Modeling and Performance Assessment of a Millimeter-Wave CVD Film-Graphene Based Antenna

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Abstract. The transfer of graphene onto dielectric substrates to form an antenna needs to be performed with care, as tears and cracks may appear on the samples transferred improperly. This paper studies a detailed method in estimating the performance of a millimeter-wave (MMW) antenna built using commercially-available graphene layers. In contrast to the widely studied monolayer graphene, the proposed antenna is produced based on the chemical vapor deposition (CVD) technique, which is to be secured onto the antenna substrate via adhesive material without removal of the transition metal substrate from the graphene layer sample. The antenna performance modeled using this technique indicated quite similar results to a model using ideal monolayer graphene in terms of gain, radiated power and radiation efficiency. Its performance benchmarked against a copper antenna operating at the same MMW frequency also indicated similar performance improvements as with another antenna designed using monolayer graphene.

Keywords. Antenna, millimeter wave, adhesive, CVD, monolayer graphene

1. Introduction
The technology of incoming 5G requires an antenna that should have high gain, capacity and wide spectrum beside the ability of steering. the classical antennas are incapable to serve the new higher frequencies due to the fabrication and installation restrictions, mainly for miniature sizes. Material like graphene is promised for small size antennas with thinner dimensions, which can radiate higher frequencies[1]. Graphene has been intensively researched considering its promising potential for the new generation of wireless communication systems that need low power, high mobility, and broad-band operation[2][3]. Graphene can be potentially applied in wireless nanosensors and THz band devices [4]. Originally, exfoliating graphene oxide or graphite is the common method for the production of high-quality monolayer graphene (HQMG). The other efficient approach for the production of HQMG is using chemical vapor deposition (CVD) technique [5][6]. However, the transfer procedure of CVD-grow graphene, requires the removal of the metal backing beneath the graphene layer to the intended substrate [7]. In other cases, a polymer support layer Polymethyl methacrylate (PMMA) was employed in [8], while a simple technique for the transfer of graphene from the copper backing has been proposed...
in [9]. However, such process of graphene transfer is not entirely mature, as a study has shown that several samples produced indicated tears and cracks upon its placement on the target substrate [6]. Besides that, the used solvent was also incapable of completely cleaning PMMA away [10]. As a result, the PMMA residue tend to behave like scattering centers for charge carriers, which then leads to a degradation in the electrical properties of graphene [11].

The bonding between two wafers or substrates enables the fabrication of new substrates and packaging of micro-components [12]. The wafer bonding process is increasingly used in the integration of materials in micro-electronics, optoelectronics, and MEMs [13]. Meanwhile, the application of wafer bonding in the building of silicon on insulator (SOI) substrate, and its packaging method was studied in [14]. This type of adhesion technology is also used in other fields such as mechanical engineering, polymers, microelectronics, medical etc [15]-[16]. Widely used adhesion technology includes the adhesive wafer bonding (AWB) [16]. This process uses an adhesive intermediate layer to bond two surfaces. AWB features insusceptibility to the surface contour, lower bonding temperatures, compatibility with integrated circuit wafer process and capability to bond various wafers. AWB also does not need any specific treatments to the wafer surface. Particles on wafer surfaces can be reduced using the adhesive material [16]. A review of the recent studies on adhesion with a specific concentration on its mechanisms was presented in [17]. Despite AWB being indicated as a significant technique, there are limited studies applying such technique for the fabrication of antennas, especially based on graphene [18] [19].

In this work, a rectangular microstrip antenna operating in MMW is designed and modeled using adhesive CVD film (CVDF) as its conducting layers. This is referred to as the graphene-based antenna (GBA). Such method potentially simplifies the GBA fabrication process without the need for specialized processes and equipment for the graphene to be transferred onto a target substrate. This work also attempts to assess the difference in performance when this technique is used in comparison to antennas made using ideal monolayer graphene and copper in the MMW band.

