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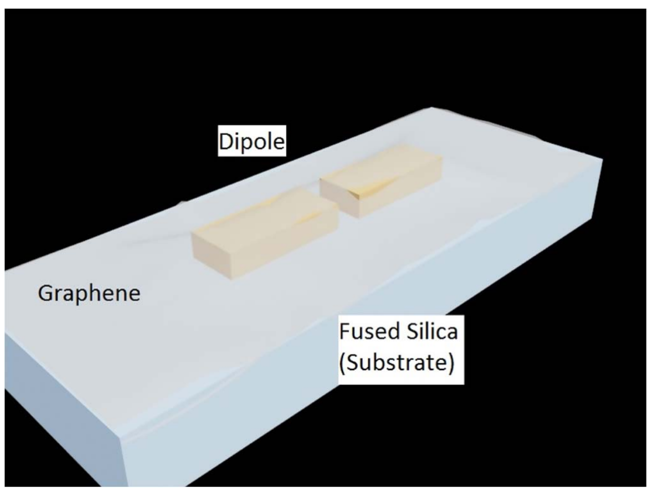

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Tuning the Scattering Response of the Optical Nano Antennas Using Graphene

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Abstract: In this paper, we propose the tuning of the optical nano antenna in the visible spectrum using graphene. A dipole structure for the nano antenna is considered with the resonating wavelength at the VIS-NIR spectrum range. Resonance is determined using the scattering characteristics of the dipole antenna. Placing monolayer and bilayers of graphene sheets on top of the optical nano antenna will result in a change in the resonating wavelength. The input impedance of the resultant structures is calculated. The FDTD simulation results for resonance characteristics were verified with the experiment results. Such architecture of graphene on top of the dipole nano antennas can be used for different biological and chemical gas sensors.

Index Terms: Graphene, nano antennas, plasmonics.

1. Introduction

Optical antennas are the antennas that have their resonating frequency in the visible spectrum of electromagnetic radiation [1], [2]. This makes the size of the optical antennas very small in the range of 100–200 nm. Due to the recent advancement in the fabrication technology, it is possible to fabricate optical nano antennas with such small sizes. The material used for the fabrication of the nano antenna is metal such as silver, gold, and aluminum. The main reason to use these metals for the optical antenna structure is because they behave as plasma of electrons at visible frequencies [3].

Plasmonic resonances in graphene have also been studied by different groups [4]–[7]. The plasmonic resonance frequency for graphene lies in the far IR range [7]. The main reason for the graphene to have plasmonic resonance in the far IR range is because at the far IR range, the energy of the incident wave has energy less than the chemical potential of the graphene [7]. Recent work has shown that tuning of the plasmonic resonance frequency can also be achieved in a graphene structure by controlling the chemical potential through applying the gate bias [8]–[10]. However, it is to be noted that for all the devices mentioned [8]–[10] the resonance frequency lies in the mid-IR to far-IR frequency range. Graphene does not generate plasmons when visible light is incident on it.

In this paper, we do not generate any plasmons in graphene but use graphene as a material, which will be transferred on top of the plasmonic antennas, to control the resonant frequency of the antenna structures, which lie in the visible spectrum (400–1000 nm). In this paper, we analyze the response of the nano dipole antenna structure when it is covered with single and multi layers of graphene. Dipole antenna is a standard structure for analysis of optical nano antenna [2], [4].

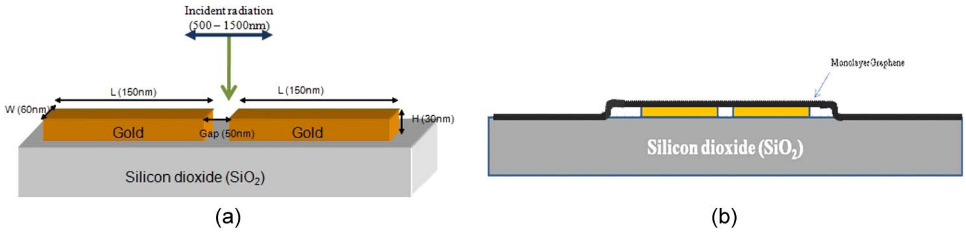


Fig. 1. Dipole structure and graphene on dipole structure. (a) Dipole structure with the incident light. (b) Dipole structure with graphene.

