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Experimental Investigation of the Electrical Effect of Twisted Lights on a Semiconductor

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ABSTRACT

Orbital Angular Momentum (OAM) beams are a special type of light that disrupts the circular symmetry of the optical field and carries the angular momentum of light. These beams enable new applications in optical devices and communication. In addition, as a result of their interaction with matter, OAM beams can transfer both photon energy and angular momentum, enabling the formation of higher currents. Thus, it has been shown that OAM beams can be used to obtain higher energies in increasing photovoltaic efficiency. The effect of OAM beams on photovoltaic efficiency has been a research topic in recent years. Some studies have theoretically shown that OAM beams can increase the electrical production of solar cells. The reason for this is that OAM beams impart angular momentum to electrons in addition to photon energy. The aim of this study is to experimentally investigate the electrical effect of an OAM beam spot produced using an SLM (Spatial Light Modulator) on a semiconductor solar panel. Higher currents were obtained by dropping the OAM beam onto photovoltaics. The current increase was 18.2%.

Keywords: Photovoltaics, Light-matter interaction, Orbital Angular Momentum

Bükümlü Işıkların Yarıiletken Üzerindeki Elektriksel Etkisinin Deneysel Olarak İncelenmesi

ÖZ

Orbital Açısal Momentum (OAM) ışınları, optik alanın dairesel simetrisini bozan ve ışığın açısal momentumunu taşıyan özel bir ışık türüdür. Bu ışınlar, optik cihazlarda ve iletişimde yeni uygulamalara olanak sağlamaktadır. Bunun yanı sıra, OAM ışınları madde ile etkileşimi sonucunda hem foton enerjisi hem de açısal momentum aktarabilmeleri, daha yüksek akımların oluşumunu sağlamaktadır. Böylece OAM ışınları fotovoltaik verimliliğin artırılmasında ve daha yüksek enerjilerin elde edilmesinde kullanılabileceği göstermektedir. OAM ışınlarının fotovoltaik verimlilik üzerine etkisi, son yıllarda araştırma konusu olmuştur. Bazı çalışmalar, OAM ışınlarının güneş hücrelerinin elektrik üretimini artırabileceğini teorik olarak göstermiştir. Bunun nedeni, OAM ışınlarının elektrona foton enerjisine ek olarak açısal momentum kazandırmasıdır. Bu çalışmanın amacı, SLM (Spatial Light Modulator) kullanarak üretilen OAM ışın spotunun, yarıiletken bir güneş paneli üzerindeki elektriksel etkisini deneysel olarak incelemektir. OAM ışını fotovoltaikler üzerine düşürülerek daha yüksek akımlar elde edilmiştir. Akım artışı %18,2 oranında gerçekleşmiştir.

Anahtar Kelimeler: Fotovoltaik, Işık-madde etkileşimi, Orbital Açısal Momentum

INTRODUCTION

Light carrying OAM has opened the way for new applications in many fields such as electronics and natural science, quantum science, astronomy, optical telecommunication, wireless communication and data transmission [1-9]. For example, OAM beams allow for the capture, rotation and manipulation of microscopic objects, atoms, molecules and Bose-Einstein condensates. In addition, an OAM beam is a type of electromagnetic wave that carries optical angular momentum [3,10]. These beams can create electric current loops in quantum rings associated with light-controlled magnetic field pulses. These loops can affect the magnetic properties and electronic behavior of quantum rings [11]. An OAM beam is a type of beam in which the phase front of the optical field forms a spiral shape. Mathematically, it can be shown that these beams contain an $\exp(i\ell_{OAM}\varphi)$ term in the spatial distribution of the field when it is assumed that the z-axis is the direction of light propagation in cylindrical coordinates. Here φ is the azimuth angle and ℓ is an integer indicating the angular momentum of the OAM beam [12]. As light rotates around the optical axis, it gains a kind of rotational energy. This energy is called orbital angular momentum and each light particle (photon) has a certain value. Allen et al. found that this value is constant in the z direction and is $\hbar\ell_{OAM}\varphi$ per photon.

