Polarization Switch of Carbon Nanotubes

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Abstract

Polarized light is used in liquid crystal display televisions and other products and is therefore familiar in our daily lives. It is also closely related to optical communications. In this article, we explain a theoretical prediction that a polarizer composed of carbon nanotubes exhibits a novel phenomenon of switching between two polarization components.

Keywords: polarizer, carbon nanotubes, plasmons

1. Introduction

When we write a straight line on a blank sheet and look at it through a transparent mineral called calcite, the single straight line appears as two parallel lines to the eye. This phenomenon is an easy way to understand that light consists of two polarization components. When those two parallel lines are viewed through a polarizer (a linear polarized filter), there is an angle of the polarizer in which only one straight line is visible. If the angle of the polarizer is rotated a further 90°, the straight line that was visible is not visible, and the straight line that was not visible becomes visible. In this way, we can also see that the two components of polarized light are orthogonal, so we call the two polarization components corresponding to the XY orthogonal coordinate axes as X-polarization and Y-polarization components. These two polarized components are closely related to our daily lives, although we do not have much consciousness of them. For example, we can see that with a polarizer the image on a liquid crystal display television is polarized.

Interestingly, polarization is also closely related to advanced technology in modern optical communications. The reason is that if two polarization components are used, it is possible to double the amount of information to be transmitted at the same time in optical communications. Different information containing voice and video data can be transferred to the two polarized components and propagated at the speed of light.

2. Basic science of polarized light

Thought experiments using polarized light have resulted in new knowledge concerning the laws of nature [1]. To cite one example, the well-known proposition in quantum information science that a general quantum-mechanical state cannot be copied was made based on the polarization of light [2]. According to quantum mechanics, light shows not only properties as waves (electromagnetic waves) but also behavior as particles. The light that we can see in our everyday life is propagated in a massive number of point particles called photons. Two components of polarized light correspond to two states that can be taken by one photon, and the state where the two X- and Y-polarization components are superimposed is a general polarization state. We can theoretically prove that this superimposed general polarization state cannot be cloned.

In light of this pioneering achievement, we surmise that the polarization possessed by classical electromagnetic waves is itself a degenerate quantum state of photons, and by applying these corresponding relationships, researchers like us—who are accustomed to classical mechanics—will be able to understand the strange mechanism of quantum mechanics represented in the superposition of states. In fact,

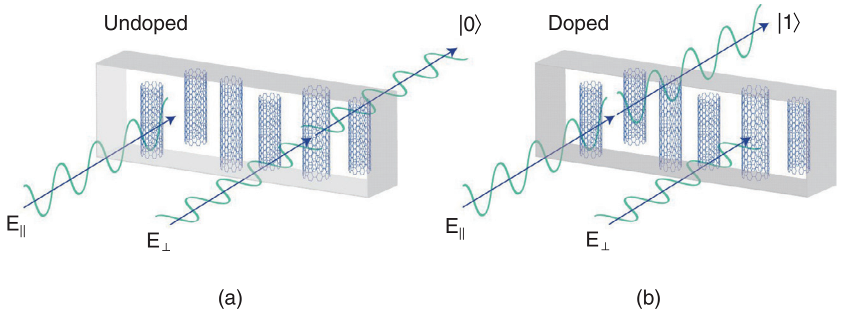


Fig. 1. (a) Undoped carbon nanotubes transmit only perpendicular polarized light. (b) Doped nanotubes transmit only parallel polarization. Since the polarization of the transmitted light rotates 90 degrees by doping, the aligned nanotubes function as a polarization switch.

well-known textbooks on quantum mechanics use polarization to introduce the subject of quantum mechanics [3].

Polarized light therefore has many interesting aspects in a wide range of fields from classical electromagnetism to quantum mechanics and is therefore of great interest to us. Devices (a polarization beam splitter and waveplate) currently exist that can rotate the direction of polarization, but there are no devices that can freely switch the two polarized components. We introduce here a theoretical prediction that such a polarization switch can be done with carbon nanotubes.

3. Polarizer of carbon nanotubes

Carbon nanotubes are cylindrical molecules with diameters as small as 1 nm and lengths up to several micrometers. They consist of carbon atoms and can be thought of as graphene sheets wrapped into cylinders. The diameter of a human hair is about 50 µm and is therefore approximately 50,000 times larger than the diameter of a nanotube. This comparison indicates just how thin carbon nanotubes are. By dispersing a large number of carbon nanotubes on an organic film and then pulling on the film, we can produce a film in which the axial direction of the carbon nanotube is oriented towards the pulling direction.

It has been confirmed that aligned carbon nanotubes function as a polarizer [4, 5]. That is, a carbon nanotube absorbs light whose linear polarization is parallel to the tube's axis, but not when the polarization is perpendicular to it.

Why does a carbon nanotube transmit only perpendicular polarized light? The electric field has a screening effect—called a depolarization effect—that plays a very important role. The depolarization effect occurs when an electric field is applied perpendicularly to the axis. Positive and negative charges are then polarized on the surface of the tube, which creates a new electric field. This newly generated electric field plus the added external electric field becomes the total electric field that the electron actually *sees*. Interestingly, the new electric field is almost the same as the added electric field in magnitude, but the sign is opposite, which cancels them out. As a result of this cancellation, the total electric field almost disappears. Because the absorption of light is proportional to the total electric field, the absorption is suppressed, and a nanotube is almost transparent against a perpendicular polarization.

4. Polarizer of doped carbon nanotubes

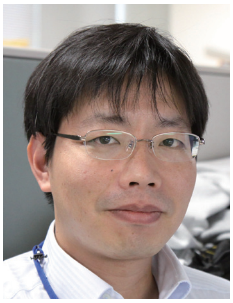
Suppose that the polarization component to be transmitted by a nanotube polarizer is X-polarization. To switch it to Y-polarization, we can rotate the nanotube film by 90° in the same manner as with a normal polarizer. We found theoretically that with carbon nanotubes, the direction of the transmitted light could be changed by 90° without any spatial rotation by adjusting the number of electrons in the nanotube through charge doping [6]. That is, a doped carbon nanotube transmits parallel polarized light and absorbs perpendicular polarized light, as illustrated in **Fig. 1**.

The absorption of perpendicular polarized light in a doped nanotube is a *many-body effect* that excites electrons in a collective manner, which is known as plasmon resonance. Doping increases the contribution of the depolarization field. Even if an infinitesimal external electric field is applied, a finite electric field is generated. The plasmon excitation is essentially different from the single-particle excitation caused by parallel polarized light in an undoped nanotube.

In our study, we intend to provide the opportunity to investigate transitions between two polarized components by means of an electrical method (doping) as well as general-purpose optical measurements (namely, optical absorption). Accordingly, while the study will experimentally investigate the scientific potential of nanotubes through basic research, it will also revitalize applied research on optical devices.

5. Significance of results

To change the polarization direction of light transmitted through a typical polarizer, it is necessary to rotate the lens itself. However, on the basis of our theory of doping dependence, it is anticipated that a nanotube polarizer can reverse the polarization of the transmitted light by 90° without the need for such spatial rotation. The significance of the phenomenon we have discovered can be easily understood from the standpoint of optical transmission. In regard to cutting-edge optical-transmission technology, as represented by digital-coherent devices, the two degrees of freedom of polarization of light are utilized to double the amount of information that can be transmitted. Different kinds of information such as images and sound are transcribed to orthogonally polarized light and transmitted. A polarization switch based on carbon nanotubes can be used to manipulate information within a highly miniaturized structure for optical transmission.



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