This paper is structured as follows. The upcoming section explains the method of determining the monolayer graphene conductivity across the frequencies of interest, followed by the chosen antenna patch topology and parameters. The improvement levels in terms of gain, radiated power and radiation efficiency are investigated among the microstrip antennas made using a conducting layer based on copper, monolayer graphene (ML-G) and CVDF. Both non-doped (ND) and doped (D) are used for both techniques of GBA. Finally the results are concluded.

2. Materials and Method

The investigated graphene based on the use of a composite that consisting of monolayer graphene deposited on a copper foil as a conductor as its transition substrate. This is similar to the commercially-available CVD graphene film which is a combination of graphene-coated metal composite shown in Figure 1. Such antennas are fabricated by dimensioning the graphene-based material according to the optimized antenna geometry and securing them onto PET (polyethylene terephthalate) substrate using epoxy resin as adhesive materials or any other materials suitable for use as intermediate layers for bonding such as polymers or polyimides [20]. However, steps must be taken to ensure that the dielectric constant of the adhesive is accounted for as part of the dielectric constant of the substrate. In this case, the adhesive material used is epoxy resin. Similar to using monolayer graphene, CVD-based antennas produced in this way are still expected to improve the gain, radiated power and radiation efficiency when operating in the MMW band compared to a copper-based antenna. Figure 2 shows the surface conductivity of a monolayer graphene while Figure 3 illustrates its surface impedance, which calculated based on surface conductivity. Then, the calculated values of surface impedance are used in the modeling of monolayer graphene in the CST electromagnetic solver [21] [19]. Next, the CVDF is modeled by combining the monolayer graphene on a copper backing before these layers are dimensioned as the patch, feed line, and ground layers of the microstrip antenna as shown in Figure 4(a). The behavior of this new antenna model is benchmarked against the conventional patch model with the same dimensions shown in Figure 4(b) using: copper-based antenna (CBA) and monolayer graphene based.
antenna (ML-GBA) as its conducting layers. These dimensions that summarized in Table 1 are calculated based on the desired resonant frequency at E-band operating within the 70 GHz [22] [23]. These layers are secured onto the substrate using the AWB technique and epoxy resin as adhesive material. For comparison, a copper and monolayer graphene version with the same geometric dimensions of the proposed antenna is also designed and assessed. Besides that, this study also aims to evaluate the effects of using non-doped graphene (NDG, with \( \mu_c = 0 \) eV chemical potential) and doped graphene (DG, with \( \mu_c = 0.5 \) eV chemical potential) using different configurations. This indicates that different materials (either copper or graphene) will be used as the patch and ground. The performance for both models (NDG and DG) are finally compared to an antenna based on conventional conductor (CBA) in terms of gain, radiation efficiency and radiated power.

**Figure 1.** Monolayer graphene deposited on a copper foil [24]

**Figure 2.** Real and imaginary parts of graphene conductivity for different chemical potentials

**Figure 3.** Calculated surface impedance of graphene in the mm-wave band for different chemical potentials
Table 1. Dimension of an antenna suggested model

| Parameters                              | Symbol | Value       |
|----------------------------------------|--------|-------------|
| Resonant frequency                     | \( f_r \) | 74.5GHz     |
| Width of Patch                         | \( W \) | 1500 μm     |
| Length of Patch                        | \( W \times 0.75 \) | \( W \times 0.75 \) |
| Width of Substrate                     | \( W_s \) | \( 2W \)     |
| Length of Substrate                    | \( L_s \) | \( 2L \)     |
| Thickness of Substrate                 | \( h \) | \( W/20 \)   |
| Relative Permittivity                  | \( \varepsilon_r \) | 3            |
| Length of feed line                    | \( L_f \) | \( (L/2+L_g) \) |
| Width of feed line                     | \( W_f \) | \( W/10 \)   |
| Length of the inset gap                | \( L_g \) | \( L/10 \)   |
| Width of the inset gap                 | \( W_g \) | \( W_f/10 \) |
| Thickness of Adhesive Material         | \( E_t \) | \( h/20 \)   |

Figure 4. Schematic diagram of microstrip patch antenna (a) The proposed CVDF-GBA (b) CBA