There are different methods for generating OAM beams: These include computer-generated holograms scanned on SLMs, spiral phase plates and astigmatic mode converters. These methods have different advantages and disadvantages. SLM beam production has low efficiency. In general, the quality of the beam varies with pixel size. However, the ability to dynamically control SLMs is a significant advantage. Other methods are static. But their efficiency is high [1,13-16].

One of the important areas of study for OAM beams is related to light-matter interaction. When OAM interacts with matter, it changes the angular momentum of charge carriers over time. This means that torque is applied to these charge carriers. In other words, OAM applies a force to rotate electrons. For example, Wätzel et al. found that an OAM light spot can affect the movement of electrons on a semiconductor strip and that the electron has obtained a transverse drag depending on the properties of the OAM light [17]. In a different study, the effect of an OAM beam focused on a micro-sized GaAs AlGaAs-based quantum ring was investigated. This effect was achieved by transferring the rotational momentum of the light to the electrons of the semiconductor material and pushing them towards the edges of the ring with centrifugal force. In this way, it was shown that an electric potential was formed between the inner and outer parts of the ring. This potential can be controlled by changing the topological charge of the light and can be used as a fixed voltage source [12]. There are also many theoretical studies related to the light-matter effect of OAM beams [5,18,19].

Photovoltaic cells are semiconductor devices that directly convert sunlight into electrical energy. There are various methods to increase the efficiency of photovoltaic cells [20-25]. One of these is to manipulate light (by creating OAM) to change its effect on the semiconductor material. In this way, the angular momentum of light can affect the formation of higher photovoltaic currents by activating the electrons of the semiconductor material. This approach offers a new opportunity to improve the performance of photovoltaic cells. This study also experimentally demonstrated that OAM beams can be generated and higher current values can be obtained by dropping this beam onto a photovoltaic cell.

THEORY

Twisted light is a type of light beam that carries OAM; this means that the light rotates around its propagation axis. Twisted light can interact with semiconductor materials that have a bandgap between the valence and conduction bands. When twisted light interacts with a semiconductor, an electrical effect occur due to OAM transfer, which produce a voltage or current.

To mathematically disclose this effect, we need to consider the Hamiltonian of the system that defines the total energy of the light beam and the semiconductor. The Hamiltonian can be written as follows:

$$H = H_S + H_L + H_{LS} \tag{1}$$

Here H_L is the Hamiltonian of the twisted light beam, H_S is the Hamiltonian of the semiconductor and H_{LS} is the Hamiltonian of their interaction. The twisted light beam can be modeled as a superposition of plane waves with different OAM values:

$$E(\vec{r},t) = \sum_{l=-\infty}^{\infty} E_l(\vec{r},t)e^{il\phi} \tag{2}$$

Here $E(\vec{r},t)$ is the electric field of the beam, $E_l(\vec{r},t)$ is the electric field of each plane wave component, l is the OAM quantum number and ϕ is the azimuth angle. Semiconductors can be modeled as a collection of electrons and holes with different energy levels:

$$\Psi(\vec{r},t) = \sum_{n,k} c_{n,k}(t)\psi_{n,k}(\vec{r}) \tag{3}$$

Here $\Psi(\vec{r},t)$ is the wave function of the semiconductor, $c_{n,k}(t)$ is the probability amplitude of each state, n is the band index (valence or conduction) and k is the wave vector. The interaction between the twisted light beam and the semiconductor can be defined by the dipole approximation. This assumes that the electric field of the beam creates a dipole moment in each electron-hole pair:

$$H_{LS} = -\sum_{n,k} c_{n,k}(t)^* e\vec{r}E_l(\vec{r},t)c_{n,k}(t) \tag{4}$$

Here e is the elementary charge and $\vec{r}$ is the position vector. By solving the Schrodinger equation of this system, we can obtain the dynamics of the probability amplitudes and calculate the electrical effect of twisted light on semiconductors. When the behavior of electrons in a semiconductor material under an electric field is examined, the given Hamilton operator defines the interaction of electrons with the field. Using this Hamilton operator, the Schrodinger equation of the system can be written as follows:

$$i\hbar\frac{\partial}{\partial t}c_{n,k}(t) = -e\vec{r}E_l(\vec{r},t)c_{n,k}(t) \tag{5}$$