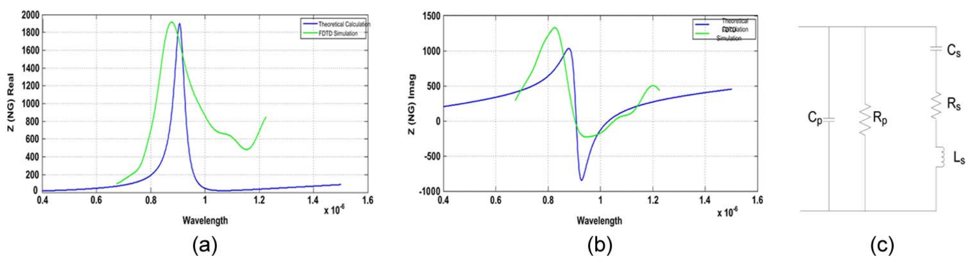


Fig. 2. (a) Real (Z) impedance. (b) Imaginary (Z) impedance. (c) Equivalent circuit of the dipole shown in 1a. Green curve represents FDTD simulation output and blue curve represents calculations.

Resonance characteristics and the input impedance characteristics are simulated using FDTD (Finite Difference Time Domain) [11], [12] method for the dipole structure.

2. Simulation of Optical Nano Antennas

The structure for the optical dipole antenna is shown in Fig. 1(a). As shown in the structure, the length of the arm of these nano antennas is 150 nm. The gap separation between the two arms of the dipole antenna is 50 nm, and the width and the height of the dipole arm of the antenna is chosen to be 60 nm and 30 nm, respectively. These dimensions of a dipole antenna, made of gold, will have a resonance peak in the range of the spectrometer (500–1100 nm). The base substrate over which this dipole antenna structure is built is transparent fused silica. The model, used in the FDTD simulation, for gold is obtained from [13], and fused silica model is obtained from [14]. Fig. 3 shows the scattering spectrum of the dipole nano antenna.

Fig. 2(a) and (b), respectively, shows the plot of the input resistance (Re (Z)) and the input reactance (Im (Z)) for the dipole structure shown in Fig. 1(a). Highest mesh accuracy was selected to give the most accurate results. The wavelength of the input dipole source was varied from 500 nm to 1500 nm. Fig. 2(c) shows the equivalent circuit for the dipole antenna shown in Fig. 1(a).

The electrical equivalent circuit of the dipole structure is shown in Fig. 2(c). This equivalent circuit is drawn based on the techniques discussed in [15]. The series resonance observed in Fig. 2(a) and (b) is represented by the series combination of L_s, C_s, and R_s. The parallel resonance is determined by the combination of C_p and R_p. The values of C_s, L_s, R_s, C_p, and R_p are determined to be 0.472 aF, 0.538 pH, 25 ohms, 1.15 aF, and 10 k ohms, respectively. These values are calculated using (1)–(3). The air gap represents a capacitive reactance and is a major contributor to the term of C_s. Assuming the value of C_s to be equal to the capacitance by the gap and ignoring any fringe capacitance, we calculate its value using equation (1) [16]. We assume the value of the R_p to be 10 k ohms so that the peak of the resonance curve of equivalent circuit matches with the FDTD simulation output

$$Z = \frac{i * length}{\omega \epsilon \epsilon_0 (width * thickness)}. \tag{1}$$