3. Results and Discussion

The GBA fabricated using the proposed adhesive technique indicated satisfactory results. Simulations showed that the GBA using this technique improved the antenna performance relative to CBA, especially in terms of gain, radiation efficiency and radiated power. Figure 5 illustrates the reflection coefficient (\( S_{11} \)) variations using different materials as the antenna conducting layers. It is shown that the DG and NDG of the CVDF-GBA and DG ML-GBA featured better \( S_{11} \) compared to CBA, while NDG ML-GBA did not indicate significant \( S_{11} \) improvements. The ML-GBA resonated at the same frequency as the CBA (at 74.5 GHz) while the CVDF-GBA resonate at (69.5 GHz), which is lower than the CBA. The shift in the resonant frequency is due to the changes to its bulk material properties due to the additional composite and adhesive materials on the patch and ground plane. Moreover, the substrate thickness of the CVDF-GBA also increased more than that of the CBA and ML-GBA due to the adhesive intermediate layers [25] [16]. The variation in radiated power is clear when the conducting layers of the rectangular patch antenna were changed to graphene (ML or CVDF), as the DG radiates higher power
compared to copper. Meanwhile, the NDG based antenna radiated similar amount of power as the copper-based antenna. CVDF-GBA also indicated higher radiated power compared to ML-GBA in the case of using NDG, see Figure 6.

![Figure 5](image5.png)

**Figure 5.** Reflection coefficients ($S_{11}$) of the rectangular patch based on copper, ML and CVD (NDG and DG) graphene.

![Figure 6](image6.png)

**Figure 6.** Radiated power for rectangular patch antenna based on copper, ML and CVD (NDG and DG) graphene

The calculated antenna performance parameters for the three antenna models: CBA, ML-GBA and adhesive CVDF-GBA are summarized in Table 2. It shows the effects of using different antenna conducting layer materials on reflection coefficient, gain, radiation efficiency and radiated power. Figure 7 shows the farfield radiation pattern of these antenna models based on different materials, which are simulated using CST software. The proposed CVDF-GBA is validated to be efficient and comparable terms of performance when benchmarked to the behavior of antenna based on ML-G.
Figure 7. The farfield radiation pattern of antenna models based on (a) CBA, (b) ML-D-GBA, (c) CVDF-ND-GBA, (d) CVDF-D-GBA

Table 1. Antenna performance when copper, NDG and DG is used as the conductive layer.

|                | CBA  | ML GBA | CVDF GBA |
|----------------|------|--------|----------|
| Patch Width    | 1500 | 1500   | 1500     |
| $f_r$ in GHz   | 74.5 | 74.5   | 69.5     |
| $S_{11}$ at $f_r$ | NDG  | 19.22  | 17.89    | 32.09    |
| $S_{11}$ in dB | DG   | 23.93  | 35.04    |
| Gain in dB    | NDG  | 6.74   | 6.56     | 6.71     |
|                | DG   | 7.33   | 6.93     |
| $\eta_{rad}$ at $f_r$ (%) | NDG  | 80.37  | 76.94    | 86.06    |
|                | DG   | 91.57  | 89.43    |
| $P_{rad}$ in watt | NDG  | 0.396  | 0.378    | 0.426    |
|                | DG   | 0.454  | 0.440    |
4. Conclusions
The modeling of CVD graphene film when applied as the conducting layer of a rectangular microstrip antenna operating in the MMW band is proposed and conducted. This is motivated by the complexities of fabricating a monolayer graphene on a target substrate, or the transfer process of monolayer graphene from a transitional substrate to this substrate. This process may lead to crack and tear in the graphene layer, affecting its final quality. The proposed technique of using adhesive and the CVD film without the removal of its metallic backing potentially enables a simpler fabrication process for MMW antennas. Moreover, the employment of such technique at the proposed frequency range indicated comparable performance with antenna designed using ideal doped monolayer graphene, and similar improvements when compared to a copper-based antenna. Such technique, particularly when using DG, improves reflection coefficient, gain, radiation efficiency and radiated power, besides enabling the use of commercial off-the-shelf graphene to overcome the limitations of facilities and technical knowledge on producing graphene-based components.

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