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Carbon nanotube attached subwavelength grating for broadband terahertz polarization conversion and dispersion control

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ABSTRACT

Carbon nanotube (CNT), as a recently emerged newfangled nanomaterial, has been applied in terahertz (THz) polarizer due to its anisotropic hyper-ordered orientation. Herein, we simply adhere two orthogonal CNT sheets to the both sides of dielectric subwavelength grating to form a compound structure (i.e. CNT@Grating). Due to the subwavelength integration and cavity modes, the CNT@Grating presents local resonances between two CNT sheets, which greatly enhances the polarization rotation and expands the bandwidth. Compared with the large phase shift dispersion of single subwavelength grating, its phase shift dispersion and impedance can be manipulated by adjusting the layer number of CNT, and finally a broadband close zero dispersion from 0.4 to 0.95 THz has been obtained, which leads to a broadband THz polarization conversion. This work provides a new design idea towards practical applications for THz broadband polarization conversion and dispersion control.

1. Introduction

Terahertz (THz) wave, as the lasted known electromagnetic frequency range from 0.1 to 10 THz, has the superiority of low photon energy, high penetrability and fingerprint spectrum, which can apply in nondestructive detection, material spectroscopy, and wireless communications [1–4]. Phase and polarization are the basic parameters of electromagnetic wave. They can not only carry useful electromagnetic information, but also manipulate the propagation and states of light. With the development of THz technology and its application system, high performance THz phase and polarization control devices are urgently needed [5,6]. Traditional THz polarization conversion devices are based on the natural birefringence properties of uniaxial crystal, but their performance of these devices is not ideal due to the large volume, high loss, and large dispersion as well as narrow bandwidth for a certain phase shift [7,8].

Over the past decade, artificial electromagnetic microstructures have been proposed, such as metamaterial or metasurface [9–15], which can be excellent candidates to realize polarization conversion via introducing artificial mode birefringence or chiral polarization rotation [16–21]. For example, Yu et al. demonstrated a background-free quarter wave plate with V-shaped metasurface. By properly adjusting spatially inhomogeneous antenna array, the high polarization degree of 97% was obtained at infrared band [22]. Cong et al. realized a cross polarization control with flat split-ring resonator through varying the orientation and preserving the rotational symmetry [23]. Compared with natural birefringence crystals, it is superior in ultrathin size, easy to integrate and flexible to control. Nevertheless, the metallic materials often bring much loss in the transmission devices. Such as, Liu et al. proposed a novel single-layer metasurface, which can realize the cross-polarization conversion from 0.8 to 1.4 THz, but the highest transmittance is only less than 30% [24].

The artificial birefringence of subwavelength dielectric gratings can be applied in the phase and polarization manipulation of light

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[25]. Moreover, the use of dielectric material can bring high transmittance. For example, Chen et al. reported an artificial THz waveplate that based on high birefringence gradient grating. However, it only works in a narrow band for half wave plate due to the large phase shift dispersion in the THz regime [26]. Carbon nanotube, as a recently emerged newfangled nanomaterial, made by rolled-up graphene sheet, can acts as an excellent THz linear polarizer due to their anisotropic hyper-ordered orientation [27–30]. For example, Ren et al. achieved an ideal polarizer in a broadband with the polarization extinction ratios of 10^{-3} based on triple-layer single-walled CNT films on sapphire substrates [31]. Kyoung et al. demonstrated a reel-wound CNT polarizer at THz frequency from 0.1 to 2 THz with little dispersion [32]. Therefore, the combination of dielectric gratings and CNT may bring the opportunity for THz polarization conversion with broadband and low dispersion.

In this letter, we proposed a broadband THz linear polarization convertor, which integrated with the dielectric grating and CNT (CNT@Grating). Here, CNT plays a role of polarizer like the commercial metal wire grid and dielectric grating has a large birefringence that can employ as artificial wave-plate. Due to the subwavelength integration, the CNT@Grating structure presents local resonance between dielectric grating and CNT, which greatly enhances the polarization rotation and expands the bandwidth. In addition, this structure has the superiority of easy fabricating, just via physical deposition on dielectric grating, instead of complex processing techniques.