A comparison of the outcomes from the FDTD simulation and the model values determined is shown in Fig. 2(a) and (b). There is a little difference in the values as the FDTD simulation tool also takes into consideration the effects of any fringe and parasitic components. The series frequency of the device can be calculated using equation (2) below

$$f_{series} = \frac{1}{(2\pi\sqrt{L_s C_s}}). \tag{2}$$

From the graphs in Fig. 2(a) and (b), we can say that series resonance takes place at 1055 nm. Using the series resonance value of 1055 nm and the value of C_s calculated from equation (1), we can determine the value of the different components. The formula for the parallel resonance is given as follows in equation (3):

$$f_{parallel} = \frac{1}{2\pi}\sqrt{\frac{1}{L_s C_s} + \frac{1}{L_s C_p}}. \tag{3}$$

At parallel resonance, the value of the reactance is zero. This results in a peak in the resistance at 915 nm. Using the values of C_s and L_s calculated using equations (1) and (2), we determine the values of C_p from equation (3). So as the output of this equivalent circuit matches with the output from the FDTD simulation, we can say that the model for the dipole antenna is correct. The values of R_s and R_p are used to fit the peak values of the theoretical curves with the FDTD simulation curves.

3. Adding Single Sheet of Graphene to Optical Nano Antenna

Now, we simulate the dipole structure under different conditions in which the dipole antenna is covered with a monolayer/bilayer graphene. The structure looks as what is shown in Fig. 1(b). The optical conductivity of graphene is given by the following equations (4)–(10), [17], [18]:

$$\sigma_r = \sigma_0 \left[\frac{(18 - (\hbar\omega/t)^2)}{(\pi 12\sqrt{3})}\right]\psi_r \kappa \tag{4}$$

where

$$\psi_r = tanh\left(\frac{\hbar\omega + 2\mu_c}{4k_B T}\right) + tanh\left(\frac{\hbar\omega - 2\mu_c}{4k_B T}\right) \tag{5}$$

$$\kappa = 4.6936 - 2.897 tanh\left(|\hbar\omega - 2t|^{0.546}\right), \hbar\omega < 2t \tag{6}$$

$$\kappa = 4.6936 exp\left(-0.7714|\hbar\omega - 2t|^{0.4727}\right), \hbar\omega \geq 2t \tag{7}$$

$$\sigma_i = \frac{\sigma_0}{\pi}\left\{\frac{4\mu_c}{\hbar\omega}\left[1 - 2\left(\frac{\mu_c}{3t}\right)^2\right] - \left[1 - \left(\frac{\hbar\omega}{6t}\right)^2\right]\Psi\right\} \tag{8}$$

where

$$\Psi = log\frac{|\hbar\omega + 2\mu_c - \psi_i|}{|\hbar\omega - 2\mu_c + \psi_i|} \tag{9}$$

$$\psi_r = 2k_B T\left\{tanh\left(\frac{\hbar\omega + 2\mu_c}{4k_B T}\right) - tanh\left(\frac{\hbar\omega - 2\mu_c}{4k_B T}\right)\right\} \tag{10}$$

where, T is the temperature (300 K), t is the hopping parameter (2.7 eV) [17]–[20], ω is the frequency of the incident light, and μ_c is the chemical potential of graphene. σ_r and σ_i are the real and imaginary parts of the optical conductivity. The dielectric constant of the graphene was calculated using the optical conductivity calculated from the above equations (4)–(10). From [17] we can use a single layer of graphene as a 3-D material with a thickness of 0.34 nm for simulation

