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Stretchable carbon-nanotube films as opto-mechanically controllable modulators of terahertz radiation

M.I. Paukov [1] ✉, V.V. Starchenko [1], D.V. Krasnikov [2], S.S. Zhukov [1],
B.P. Gorshunov [1], A.G. Nasibulin [2], A.V. Arsenin [1], V. Volkov [1]

[1] Moscow Institute of Physics and Technology (State University), Dolgoprudny, Moscow Region, Russia;
[2] Skolko Institute of Science and Technology, Moscow, Russia
✉ paukov.mi@phystech.edu

Abstract. This study considers the optical modulation parameters of THz radiation generated via optical-pump terahertz probe spectroscopy, passing through thin films of single-walled carbon nanotubes (SWCNT), attached onto the stretchable substrate. We investigated the dependence of photoconductivity of the stretched film on the elongation and orientation of its direction towards THz beam polarization. We interpreted the changes observed, establishing the key factors affecting the photoconductive pathways. The obtained modulators were characterized practically: the wide range of modulation depths (MD) (up to 100%) and fast lifetimes of photoinduced charge carriers (5 ps) were marked. This research guides the way to construct the devices of switchable optoelectronics, which are of a perspective in the THz data transfer systems.

Keywords: Terahertz modulator, carbon nanotubes, THz-TDS, optical-pump terahertz probe spectroscopy, ultrafast devices

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Растягиваемые плёнки углеродных нанотрубок как опто-механически контролируемые модуляторы терагерцового излучения

М.И. Пауков [1] ✉, В.В. Старченко [1], Д.В. Красников [2], С.С. Жуков [1],
Б.П. Горшунов [1], А.Г. Насибулин [2], А.В. Арсенин [1], В. Волков [1]

[1] Московский физико-технический институт (государственный университет), г. Долгопрудный, Московская область, Россия;
[2] Сколковский институт науки и технологий, Москва, Россия
✉ paukov.mi@phystech.edu

Аннотация. В данной работе изучались параметры оптической модуляции терагерцового сигнала при прохождении через тонкие плёнки одностенных углеродных нанотрубок УНТ, нанесённых на растягиваемую подложку, методом спектроскопии оптической накачки терагерцового зондирования. Было проведено исследование поведения фотопроводимости в зависимости от ряда параметров: относительного удлинения и сжатия плёнки, расположения по отношению к поляризации терагерцового излучения. Мы представили интерпретацию изменения параметров фотопроводимости в зависимости от растяжения, отметив факторы, влияющие на изменение фотопроводящих путей. Полученные модуляторы также были охарактеризованы с практической точки зрения: были отмечены широкий диапазон глубины модуляции (от 5 до 100%) и малое время релаксации фотовозбуждённых носителей зарядов (порядка 5 пс), Данное исследование позволяет создавать устройства перестраиваемой оптоэлектроники перспективные в терагерцовых системах передачи информации.

Ключевые слова: Терагерцовый модулятор, углеродные нанотрубки, терагерцовая спектроскопия во временной области, спектроскопия оптической накачки терагерцовой пробы, ультрабыстрые устройства

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Introduction

Terahertz radiation has found application in many spheres of life, from detection of exploding weapons to tumor diagnostics. Thanks to wide bandwidth and relatively small attenuation, THz waves may come into practice for secure connections, which makes them promising candidates for high-speed wireless data transfer. Modulation of a signal is an important feature which should be taken into account in design of these communications. It is determined by the conductivity of the medium through which THz radiation is passing. This makes it possible to control the modulation parameters optically, thermally and electrically.

Traditional bulk semiconductors like GaAs, Ge and Si, being modulated electrically or optically, have only one high parameter, either modulation depth or modulation speed (order of hundreds of GHz) [1–3]. At the same time, low dimensional structures like graphene, carbon nanotubes and 2D transition metal dichalcogenides demonstrate both high MD and modulation speed (MS).

However, no stretchable modulators with such parameters are found. In this paper, the parameters of opto-mechanical THz modulation for the samples of carbon nanotube films, applied onto stretchable substrate, are studied by means of OPTP spectroscopy. The given modulators are characterized from practical view. High modulation depth (approximately 100%) and small relaxation time of photoinduced charge carriers (5 ps) have been reported. This study allows to construct switchable devices for optoelectronics, promising for THz-range systems for data transfer.

Materials and Methods

SWCNTs were synthesized by the aerosol chemical vapor deposition (CVD) method and then transferred on a 0.2 mm thick elastomer [4, 5]. The SWCNT film with thicknesses of 106 nm, corresponding to optical transmittance of 60% at 550 nm wavelength, consisted of one-third metallic and two-thirds semiconducting SWCNTs, which were initially randomly aligned. SWCNT film on the elastomer was placed into the home-made mechanical stretcher. The film holder was placed into the spectrometer so that the probe THz beam polarization was perpendicular and parallel according to the stretching direction.

The pump beam was generated by an optical parametric amplifier, seeded by a 1 kHz, 40 fs, 800 nm pulse. The average pump power was estimated as 3.92 mW, the and the width of the pump beam on the sample was 0.9 mm. Here, a wavelength of 600 nm for pump was used (above the E11 and E_{22} excitonic transitions of the CNTs). The probe beam was generated using home-made conventional THz-TDS setup as described in [6], allowing us to measure both equilibrium conductivity and photoconductivity. The extraction of the photoconductivity was implemented according to our previous study [7].