2. Experimental methods

2.1. Device fabrication

Fig. 1 shows the SEM photos and schematic diagram of CNT@Grating. The dielectric grating is fabricated by MEMs technology. A 500 μm thickness Si wafer with a high resistivity of 10 KΩ•cm is cleaned and a 5 μm layer of photoresist is spun onto the wafer. Then, the wafer is exposed by UV light through a mask to yield the expected structure, and is shaped by the inductively coupled plasma etching. The etched depth is controlled by the different etching time, about 70 min for 200 μm. Then, it is measured by a step profiler. So a series of periodic ridges and grooves are obtained with the grating constant of 50 μm and the groove of 20 μm width, as shown in Fig. 1c.

The CNTs are highly aligned CNT sheet, which is drawn from a sidewall of a MWCNT forest [32]. We firstly twine one side of single layer CNT on glass rod, and pull it out from the CNT forests, then fix it on the rectangular frame. Secondly, we use tweezer grip the corner of the grating and make sure it has a 45° orientation to the CNT, then quickly pressure it on the impending CNT. After that, we use the ethanol spray-coated onto the sample, in order to make the CNT well attach to the surface of grating. Repeat the above steps, the multi-layer CNT can adhere on the two surface of grating. The layer number of one CNT sheet can be controlled from 1 to 20 or even more. On the front surface of grating, the CNT1 forms a special bridge structure between the two grating ridges as shown in Fig. 1c and (d). The alignment of CNT1 is along *x*-direction, the alignment of CNT2 is along *y*-direction directly on the back surface of the Si grating, and the alignment directions of these two CNT sheet are oriented ±45° to the grating ridge as shown in Figs. 1d and 2(a). The thickness of single layer of CNT sheet is about 10 nm. In fact, there are some gaps between CNTs in the same layer, so the multi-layer of CNTs will makes the CNT from adjacent layer to filling the gap. For example, the total thickness of 15 layers of CNTs is slightly less than 150 nm. More SEM photos of CNT@Grating are shown in Fig. S1 of Supplementary Information.

2.2. Experimental system

We do our experiment by using standard THz time domain spectroscopy (THz-TDS) system. THz pulse is generated by a low-temperature grown GaAs photoconductive antenna (PCA). The excitation source is a Ti:sapphire laser with 75fs duration of 80 MHz repetition rate at 800 nm. A ZnTe crystal is used for detection. All the experiments are carried out at room temperature with the humidity of less than 5%.

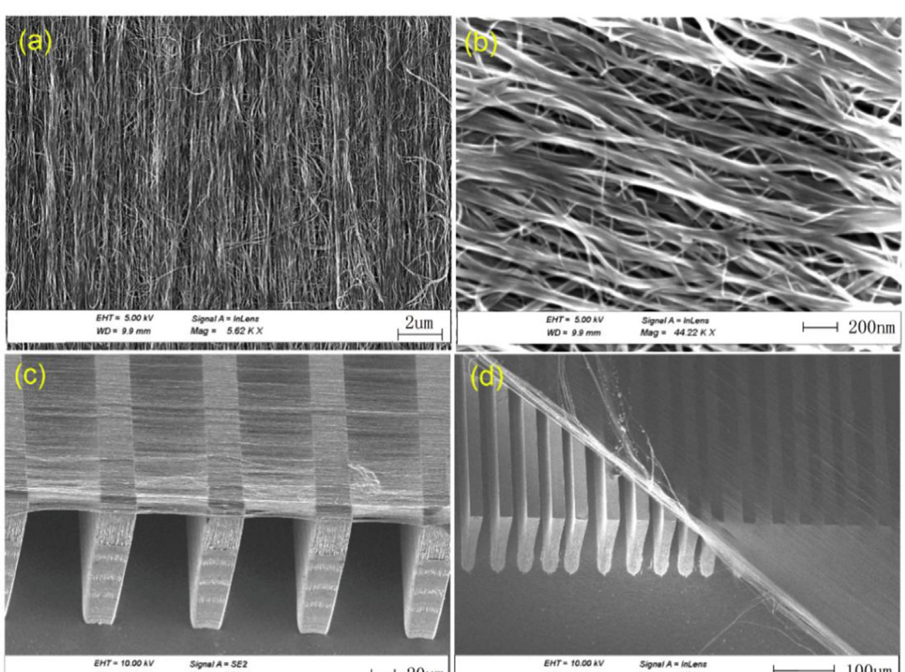

Fig. 1. SEM representation: (a) and (b) SEM photos of CNT sheet; (c) and (d) SEM photos of CNT@Grating. (A colour version of this figure can be viewed online.)