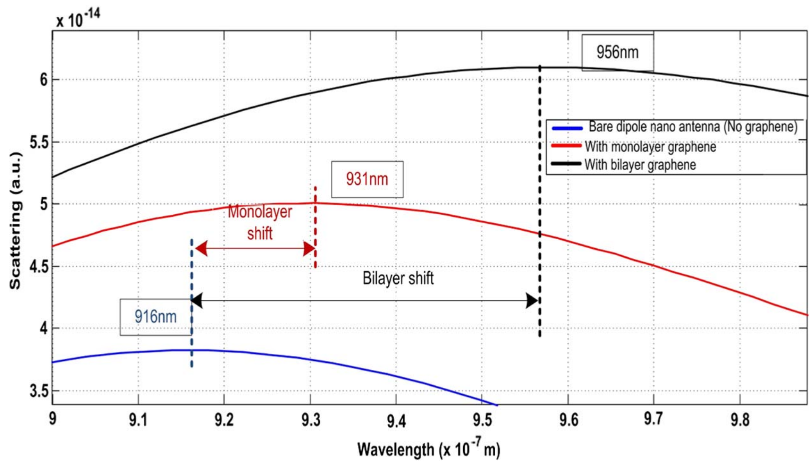


Fig. 3. Scattering spectrum of dipole shown in Fig. 1.

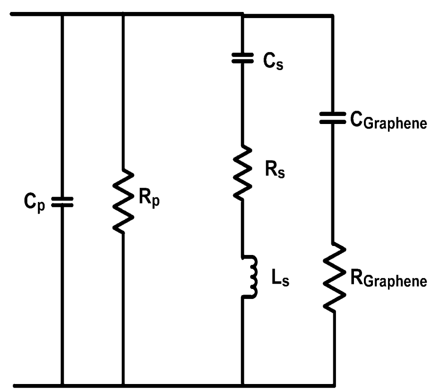


Fig. 4. Equivalent circuit for the dipole nano antenna covered with graphene. Graphene is represented as a combination of capacitor and resistor.

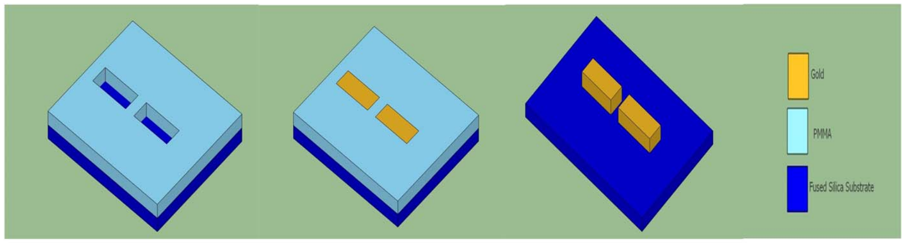
purposes in the FDTD solver. We use single layer graphene as a 3-D material with 0.34-nm thickness in our analysis.

The dipole structure with graphene on top is as shown in Fig. 1(b). We use the same technique for the calculation of the resonance wavelength as we had used it for the dipole structure in Section 2. The scattering spectrum is as shown in Fig. 3. We see that the resonance wavelength has red shifted by 15 nm and 40 nm upon introducing a monolayer and bilayer of graphene, respectively, on top of the dipole structure. This shift is proportional to the number of layers of graphene used. The equivalent circuit for the graphene loaded dipole nano antenna is as shown in Fig. 4.

4. Graphene as a Optical Capacitor

Plasmonic oscillations are generated in graphene at mid and far IR frequencies [4]–[7]. Thus at optical frequencies graphene is not plasmonic and also has a real part of the dielectric constant greater than zero at visible frequencies. The complex electrical permittivity for graphene is given by following equation (11) [17], [18]:

$$\epsilon_{eff} = 1 - j\frac{\sigma_c}{\omega\epsilon_0 d} = \left(1 + \frac{\sigma_i}{\omega\epsilon_0 d}\right) - j\frac{\sigma_r}{\omega\epsilon_0 d} \qquad (11)$$



(a) (b) (c)

Fig. 5. Fabrication steps for dipole nano antennas. Steps include e-beam lithography, metal deposition and lift-off process.