This expression is a form of the Schrödinger equation that shows how the wave function of an electron under the influence of an electric field changes over time. Here $c_{n,k}(t)$ is the probability amplitude of the electron in the n -th band and k -th wave vector. To solve this equation, let us assume that the electric field is constant and homogeneous. Then we can simplify the equation as follows:

$$i\hbar\frac{\partial}{\partial t}c_{n,k}(t) = -e\vec{r}Ec_{n,k}(t) \tag{6}$$

The solution of this equation contains a phase factor as follows:

$$c_{n,k}(t) = c_{n,k}(0)e^{-ie\vec{r}\,.\,Et/\hbar} \quad (7)$$

This result shows that the wave function of the electron $c_{n,k}(0)$ does not change over time, only its phase changes. This phase change causes a change in the momentum of the electron. The momentum of the electron can be calculated as follows:

$$\vec{p} = i\hbar\nabla_k c_{n,k}(t)^* c_{n,k}(t)$$
$$= i\hbar\nabla_k \left|c_{n,k}(t)\right|^2 e^{-ie\vec{r}\,\cdot\,Et/\hbar} \quad (8)$$

Here $\vec{p}$ is the momentum vector, ∇_k is the partial derivative of the wave vector, and $c_{n,k}(t)$ represents the electron wave vector. To simplify this expression, let us assume that k is small and that the wave function changes slowly with respect to k. Then, by doing a Taylor series expansion, we obtain:

$$\vec{p} = i\hbar\nabla_k \left|c_{n,k}(0)\right|^2 - e\vec{r}\,\cdot\,Et^{-ie\vec{r}\,\cdot\,Et/\hbar} \quad (9)$$

This result shows that the electron's momentum increases linearly [5,12]. The rate of this increase is proportional to the magnitude and direction of the electric field. This means that the electric field creates a current on the semiconductor. To calculate the electrical effect of oblique light, we need to know the angle at which the light hits the surface of the semiconductor and its refractive index. If the angle at which the light hits the surface is θ_i and the refractive index is n, we write Snell's law as follows:

$$n\sin(\theta_i) = (\sin\theta_r) \quad (10)$$

Here θ_r is the angle at which the light is refracted. The momentum of the light is given as follows:

$$\vec{p}_{photon} = \frac{hf}{c} \quad (11)$$

Here h is the Planck constant, f is the frequency of light and c is the velocity of light. If we write the components of the momentum of light:

$$\vec{p}_x = \vec{p}_{photon}\cos(\theta_i) \quad (12)$$

$$\vec{p}_y = \vec{p}_{photon}\sin(\theta_i) \quad (13)$$

As a result of the refraction of light within the semiconductor, while the horizontal component of the momentum is conserved, the vertical component changes. The new vertical component is as follows:

$$\vec{p}_y = \vec{p}_{photon}\sin(\theta_r) = n\,\vec{p}_{photon}\sin(\theta_i) \quad (14)$$

In this case, the change in the vertical component of the momentum is used to create an electron-hole pair from some of the photons entering the semiconductor. This event is called photonic emission. The efficiency of photonic emission is related to the bandgap of the semiconductor and the energy of the photon. If the energy of the photon is greater than the bandgap, the probability of photonic emission increases. If the energy of the photon is equal to or less than the bandgap, the probability of photonic emission decreases.

