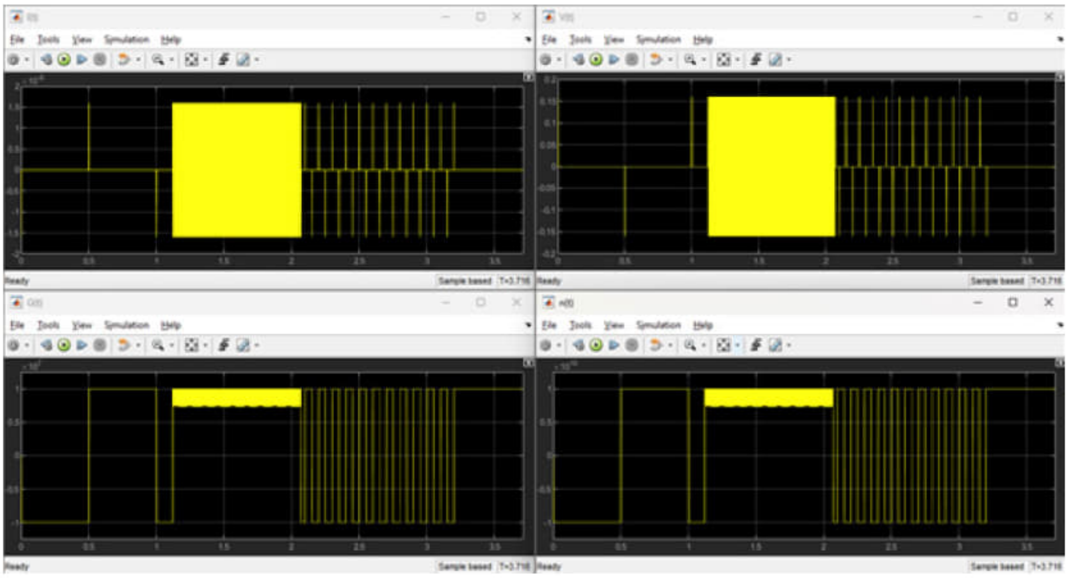

Figure 7. Simulated images of the dynamics of charge carriers in a photovoltaic cell under non-stationary lighting conditions.

From the graph and analysis, it is clear that if the illumination process is sinusoidal in nature, then under sinusoidal illumination the concentration and photocurrent oscillate sinusoidally. When the light intensity increases, photogeneration increases and the number of carriers increases, while when the light intensity decreases, recombination prevails. In pulsed illumination, the charge carriers and current increase sharply at the beginning of the light pulse, and then slowly decrease after the pulse ends; this relaxation rate depends on the recombination time constant. Studies using linear array illumination have shown that when the light intensity increases linearly, the charge carriers and photocurrent also increase linearly.

Conclusion

Based on the theoretical research conducted, the following conclusions can be drawn, which can be summarized as follows:

• Photocurrent density J(t): When light is applied, the charge carriers are rapidly generated and reach the p–n junction, resulting in a sharp increase in the current. Later, it stabilizes under the influence of diffusion and recombination processes. When light is turned off, J(t) does not immediately fall to zero, but gradually fades away through a "tail". This is related to the charge carrier residence time τ.

• Output voltage U(t): In the presence of a load resistance, the p–n junction is charged like a capacitance. U(t) first increases rapidly and then approaches an equilibrium state. After light is turned off, the voltage decreases more slowly than J(t) due to diffusion and charge in the capacitance.

• Load current I(t): it is related to I(t)=U(t)/R and J(t)·S, it rises rapidly at the beginning, then approaches the operating point with U(t), and decreases after the light is turned off.

• Voltage rate of change dU/dt: positive and negative peaks are formed during the on and off periods. This indicates the presence of a "long tail" due to the rapid charging-discharging of the transition capacitance and recombination processes.

Thus, this research work helps to identify transients during operation of pulsed photovoltaic cells through theoretical models and simulations; such analyses provide an important basis for predicting and optimizing device transient power variations in real systems, such as cloud shadows, laser pulses, or light oscillations..

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