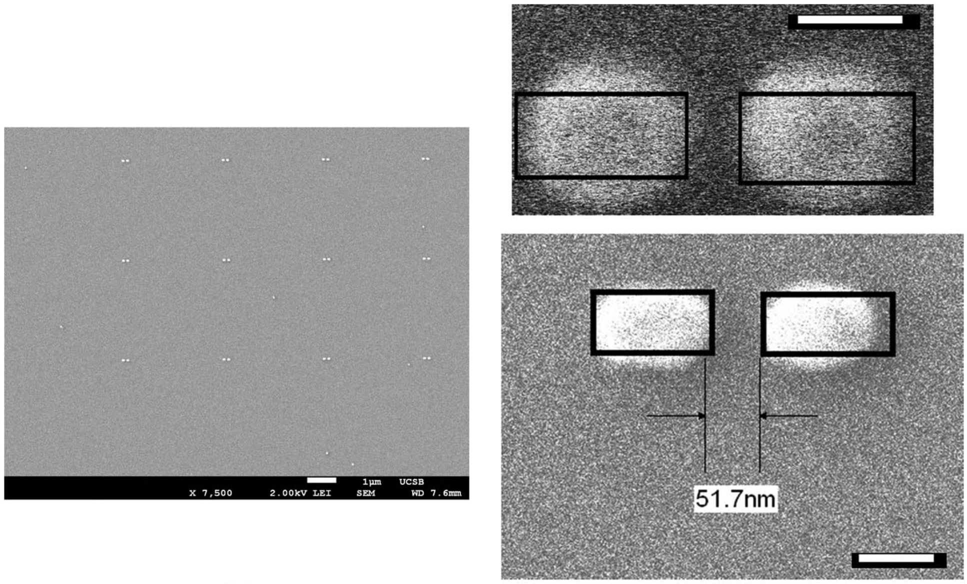
where, σ_c is the optical conductivity, and σ_r and σ_i are calculated using (4)–(10). From the concepts discussed in [21], any material at a given frequency of incident radiation in the visible spectrum, if $\epsilon_r > 0$, it acts as a capacitor and if $\epsilon_i \neq 0$, it acts as a resistance in its electrical equivalent circuit. The refractive index for graphene has been experimentally verified in [22]–[24] by reflective spectroscopy. So, from both the techniques mentioned in [17] and [22]–[24], we can say that for graphene as $\epsilon_r > 0$ and $\epsilon_i \neq 0$, at optical frequencies, therefore, it acts as a combination of capacitor and resistor, as shown in Fig. 4.

5. Experimental Results

5.1. Fabrication Process

The simulation results were verified using the experiments. For experiments, an array of dipole nano antenna structures was fabricated using e-beam lithography, thermal deposition, and lift-off. The fabrication steps are as shown in Fig. 5. Gold was used for the fabrication of the dipole nano antennas. Fused silica is used as the substrate and titanium is used as an adhesion layer between gold and fused silica substrate. Fig. 6 shows the SEM images of the dipole structure. The two consecutive dipole nano antennas were separated by a gap of 3 μm. The dipole structure was fabricated in an area of 1 mm by 1mm. This resulted in a large number (more than 250 000) of dipole nano antennas in the array. The fabrication was done in 1 mm by 1 mm area to simplify the optical measurement setup needed to test the device.