EXPERIMENTAL SETUP and FINDINGS

The effects of OAM beams on matter-light interaction emerge as a method that can be used to increase the efficiency of photovoltaic cells. In this study, OAM beams with different topological values were generated with SLM and focused on a photovoltaic cell. The effect of OAM beams on the current values on the photovoltaic cell was experimentally measured (Figure 1). The results showed that OAM beams increased the current generation of photovoltaic cells.

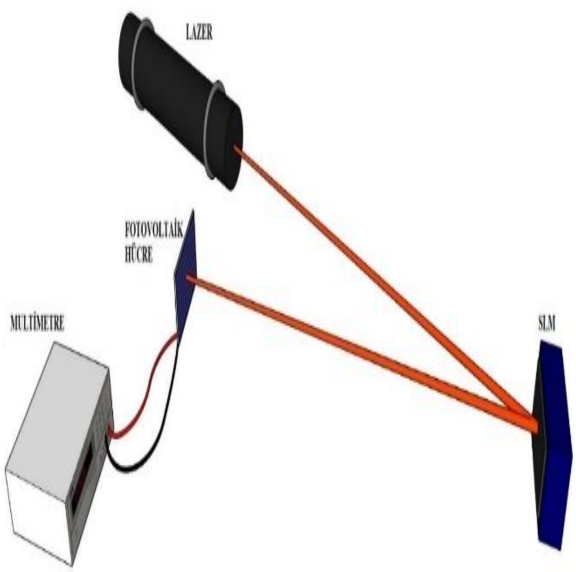

Figure 1. Schematic of the experimental setup established to investigate the electrical effect of OAM on a photovoltaic cell [26].

In the experimental setup, the distance between the SLM and the photovoltaic panel is 1.5 meters and the experimental set-up used are as follows: diode laser (wavelength $500\,nm - 570\,nm$ and output power is $200\,mW$), Photovoltaic cell panel (panel size is $50\,mm \times 50\,mm$) and measuring device. The resolution and accuracy specifications of the meter are given in Table 1 and other specifications of photovoltaic panel are given in table 2.
In this study, very low currents were measured. These currents can easily be affected by environmental factors such as light. Therefore, the experimental setup was

established in a dark optical laboratory to protect the photovoltaic photovoltaic panel from environmental effects. Measurements were made by focusing an OAM light spot with topological values of -2, -1, 0, 1 and 2 on the photovoltaic panel.

Table 1. DC current characteristics of GW Instek GDM-8245 benchtop digital multimeter [26]

Range	Resolution	Accuracy
500 μA	0.01 μA	$\pm(0.2\% + 2)$
5 mA	0.1 μA	$\pm(0.2\% + 2)$
50 mA	1 μA	$\pm(0.2\% + 2)$
500 mA	10 μA	$\pm(0.2\% + 2)$
2 A	100 μA	$\pm(0.3\% + 2)$
20 A	1 mA	$\pm(0.3\% + 2)$

Table 2. Photovoltaic panel features [26]

Panel Parameters	Explanation
Nominal Voltage (VMP)	2 V
Nominal Current (IMP)	160 mA
Open Circuit Voltage	2.4 V
Short Circuit Current (ISC)	190 mA
Photovoltaic Material	Monocrystalline Silicon

The aim of this study is to experimentally investigate the photovoltaic effect of OAM. For this purpose, an OAM beam was focused on a photovoltaic panel. Our experimental results showed that the current values of beams with positive OAM values ($\ell_{OAM} = (+)$) were higher than those of beams with zero OAM values ($\ell_{OAM} = 0$). The current values of beams with negative OAM values ($\ell_{OAM} = (-)$) were found to be lower than those of beams with zero OAM values ($\ell_{OAM} = 0$). These results are consistent with theoretical expectations. The experimental results are as follows [26]:
Observations show that as the OAM value increases, the current increases in the positive direction and as the OAM value decreases, the current decreases in the negative direction. These results show that it is possible to transfer the OAM value from a photon to an electron. The rate of increase relative to zero OAM value was measured as 9.1% for $\ell_{OAM} = +1$ and 18.2% for $\ell_{OAM} = +2$. In addition, the current decrease was 3.65% for $\ell_{OAM} = -1$ and 9.1% for $\ell_{OAM} = -2$. Theoretical studies by Watzel et al. showed that the expected increase rate for $\ell_{OAM} = +1$ was 2.6% and the expected current decrease for $\ell_{OAM} = -1$ was 4.2% [17]. The results obtained in this paper clearly show that better results were obtained for positive OAM values [26].

