Physica E 66 (2015) 67–73

Contents lists available at ScienceDirect

Physica E

journal homepage: www.elsevier.com/locate/physe

Analysis of graphene based optically transparent patch antenna for terahertz communications

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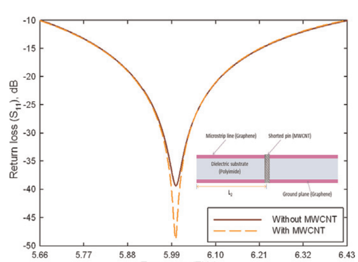
HIGHLIGHTS

- Application of graphene as a transparent conducting material for the patch antenna with and without MWCNT short is analyzed in the 5.66–6.43 THz band.
- The MWCNT loaded graphene based antenna yields a return loss improvement of 9.38dB as compared to that without the MWCNT loaded antenna.
- Both the transparent antennas achieved broad bandwidth (12.83%), high directivity (7.56dB), and high gain (≥ 2dB).

GRAPHICAL ABSTRACT

By shorting the microstrip line and ground plane of the antenna with a MWCNT, the return loss of the antenna is improved. It is observed that the return loss of −48.75dB is obtained for a MWCNT loaded antenna as compared to −39.37dB obtained for that without a MWCNT loaded antenna. Return loss improvement of 9.38dB is achieved for antenna loaded with MWCNT. Thus by optimizing the position of the MWCNT short return loss of the antenna is significantly improved for the same impedance bandwidth. Both the graphene based transparent antennas achieved the −10dB impedance bandwidth of 12.83%. The graphene based transparent antennas have broad bandwidth (12.83%), high directivity (7.56dB) and high gain (≥ 2dB).



ARTICLE INFO

Article history:
Received 8 May 2014
Received in revised form
17 August 2014
Accepted 30 September 2014
Available online 7 October 2014

Keywords:
Graphene
Transparent antenna
Graphene antenna
Patch antenna
MWCNT loaded antenna
Terahertz

ABSTRACT

With and without multi walled carbon nanotube (MWCNT) loaded graphene based optically transparent patch antennas are designed to resonate at 6 THz. Their radiation characteristics are analyzed in 5.66–6.43 THz band. The optically transparent graphene is deployed as the patch and ground plane of the antennas, which are separated by a 2.5 μm thick flexible polyimide substrate. By shorting the microstrip line and ground plane of the antenna with a MWCNT via, the return loss of the antenna is improved. The peak gain of 3.3dB at 6.2 THz and a gain greater than 3dB in 5.66–6.43 THz band is obtained for antenna loaded without MWCNT. Both the antennas achieved a −10dB impedance bandwidth of 12.83%. Gain, directivity and radiation efficiency of the proposed antennas are compared with conventional transparent patch antennas and graphene based non-transparent antennas. The antenna structures are simulated by using finite element method based electromagnetic simulator-Ansys HFSS.

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http://dx.doi.org/10.1016/j.physe.2014.09.023
1386-9477/

1. Introduction

In recent years, transparent conducting material (TCM) has been a critical component in many photoelectronic devices such as liquid crystal displays (LCD) [1], solar cells [2], organic light emitting diodes (OLED) [3] and antennas [4–6]. Traditionally, this role has been well served by ITO (Indium Tin Oxide) material. But ITO is becoming very expensive due to the limited supply of element indium. In the race to overcome the ITO limitations, monolayer and multi-layered transparent carbon based conductors such as graphene, carbon nanotubes (CNTs) have emerged as the viable alternatives which satisfy the future requirements of TCM for optoelectronic applications [7]. Recent advances in graphene film synthesis and its characterization indicate that it is suitable for photoelectronic applications including its use as a flexible transparent conductor [8,9]. The electrical properties of graphene are analyzed theoretically and experimentally in [10–13]. The challenge in using TCM as the antenna patch is retaining the optical transmittance of the material while optimizing its electrical conductivity [14]. In [15], optical transmittance greater than 90% was observed in graphene films with a thickness of tens of nanometres in the 400–1800 nm wavelength range. Integration of optically transparent antennas with solar cell can reduce the overall system size, weight, cost and visual disturbances [16]. In space applications like satellites, size and weight of the on-board payload are the two critical parameters. By designing optically transparent antennas on solar cell panel displays such that the display itself can act as antennas, the overall size and weight of the satellite system can be reduced [17].