From the SEM images it can be noticed that dipole nano antennas are reduced in size. It is challenging to fabricate exactly rectangle structure, as shown in Fig. 5. The fabricated structures have curved corners. This results in a blue shift from the expected simulation response. The blue shift is because of the smaller volume of the fabricated devices than the devices used in the simulation [25]. The fabrication of the dipole nano antenna was specified with a 5% tolerance to reduce the cost. Proximity corrections can be used to fabricate structures close to the dimensions used for the simulation; however, it increases the cost. So in the 1 mm by 1mm area of interest, there are more than 250 k nano antennas. These nano antennas have a tolerance of 5% in their dimensions and, additionally, there are random variations introduced in the dimensions during the fabrication, as shown in Fig. 6(b), where the length of both the arms of the dipole is not exactly the same. It is to be noted that a small variation in the dimension shifts the resonance frequency from the desired value. This is explained using the Fig. 7. These variations in the dimensions of the individual antennas affect their resonance spectrum resulting in either red or blue shifted resonance spectrum. The spectrum acquired for the experiment is the cumulative spectrum of all the nano antennas placed in the 1 mm by 1 mm area. As there is random variations in the fabricated nano antennas, this results in over all broadening of the resonance spectrum, as shown in Fig. 7. In addition, the spectrum for plasmonic nano antennas always show a broad spectrum and have a low Q-factor. CVD grown graphene used for this experiment was purchased from CVD Corporation. It was determined to be monolayer graphene from the Raman Spectrum.



(a) (b)

Fig. 6. SEM images of the dipole nano antennas. (a) SEM Image of dipoles in an array. (b) SEM image of a single dipole. The black box represents the actual expected size and shape. The SEM image is in the background. Scale bar is 100 nm.

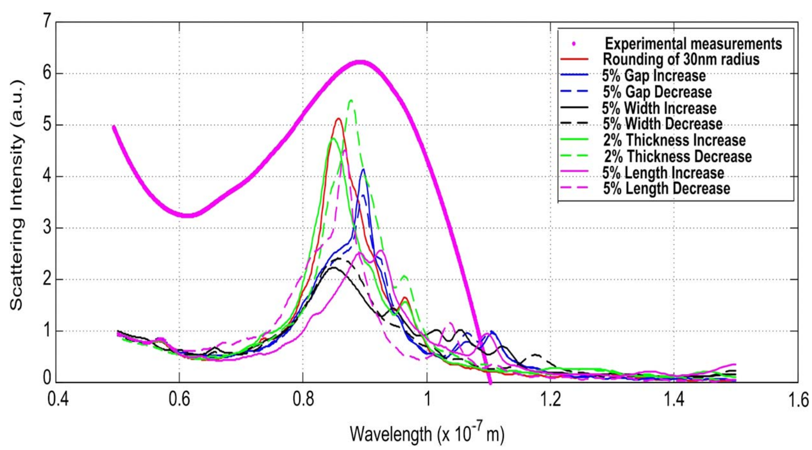


Fig. 7. FDTD simulation of the realistic devices fabricated with 5% tolerance.

5.2. Experimental Setup and Measurements

The spectrum for the fabricated dipole was obtained by determining the transmission spectrum for the dipole nano antennas. The experimental setup is as shown in Fig. 8(b). CCS 175 spectrometer, from Thorlabs, was used to determine the spectrum of the dipole antennas. Integration time of 1 sec with 50× blocking average and 3× average scans was used to determine the spectrum. Broadband light source was used for illuminating the dipole nano antennas. Transmitted light was collected using a 10× objective and focused on the fiber optic cable ($NA = 0.22$), which was connected to the optical spectrometer. Spectrum was acquired for two conditions, one was for simple dipole structure without any graphene on top of the dipole nano antennas and the second one was for graphene covering the dipole structure. The Raman spectrum of graphene on dipole nano antennas is as shown in Fig. 8(a).