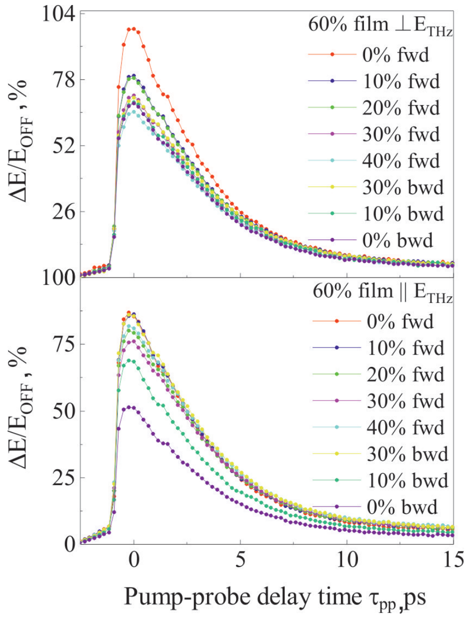

Fig. 1. Modulation depth in transmission as a function of pump-probe delay time when the elongation is perpendicular (top) and parallel (bottom) to the polarization of the THz probe beam.

Results and Discussion

Studying the dynamics of photoinduced charged carriers for different stretching parameters, we discovered that the modulation depth, defined at the peak (see Fig. 1), decreases with growing elongation and becomes irreversible when compressed. It is observed that CNTs possess high modulation depth of approximately 100% at the start, which was seldom reported for any other materials. In addition, CNTs demonstrate high modulation speed (MS), which is a frequency of relaxation and defined as the inverted lifetime of the photoexcited charge carriers. The latter was estimated from the exponential decay as the time, when the amplitude of the detected THz radiation is reduced by e times with respect to its maximum. Since the relaxation time is approximately estimated as 5 ps, MS is 210–250 GHz (it is different due to the stretching). Particular factors that may affect the behavior of photoconductivity and the defined parameters MD and MS include alignment of the SWNTs in the direction of stretching and their tendency to form bundles because of the electrostatic interaction between nanotubes. These contributions influence the photoconductivity pathways and, hence, the aforementioned quantities. However, these changes should be analyzed separately for clearer understanding.

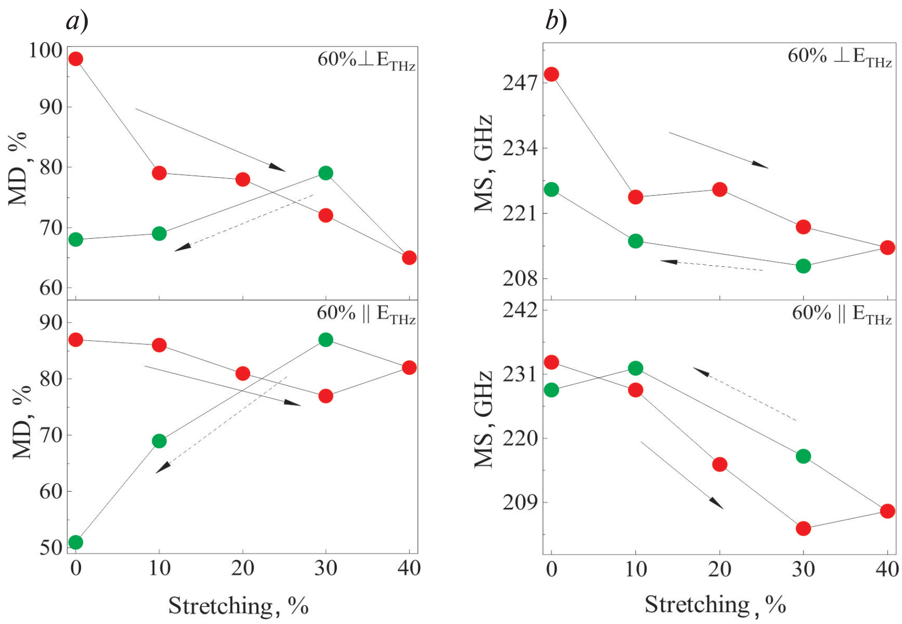

Fig. 2. Transmission-mode MD (*a*) and MS (*b*) for sample with transmission 60% at 600 nm (60% film in Fig. 1) at stretching varying from 0 to 40 % (‘fwd’ in the graph) and compression from 40 to 0 % (‘bwd’ in the graph). The arrows indicate the direction of stretching and the following compression.

Conclusion

In this work, we showed the influence of stretching on optically controlled SWCNT modulators for the first time. They show almost 100% modulation depth and relatively high modulation speed of almost 250 GHz. At the same time, it was shown that the simultaneous optical modulation and stretching make modulators more tunable. This information can be used to predict the performance of stretchable modulators based on SWCNT. The backward contraction reveals that modulation depth before and after stretching is different, which reflects irreversible properties of SWCNTs photoconductivity. However, once the mechanical modulation is performed, then it can be corrected via the change of the optical pump.

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THE AUTHORS

PAUKOV Maksim I.
Paukov.mi@phystech.edu
ORCID: 0000-0003-1039-3170

STARCHENKO Vladimir V.
Starchenko.vv@ phystech.edu

KRASNIKOV Dmitriy V.
d.krasnikov@skoltech.ru
ORCID: 0000-0002-6721-6530

GLADUSH Yuriy G.
y.gladush@skoltech.ru
ORCID: 0000-0002-1289-2654

ZHUKOV Sergey S.
zhukov.ss@mipt.ru

GORSHUNOV Boris P.
bpgorshunov@gmail.com
ORCID: 0000-0002-6534-1880

NASIBULIN Albert G.
a.nasibulin@skoltech.ru
ORCID: 0000-0002-1684-3948

ARSENIN Alexey V.
Arsenin.av@mipt.ru
ORCID: 0000-0002-7506-4389

VOLKOV Valentyn S.
vsv@mipt.ru
ORCID: 0000-0003-2637-1371

BURDANOVA Maria G.
Burdanova.mg@mipt.ru
ORCID: 0000-0001-5439-2933

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