Increasing the carrier frequency of the communication system results in numerous advantages such as broad bandwidth for high data rate transmission, improved spatial directivity and resolution, reduced transmission power and system size. Most of the aforementioned advantages are achieved by operating the communication system in the terahertz spectrum [18,19]. It is of particular interest to service providers and system designers, because it offers broad bandwidth and free spectrum. The microstrip patch antenna is widely used in military and commercial wireless communication systems because of its low profile, planar and robust structure [20]. Owing to these properties, it is best suited for system miniaturization for terahertz frequency applications [21,22]. Conventional TCM patch antennas have limitations in terms of -10dB impedance bandwidth ($<5\%$), gain (<2dB) and poor radiation efficiency [23]. The slight deformation in the patch made from conventional TCMs like indium tin oxide (ITO), titanium-doped indium oxide (TIO), etc. can cause its impedance to alter. This results in an impedance mismatch [24]. But the impedance of graphene undergoes negligible change under deformation [25]. The return loss of the antenna can be reduced by shorting microstrip line and the ground plane with the conducting via [21]. The transparent multiwalled carbon nanotube (MWCNTs) is widely used for designing the interconnects in integrated circuits [26]. The performance of CNT based device undergoes minimal changes under bending on a polyimide substrate [27]. These are the considerations behind the motivation to investigate radiation performance of graphene based transparent patch antenna. In [28], graphene based terahertz frequency-reconfigurable antenna is designed using electromagnetic simulator-Ansys HFSS.

Using the Kubo formalism, the surface conductivity of graphene sheet is described as a function of frequency, chemical potential, scattering ratio, temperature and reduced Plank′s constant [29,30]. At terahertz frequencies, substantial change in temperature results in a minimal shift in resonant frequency for graphene based patch antenna. In [31], the effect of temperature on the graphene based terahertz patch antenna is studied. For 100°K change in the temperature from 250 to 350°K, resonant frequency of the antenna undergoes a shift of 0.15 THz. Graphene exhibits nonlinear elastic properties viz. third-order elastic stiffness and third-order elastic constant of 2 TPa and 690 N/m, respectively and a breaking strength of 42 N/m corresponding to Young′s modulus of 1 TPa [32,33]. The graphene deposited on polyimide substrate is reported to have very good thermal stability in the range 4.4–400°K and its resistance is stable up to a bending radius of 1 mm, suggesting excellent mechanical flexibility [34].

In this work, with and without MWCNT loaded graphene based microstrip patch antennas are designed on a 2.5 μm thick optically transparent polyimide substrate. The antenna characteristics are studied by shorting the microstrip line and ground plane with transparent MWCNT. The entire structure is optically transparent in the visible spectrum region and designed to resonate at 6 THz. Organization of the paper is as follows. Section 2 discusses the design of graphene based optically transparent microstrip patch antenna with and without shorting MWCNT. Section 3 investigates -10dB impedance bandwidth and radiation characteristics of with and without MWCNT loaded antennas and the results are compared with conventional transparent antennas and graphene based non-transparent antennas. Conclusions are made in Section 4.

2. Graphene based transparent patch antenna

The graphene based optically transparent microstrip patch antennas with and without shorting MWCNT are designed to resonate at 6 THz. Their dimensions are same and are of the order of micrometres as listed in Table 1. As shown in Fig. 1, the antennas have transparent conducting patch and a ground plane separated by 2.5 μm thick optically transparent polyimide substrate. The rectangular shaped transparent graphene sheet (patch thickness $t \ll \lambda_0$, where λ_0 is the free space wavelength) is used as the radiating patch. Thickness of the dielectric substrate material (h) should be very much less than a free space wavelength ($h \ll \lambda_0$, usually $0.003\lambda_0 \le h \le 0.05\lambda_0$) [35]. A transparent MWCNT of 10 nm diameter is used to short the microstrip line and the ground plane of the antenna. Its cross sectional view is shown in Fig. 2.

At the edges of the patch, electric field undergoes the fringing. This fringed electric field is a primary source of electromagnetic radiation [36,37]. Higher dielectric constant substrates for the antenna would result in poor radiation efficiency, narrow bandwidth and greater losses [38]. Hence, the substrate having a low dielectric constant is desirable for getting better radiation characteristics in the desired direction [39]. The microstrip transmission line, which connects the patch with the coaxial line, is employed for impedance transition to minimize the return loss (S_{11}) due to impedance mismatch. To further minimize return loss, the microstrip line is shorted with the ground plane of the antenna by using MWCNT. By varying the position of short along

Table 1
Design parameters of the graphene based optically transparent patch antenna.

Parameters	Dimensions	
Patch length, width	$L \times W$	10.71 μm × 14.87 μm
Dielectric substrate length, width and thickness	$L_s \times W_S \times h$	27.9 μm × 66.67 μm × 2.5 μm
Dielectric constant (polyimide)	ε_r	3.5
Microstrip line length and width	$L_1 \times W_1$	8.595 μm × 2.664 μm