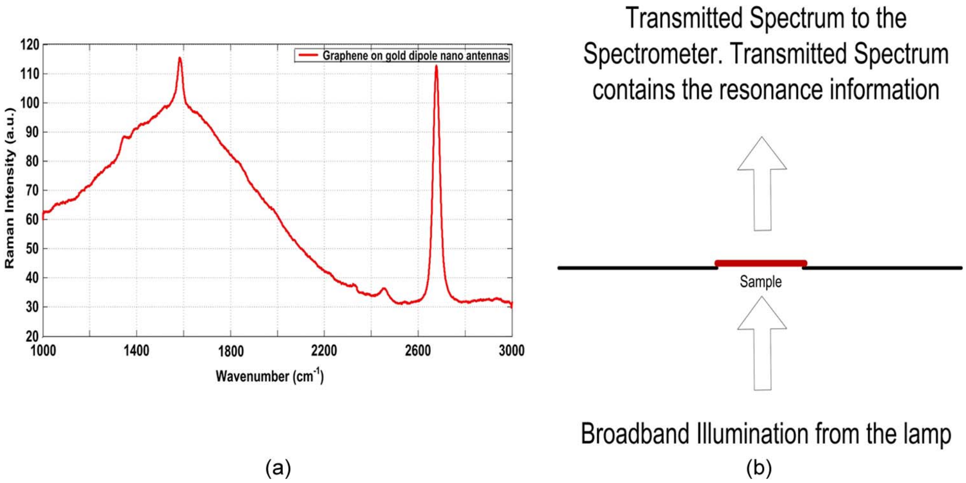


Fig. 8. Raman spectrum of the dipole nano antennas and the experimental setup for the dipole nano antennas. (a) Raman spectrum of monolayer graphene on gold dipole nano antennas (in red). (b) Transmission spectrum experimental setup.

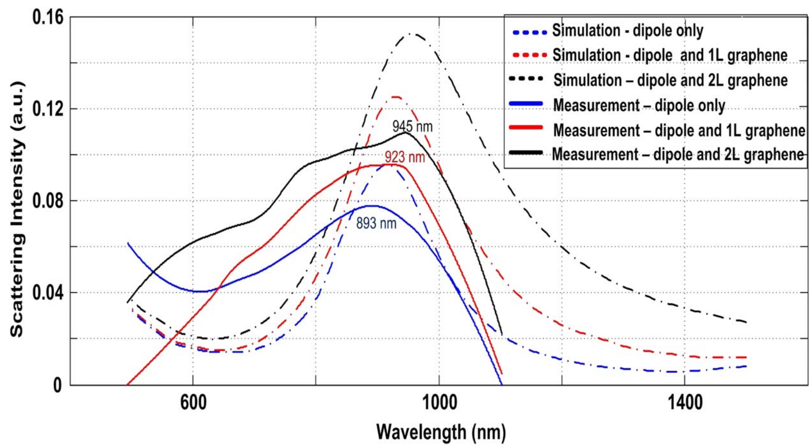


Fig. 9. Experimental measurements for monolayer and bilayer graphene on top of the dipole. Simulation outputs are drawn with dotted lines.

The results of the transmission experiment are as shown in the Fig. 9. For comparison purposes, we also have the simulation outputs along with the experimental measurements in Fig. 9.

As we see in the spectrum, there is a red shift of 30 nm and 52 nm introduced because of the monolayer and bilayer graphene on top of the dipole structure. From the FDTD simulation, we can determine there is a shift of 15 nm and 41 nm introduced because of the monolayer and bilayer graphene. From the simulation and the experiment values, it can be said that the dielectric permittivity of graphene is dependent on the number of layers used. As the number of layers vary, the dielectric permittivity also varies. This matches well with the experiments performed by Fresnel's equation by reflection spectroscopy [22] and also from equation (11).

6. Conclusion

A tuning method for the dipole nano antennas using graphene has been demonstrated in this paper. This method of tuning the nano antenna differs from the previously proposed techniques [16]. In the previous technique it is proposed to deposit a insulating material within the gap of the dipole, which involves complex fabrication techniques. However, in this work, we propose the tuning of the nano antenna by transferring monolayer of graphene. Graphene transfer is relatively simple process and does not require any complex fabrication techniques. This has been proved by FDTD simulation and verified by experimental results. This combination of dipole nano antennas coated with graphene can have extensive application in the field of chemical and biological sensors. Graphene does not affect the electric field distribution of the dipole nano antennas [26] and also results in good adsorption for different molecules and thus will result in a greater shift in the resonance frequency.

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