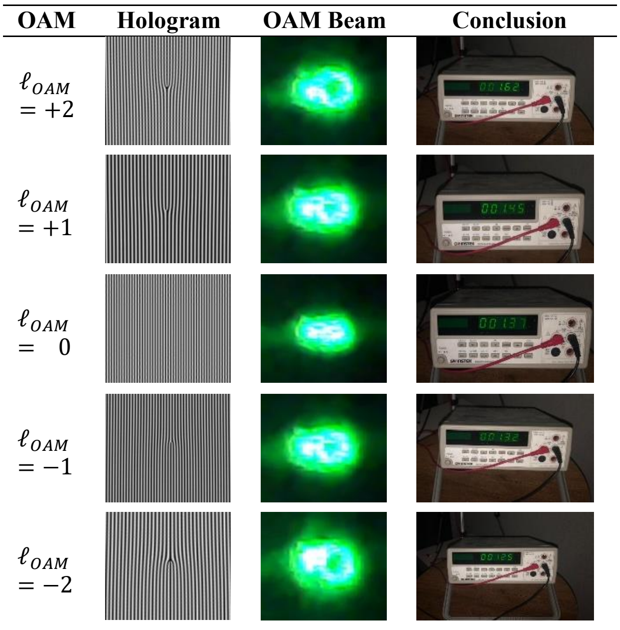

Figure 2. Current results according to OAM values

CONCLUSION

This study aims to experimentally investigate the electrical effect of an OAM beam spot obtained using SLM on a semiconductor photovoltaic panel. In experiments with OAM beams with different topological values, it was predicted that positive angular momentum values would increase the current and negative angular momentum values would cause a decrease in current. The results obtained support these predictions (Table 3). In addition, the results, which were compared with similar theoretical studies, have experimentally demonstrated the transferability of the OAM value to the electron. Furthermore, an increase in the topological value of the OAM beam in the positive direction causes higher currents to be generated.

Table 3. Comparison of the effect of OAM on a semiconductor with a theoretical study [26].

	The values obtained in this study		The theoretical values obtained in the compared study	
OAM value	$\ell_{YAM} = +1$	$\ell_{YAM} = -1$	$\ell_{YAM} = +1$	$\ell_{YAM} = -1$
Increase and Decrease rate	(+) %9.1	(-) %3.65	(+) %2.6	(-) %4.2

An OAM beam is a type of beam that can be used to generate and direct load currents on a semiconductor. The magnitude and direction of these currents depend on the topological property of the OAM beam. By changing this value, the currents can be controlled as Expected. An OAM beam can also be used to increase the photovoltaic effect in solar energy production. As the number of OAM beam spots falling on a solar panel increases, more electric current is obtained.

To increase the efficiency of photovoltaic panels, usually the properties of the material are manipulated. However, in this study, it has been shown that it is also possible to increase efficiency by manipulating the properties of light. The current increase obtained with a single OAM light spot was found to be 9.1%. This rate can be further increased by increasing the number or OAM value of OAM light spots.

Various sources are used to meet the energy needs of the world. One of these is renewable energy. Interest in renewable energy sources contributes to both reducing environmental problems and producing lower-cost energy. Therefore, it is very important to increase the efficiency of renewable energy sources. This study reveals how higher currents can be obtained by manipulating light. It is thought that this study will contribute to future studies on producing more energy from sunlight.

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